# ICCS29

## 29th International Conference on Composite Structures

Faculty of Architecture

University of Cagliari, Italy

22-26 June 2026

# Conference program

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Emanuele Reccia

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# Welcome Address

The abstracts collected in this book represent the proceedings of the conference 29th International Conference on Composite Structures, 22-26 June 2026. This book aims to help you to follow this Event in a timely and organized manner. Papers are selected by the organizing committee to be presented in phisical/virtual format. The event, held at the Faculty of Architecture, University of Cagliari (Italy), follows the success of the first 28 editions of ICCS. As the previous ones, this event represents an opportunity for the composites community to discuss the latest advances in the various topics in composite materials and structures.

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# Abstracts

## Additive manufacturing

### Process Parameters Determination for Incremental Sheet Forming of Custom 3D Printed Materials

abst. 1072
**TIGELLIO**
Wednesday
June 24
16h30

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Application of 3D printing is necessary for rapid and efficient fabrication of customized multi material/layer composite sheets [1]. Such sheets are not commercially available and should be custom-made using both commercial filaments (e.g., biocompatible) as well as in-house extruded composite filaments with functional fillers (e.g., conductive, antibacterial, etc.). Despite 3D printing capabilities to manufacture complex shape structures, 3D printing faces limitations, especially in producing thin-wall nonplanar multi-material components. Limitations include reduced part strength and durability due to inter-layer defects and surface artifacts, and the high cost, as well as limited accessibility of curved-layer printing technologies. The idea of this research is based on applying incremental sheet forming (ISF) for custom material 3D printed sheets to manufacture complex shape parts. Integration of polymer composite 3D printing and ISF processes into a hybrid manufacturing workflow has already been addressed only by several studies [2], thus it has not been well developed yet. Combination of such processes requires application of model-based engineering for early-stage evaluation of the final structure as well as ISF process to avoid failures and prevent high production costs. Existing numerical models still cannot predict forming results accurately enough for industrial demand [3]. The current work focusses on addressing this issue and creating an advanced numerical model in LS-Dyna using *CONTACT_FORMING option further extended by integral peridynamics theory [4] to evaluate possible material failure. Firstly, material properties (e.g., elastic modulus, yield strength, etc.) of formed polymer material structure are determined from experimental tests including possible different process variables: material printing parameters, printing directions, temperatures, etc. Cupping test is performed to find the failure strain of the formed material. Secondly, the ISF process of the 3D printed polymer material sheet is performed and validated finite element model (FEM) is created in LS-Dyna. Finally, FEM is used to test different process parameters and their resultant manufacturing output, which helps to create a training database for AI and then determine rational process parameters. In addition to this, peridynamics theory-based strain compatibility parameter [5] is computed, applying peridynamic differential operator to check if such parameters setup does not result in formed material failure due to cracking. References: 1.Wang, Z.; Wang, L.; Tang, F.; Shen, C. PLA-Based Composite Panels Prepared via Multi-Material Fused Filament Fabrication and Associated Investigation of Process Parameters on Flexural Properties of the Fabricated Composite. Polymers 2024, 16, 109. https://doi.org/10.3390/polym16010109. 2.Garcia-Romeu, M. L., Ferrer, I., Pasotti, C., Coma, J., Rosa-Sainz, A., Centeno, G. (2022). Preliminary study on the use of 3D printed biodegradable polymeric sheet for the manufacturing of medical prostheses by SPIF. Procedia CIRP, 110, 76-81. https://doi.org/10.1016/j.procir.2022.06.016. 3.Y.

Abdel-Nasser, N. Ma, S. Rashed, K. Miyamoto, and H. Miwa, "Numerical Modelling for Efficient Analysis of Large Size Multi-Stage Incremental Sheet Forming," J. Manuf. Mater. Process., vol. 8, no. 1, 2024, doi: 10.3390/jmmp8010003. 4.S. A. Silling and F. Bobaru, "Peridynamic modeling of membranes and fibers," Int. J. Non. Linear. Mech., vol. 40, no. 2–3, pp. 395–409, Mar. 2005, doi: 10.1016/j.ijnonlinmec.2004.08.004. 5.E. Madenci, A. Yaghoobi, A. Barut, N. Phan, A. Iliopoulos, and J. G. Michopoulos, "Peridynamics enabled digital image correlation for tracking crack paths," Eng. Comput., Feb. 2022, doi: 10.1007/s00366-021-01592-4.

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abst. 1098
**TIGELLIO**
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## Mechanical properties adjustment of continuous fiber reinforced 3D printed lattice deployable mast based on soft-hard bi-material mesoscopic structure

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Lightweighting, functionalization, and intelligence are the inevitable trends of aerospace development. Fiber-reinforced lightweight structures, with the collaborative design advantage of material and structure, have become the key to realize these trends. Based on the background of aerospace solar sail deployable mast, this study innovatively designs a lattice deployable mast to achieve lightweighting, and proposes a mesoscopic scale soft-hard bi-material strategy. The strategy achieves multi-directional mechanical properties adjustment of load-bearing and bending deformation of deployable mast through the coordinated layout of soft and hard materials. The lattice deployable mast is constructed in an alternating manner in three directions: 0°, 60°, and 120°. In the thickness direction, three layers of hard materials and two layers of soft materials are alternately arranged. Multi-material 3D printing technology and curved surface forming process realize the accurate forming of lattice deployable mast from two-dimensional plane to three-dimensional curved surface. Through the combination of numerical simulation and experimental testing, the compression and bending mechanical behavior of lattice deployable mast was systematically studied. Results show that soft and hard bi-material strategy has a significant effect on the stiffness compared with single hard material. The plane compression stiffness increased from 0.18 N/mm to 0.25 N/mm, which increased by 38.89%. In the three-point bending experiment, the bending stiffness increased from 0.15 N/mm to 0.26 N/mm within the deformation displacement of 35 mm, which increased by 73.33%. It should be noted that when the deformation exceeds 35 mm, the deployable mast begins to enter the bending and contracting stage. At this time, the deformation stiffness of soft and hard bi-material structure (1.15 N/mm) is lower than that of single hard material structure (1.33 N/mm), demonstrating better deformation compliance. In the study, the introduction of soft material not only synergistically enhanced the load-bearing and bending stiffness, but also improved its shrinkage characteristics under large deformations, effectively verifying the feasibility of this strategy in adjusting the mechanical properties of lattice deployable mast. The relevant achievements provide a new solution for the collaborative design of multi-directional mechanical properties of aerospace solar sail deployable mast.

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abst. 1112
**TIGELLIO**
Wednesday
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15h10

## Path geometry-dependent material parameters of additively manufactured fiber-reinforced composites

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Fused Filament Fabrication (FFF) is an established additive manufacturing (AM) process that employs filament-based materials in order to build structures in a layer-wise manner. To increase the structural

stiffness and strength on the material level, carbon fibers are used within the plastic filament. Compared to short carbon fibers, continuous carbon fibers provide a significant improvement in strength and stiffness. Pre-impregnated carbon fiber filament with a predefined cross-surface is extruded along with a polymer matrix to achieve a desired path geometry. The resulting structures exhibit highly anisotropic material behavior, especially due to the printing path directions within each layer. The stiffness of continuously-carbon fiber reinforced structures can be improved even further, if the material is deposited along numerically optimized orientations [1]. In order to match optimized orientation fields in three-dimensional structures as close as possible, the filament can be deposited on non-planar surfaces using varying layer [2]. However, this variation of path geometry leads to varying fiber content throughout the structure and therefore varying material properties. This work presents quantitative material stiffness and strength parameters depending on printing path width and height of continuously carbon-fiber reinforced PETG. The homogenized material properties are determined through multiple tests along and perpendicular to the fiber direction of unidirectional test specimens subject to tensile and compressive loading. References: [1] K. Steltner, J. Kipping, T. Schüppstuhl, B. Kriegesmann, A workflow for designing stiffness-optimized structures in the context of additive manufacturing of endless fiber-reinforced composites, Journal of Thermoplastic Composite Materials, (2025). [2] J. Kipping, T. Schüppstuhl, Enabling non-planar load oriented deposition of carbon fiber reinforced polymers by varying layer height, Additive Manufacturing Vol. 111, (2025).

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## High Strain-Rate Mechanical Characterization of FDM-Manufactured PEEK Using Split Hopkinson Pressure Bar Testing

abst. 1115
**TIGELLIO**
Wednesday
June 24
17h30

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Polyether ether ketone (PEEK) is a high-performance thermoplastic polymer widely employed in aerospace, automotive, and biomedical applications due to its superior mechanical strength, thermal stability, and chemical resistance. Recently, fused deposition modeling (FDM) has emerged as a promising manufacturing route for producing complex PEEK components; however, the high strain-rate mechanical behavior of additively manufactured PEEK remains insufficiently characterized. In particular, the influence of FDM processing on the dynamic response of PEEK under impact-type loading conditions is not yet well understood. In this study, PEEK specimens were manufactured using an industrial high-temperature FDM system (CreatBot PEEK-300), which enables controlled nozzle temperature, heated build plate, and elevated chamber temperature to promote proper interlayer bonding and crystallization. Printing parameters such as raster orientation, layer thickness, and thermal conditions were carefully selected to obtain repeatable and defect-minimized specimens suitable for dynamic testing. The high strain-rate compressive behavior of the printed PEEK samples was experimentally investigated using a Split Hopkinson Pressure Bar (SHPB) apparatus. Dynamic stress–strain responses were obtained over a range of strain rates representative of impact and crash-related loading scenarios. Key mechanical parameters, including dynamic elastic modulus, peak stress, strain-rate sensitivity, and energy absorption capacity, were evaluated and compared with quasi-static reference data. The effects of FDM-induced anisotropy and interlayer interfaces on wave propagation and failure mechanisms were also examined. The results reveal a pronounced strain-rate dependence in the mechanical response of FDM-manufactured PEEK, with notable increases in strength and stiffness at higher strain rates. Furthermore, printing-induced microstructural features significantly influence the deformation and failure modes under dynamic loading. The findings provide new insights into the applicability of additively manufactured PEEK components in impact-critical engineering applications and contribute to the limited experimental database on the high strain-rate behavior of high-performance thermoplastics produced by FDM. This study demonstrates the feasibility of combining high-temperature additive manufacturing with SHPB testing as an effective framework for evaluating the dynamic performance of advanced polymer materials and supports the structural use of FDM-printed PEEK in demanding engineering environments.

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abst. 1149
**RIVA**
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June 25
12h30

## Hybrid manufacturing and mechanics of titanium and nickel-based architected materials and interpenetrating phase composites

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Architected metallic materials and interpenetrating phase composites (IPCs) represent a rapidly emerging class of multifunctional systems that transcend the limitations of conventional cellular solids. By exploiting topology-driven design freedom and hybrid manufacturing, such materials can be tailored to simultaneously deliver high mechanical efficiency, enhanced damage tolerance, and improved thermal and impact performance. In this work, architected materials based on Ti-6Al-4V and Nickel alloys are systematically investigated, alongside their corresponding metal–metal IPCs, to elucidate structure–property–performance relationships under quasi-static and impact-relevant loading conditions. Sheet-based triply periodic minimal surface (TPMS) architectures, exemplified by the Gyroid topology, and stochastic spinodal architectures are employed as reinforcement phases. These two design classes represent fundamentally different load-transfer mechanisms: periodic, curvature-continuous pathways in TPMS structures versus statistically isotropic, disorder-driven connectivity in spinodal networks. Ti-6Al-4V and Nickel lattices are fabricated via laser powder bed fusion, while IPCs are produced using a hybrid approach combining additive manufacturing with vacuum-assisted infiltration of a secondary metallic phase. Microstructural characterization using SEM, EDS, and XRD confirms high-fidelity architectural reproduction, co-continuous phase formation, and strong metallurgical bonding at metal–metal interfaces. For single-phase architected materials, both Ti-6Al-4V and Nickel lattices exhibit high stiffness-to-weight ratios but limited post-yield deformation, with Ti-6Al-4V showing earlier strain localization due to its intrinsic low ductility. Nickel architected materials demonstrate comparatively enhanced plasticity and delayed collapse, particularly in spinodal configurations. Upon formation of IPCs, the mechanical response is transformed: Young's modulus and peak strength increase by factors of 2–4, while ductility and toughness are dramatically enhanced through stable, distributed plastic flow in the infiltrated phase. Gyroid-based IPCs consistently exhibit higher stiffness and peak strength due to continuous load paths, whereas spinodal IPCs provide superior damage tolerance and more progressive collapse. Impact and crashworthiness-relevant metrics, including energy absorption, specific energy absorption, mean crushing force, and crush force efficiency, reveal a strong dependence on reinforcement topology. TPMS-based reinforcements maximize peak load-bearing capacity, beneficial for structural protection, while spinodal reinforcements mitigate force spikes and promote uniform energy dissipation, advantageous for impact mitigation. Nickel-based systems further outperform titanium counterparts under impact-relevant deformation due to their higher intrinsic ductility and strain-rate tolerance. Thermal performance analysis shows that single-phase Ti-6Al-4V lattices possess inherently low thermal conductivity, whereas Nickel architectures provide moderate improvements. In contrast, IPCs achieve order-of-magnitude enhancements in effective thermal conductivity through co-continuous metallic pathways, without compromising mechanical integrity. These multifunctional gains position Ti- and Ni-based IPCs within a previously inaccessible performance space combining strength, toughness, energy absorption, and heat dissipation. Overall, the results demonstrate that reinforcement phase topology and base alloy selection critically govern mechanical, thermal, and impact responses. By judiciously combining Ti-6Al-4V or Nickel architected reinforcements with suitable infiltrated phases, next-generation multifunctional architected materials can be engineered for demanding aerospace, defense, and energy applications where simultaneous load-bearing, impact resistance, and thermal management are required.

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abst. 1151
**RIVA**
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## Relating Microstructure and Processing to Adhesion Performance for Large Area Additive Manufacturing Polymer Composite Extrusion/Deposition

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Polymer extrusion/deposition is perhaps the most popular additive manufacturing technology as it offers significant design flexibility with extensive material options at a low cost. While including chopped carbon fibers into the polymer matrix has been shown to improve thermo-mechanical properties, fiber inclusions appear to promote micro void fomration in the bead microstructure, leading to inferior part performance. This presentation considers the process-property-performance (PPP) relationship for large scale additive polymer composites extrusion deposition additive manufacturing. More specifically, the focus is on the effect of the extrusion-deposition process on fiber orientation and micro-void formation, and the subsequent effect of the printed material microstructure on bead adhesion. Micro CT is used to characterize the microstructure within printed neat and carbon fiber ABS (CF-ABS) beads where correlation between fiber alignment and void formation is explored for the pellet feed stock, a freely extruded strand, a deposited bead, and a roller compacted bead. Micro CT scans were performed with a Northstar Imaging X3000 system at 1.4 micron resolution and Volume Graphics software was used for imaging analysis. A Strangpresse Model 19 single screw extruder was used to produce the test samples. Scan results show that negligible micro-void formation occurs in the neat ABS while significant void content appears in the CF-ABS pellets, extrudate and beads. Void volume fraction increases as a result of the extrusion process, however, deposition and roller compaction both decrease void content. Further image processing reveals that a high percentage of micro-voids are positioned at the tips of the suspended fibers. To better understand the factors that may contribute to CF-ABS micro-void formation, fiber tip pressure within the extrusion/deposition polymer composite melt flow was evaluated with a custom multiscale finite element modeling procedure. Quasi-static single fiber angular velocity and surface pressure were calcualted with a Newton-Raphson iteration approach that zeros fluid induced fiber torque and force at the micro-scale. Then, fiber motion was computed as a function of time using Runga-Kutta iteration which was shown to agree with Jeffery's orbit for ellipsoidal fibers in Newtonian flows. Single fiber simulations showed a significant low-pressure zone presents itself near the tip of a fiber as it rotates into the direction of alignment with the flow. Further, evaluation of single fiber motion along macro-scale finite element generated streamlines of extrusion-deposition flows showed that low fiber tip pressures peaked as fibers exit the nozzle and the melt flow turns during deposition. While specific formation of micro-voids has yet to be simulated, these results identify a new fundamental mechanism for potential micro-void occurrence at fiber tips during processing. Finally, a finite element study and fracture toughness testing are presented which highlight the dependence of interlayer bead adhesion on fiber orientation and micro-void content. A transient thermal analysis was performed in ABAQUS where beads are added to the finite element mesh using the element birth algorithm. An eight bead single stack model was analyzed to obtain the temperature history at bead interfaces during deposition for various assumed microstructures (i.e., various scenarios of fiber orientation and micro-void content). Results show higher cooling rates in beads closest to the build platform (assumed to be a room temperature) and similarly, higher temperature gradients occur when randomly oriented fiber microstructures are assumed. Further, a degree of healing calculation was performed which indicated a significantly lower adhesion between beads occurred near the build platform and when random orientations were assumed. Fracture toughness testing was then performed on printed samples which showed that intrabead strength increased with distance from the build plate and also with decreased fiber alignment, agreeing qualitatively with the simulation results. The overall results provide significant insight into the complex relationship between large scale carbon fiber composite material extrusion-deposition process, the properties of the bead microstructure, and ultimately the bead-to-bead adhesion performance.

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## 3-D printing based innovative repair of thermoplastic composites

abst. 1170
**RIVA**
Thursday
June 25
12h10

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Thermoplastic composites are gaining increasing interest across high-performance industries due to their recyclability, rapid processing capability, and improved damage tolerance. Nevertheless, in-service damage can compromise structural reliability and necessitate efficient, high-quality repair methods. Traditional repair techniques often struggle to create strong, reproducible bonds in thermoplastic matrices without extensive heating infrastructure or complex surface preparation. This study presents a repair concept that leverages 3-D printing to fabricate patches integrating a conductive interfacial layer. The printed conductive layer enables localised Joule heating at the patch/substrate interface, allowing controlled fusion bonding without requiring bulk heating of the parent structure. Patches were manufactured using fused-filament fabrication (FFF) method with thermoplastic matrices matching the target substrates. This architecture allows precise spatial control of heat generation, enabling rapid and energy-efficient bonding. Damage was introduced in glass fibre reinforced thermoplastic laminates, followed by patch application under various current, pressure, and heating-cycle conditions. Mechanical performance evaluation was complemented by microscopy and micro-CT to assess interface quality and healing behaviour. Preliminary results show that Joule-heated fusion bonding achieves strong interface consolidation. The approach offers a highly adaptable, low-energy alternative to conventional repair methods and demonstrates the potential of multi-material additive manufacturing to enable intelligent, field-deployable repair technologies for thermoplastic composite structures.

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abst. 1174
**TIGELLIO**
Wednesday
June 24
16h50

## An Experimental-Based Design Framework for Failure Prediction of Continuous Fiber Fused Filament Fabrication Components

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In the advancement of Additive Manufacturing (AM), Continuous Fiber Fused Filament Fabrication (CF4) has recently been developed as an innovative approach to enhance the performance and strength-to-weight ratio of 3D printed parts. Through the employment of dedicated equipment, CF4 enables the fabrication of high-strength lightweight components reinforced by embedding continuous filaments of carbon fiber, fiberglass, or Kevlar along selected directions. Although the materials available for this technology have been characterized and the data on the mechanical properties of continuously reinforced specimens have been reported, a comprehensive methodology or protocol for effectively implementing CF4 equipment in the production of components for technical applications represents a gap in the literature. Therefore, this research work presents a model based on an extensive experimental campaign previously conducted, with the objective of defining safe operational thresholds for CF4 materials in automotive and aerospace applications, and predicting the failure modes and fracture mechanisms. As part of the experimental campaign, a built-in material card was obtained from multiple batches of mechanical tests, including tensile, in-plane shear, Double Cantilever Beam (DCB), End-Notched Flexure (ENF), and compression tests. These experimental activities were carried out following an elaborated Design of Experiment (DoE) developed to identify and quantify the correlation between material properties and the influence of process parameters. All specimens were additively manufactured using a Markforged® Mark Two 3D printer, which allows layer-by-layer reinforcement following defined fiber orientation paths. A regression-based approach was adopted to support the post-processing methodology, enabling the effective extrapolation and integration of the experimental results. Furthermore, the experimental outcomes were validated through Finite Element Method (FEM) analyses to assess the accuracy and reliability of the obtained data. Microscopic investigations, including optical and stereoscopic analyses, were also performed to examine the load-bearing cross-sectional areas, fibers integrity, and fracture mechanisms of the specimens. The results of the experimental campaigns shall be employed as input for the predictive model designed to estimate failure mechanisms and define safe operational parameters for the CF4 design process. Finally, the proposed model will be validated through the analysis of a real-case study in future works.

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**TIGELLIO**
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# Extrusion Behavior and Parameter Investigation of Fused Filament Fabrication of Fiber Reinforced Poly Ether Ether Ketone Including Closed-Loop and Pressure Control

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The Usage of additively manufactured components has significantly increased in several industries, especially in aviation and aerospace. Modern aircraft engines consist of around 10 percent printed metal components. Within the next decade, this proportion could rise to over 20 percent. On the other hand, polymer-based additive manufacturing involves more parameters than metal-based processes, and the basic materials have been less well researched so far, especially high-performance materials like Poly Ether Ether Ketone PEEK. Therefore, reinforced polymer-based printed components can only be approved for industrial use under significant restrictions and compromises in material performance. To address this gap, several research groups are investigating the additive extrusion process in general and using methods such as OFD, FMEA, SWOT, and TRIZ [1,2]. As result, the major characteristic is the melt state of the polymer and its solidification [3]. One factor influencing the melt state is the composition of the feedstock material, which was investigated by Sommacal et al. [4]. Another factor is the fluid pressure and thus the throughput of the nozzle [5]. Investigating the fluid pressure requires detailed understanding of the extrusion process. Therefore, we split the entire additive extrusion processing of pure and fiber-reinforced PEEK into its basic mechanisms, such as material shape, feed rate, friction losses, etc.. This approach makes it possible to measure the contribution of each parameter to the overall printing quality and enables the creation of process guidelines. The feedstock material defines the input based on its shape and feedability. Fluctuations in these parameters are not corrected without additional controls. The fluctuation from the measured mean value is between -3.1 and +1.3 percent for pure PEEK and between -2.1 and +2.1 percent for reinforced material. The surface texture, together with the force transmission of the feeding mechanism, determines the feedability. The drive-motor causes a fluctuation of less than 0.025 percent and can be disregarded. In summary, the shape of the feedstock material defines the input tolerance. In addition to material supply, the feed rate is a crucial process sequence. For this reason, the position and type of feeding recording are being investigated. A specially developed optical measuring setup is used as validation system. This enables in-process measurements of movements smaller than 5 micrometers. The difference to a mechanically based measurement is 1 percent. Since the tolerance of the measuring is significantly smaller than the position of the detection, the impact of a mechanical measurement at the print head can be clarified and be used for closed-loop control. Despite closed-loop control of the feeding rate, fluctuations in process quality still occur. Although controlling the feeding rate halves the fluctuations in feeding pressure at the print head, extrusion is not constant. In addition to the inconsistent material feed, various friction losses occur. The results show controlling tolerances based on feed control is not sustainable. Instead, the results show the use of a pressure sensor in the print head holder as an input signal provides better results. This is the next step toward a more controllable additive extrusion process. References: [1] Kabir et al.; A critical review on 3D printed [. . . ]; Composite Structures 2020;232:111476 [2] Matschinski et al.; Analysis for understanding and standardization [. . . ]; ESAform 2021 [3] Fallon et al.; Highly loaded fiber filled polymers [. . . ]; Additive Manufacturing 2019;30:100810 [4] Sommacal et al.; Detailed void characterisation by X-ray [. . . ]; Composite Structures 2023;38:116635 [5] Osswald T.A. et al.; Fused filament fabrication melting model; Additive Manufacturing 2018;22:51–9.

abst. 1196
TIGELLIO
Wednesday
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15h30

## MECHANICAL PERFORMANCE OF MULTILAYER CFRP COMPOSITES WITH POLYURETHANE COATING

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Carbon fiber reinforced polymer (CFRP) composites are increasingly used in mechanical engineering applications due to their favorable strength-to-weight ratio and high stiffness. Nevertheless, their behavior under impact loading and their sensitivity to surface damage remain important considerations in structural design. The application of protective coatings represents a potential approach to modifying the mechanical response of CFRP structures under both static and dynamic loading conditions. This study investigates the influence of a Raptor polyurethane coating on the mechanical performance of multilayer CFRP composites. The coating was applied using a number of different application methods, leading to variations in coating characteristics and coating–substrate interaction. For comparative purposes, uncoated CFRP samples were also tested to assess whether applying a Raptor polyurethane coating, regardless of the application method, would significantly improve the mechanical properties of the test material. Experimental investigations included impact resistance tests as well as quasi-static mechanical tests such as flexural bending and tensile loading. Particular attention is given to the role of the coating in altering damage initiation and progression in the composite structure. The analytical section of the article utilized a high-speed camera to observe the material's response to impacts, and analyzed graphs from an instrumented impactor in an Instron drop hammer. This allowed for the generation of accurate results and the drawing of proper conclusions. The results of this work contribute to a better understanding of the interactions between polyurethane coatings and CFRP substrates under mechanical loading. These findings provide a basis for further optimization of coating application methods aimed at improving the durability and mechanical reliability of composite structures used in mechanical engineering, as well as modifying other aspects of carbon fiber-based polymer composite manufacturing at earlier production stages. Keywords: sandwich composite, coating, impact strength, application, bending.

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abst. 1243
TIGELLIO
Wednesday
June 24
16h10

## Ultrasound-assisted 3D printing of glass fiber-reinforced polymers

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Particle-reinforced polymers attracted great attention in aerospace and automotive, where fiber alignment plays a critical role. Conventional manufacturing methods and magnetic/electric field-based fiber alignment techniques require certain filler geometries and electromagnetic properties, severely limiting their applicability. In this study, a novel ultrasound-assisted stereolithography additive manufacturing technique was developed, exploiting acoustic radiation forces generated from the acoustic property mismatches between fiber fillers and polymer matrix, manipulating multidirectional alignment of glass fibers and graphene particles during 3D printing. A method to quantify the fiber alignment level was developed and profound effects of ultrasonic driving voltage and fiber mass fraction on the fiber alignment rates were clarified, enabling up to 93.44% orientation rate within the target angular range. Tensile testing of four fiber-aligned specimens revealed that the 0° unidirectionally aligned sample exhibited superior performance, with tensile strength increasing by 46.29% compared to random-aligned samples and by 91.43% compared with pure polymers. By integrating a rotating platform with the acoustic radiation force field, layer-by-layer fiber angle control was realized, facilitating the fabrication of complex 3D structures—including bionic flowers, character patterns, and intricate geometries. The developed technique was further validated using spherical nickel-coated graphite particles, attaining a 90.20% orientation rate, expanding its potential for aligning particles with different geometries during 3D printing of particle-reinforced polymers.

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## Low and High-Strain-Rate Mechanical and Energy Absorption Performance of Additively Manufactured Re-Entrant PEEK Structure

abst. 1249
**RIVA**
Thursday
June 25
13h10

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Re-entrant lattice geometries exhibiting negative Poisson's ratio behavior have attracted significant attention for energy absorption and impact mitigation applications due to their enhanced deformation stability and progressive collapse mechanisms. When combined with high-performance thermoplastics such as polyether ether ketone (PEEK), these architected structures offer strong potential for lightweight, impact-resistant engineering components. However, the strain-rate-dependent mechanical response and energy absorption capability of additively manufactured re-entrant PEEK structures remain largely unexplored, particularly under high strain-rate loading conditions. In this study, novel re-entrant lattice structures were designed and manufactured using fused deposition modeling (FDM) with PEEK filament. The geometries were developed in-house to promote controlled deformation, delayed densification, and improved energy absorption under compressive loading. Specimens were fabricated using a high-temperature FDM system under optimized printing conditions to ensure adequate interlayer bonding and dimensional consistency. The mechanical behavior of the re-entrant PEEK structures was experimentally investigated over a wide range of strain rates, including quasi-static loading and three distinct high strain-rate levels using a Split Hopkinson Pressure Bar (SHPB) apparatus. Dynamic stress–strain responses were obtained, and key performance indicators such as peak stress, specific energy absorption, crushing efficiency, and strain-rate sensitivity were evaluated. The deformation and collapse mechanisms were examined to identify the influence of strain rate on structural stability and failure progression.

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## Energy Absorption Performance of Cylindrical Additively Manufactured Architected Structures

abst. 1272
**TIGELLIO**
Wednesday
June 24
15h50

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The mechanical properties of architected materials are controlled by modifying its geometry rather than base material. In this way, diverse mechanical properties can be attained with the use of same material. The developments in additive manufacturing (AM) technology facilitated the production of complex architectured materials. In this study, compression energy absorption performance of cylindrical architected structures is investigated. Fused filament fabrication (FFF) printer is used for manufacturing cylindrical architected structures. The specimens are made from thermoplastic polyurethane (TPU). The material properties of TPU are obtained from compression and tension tests. These data are then implemented into commercial finite element analysis (FEA) software LS-DYNA. TCylindrical compression samples are tested in quasi-static condition by exploiting universal testing machine. The experimental testing is simulated in FEA by defining fixed boundary condition for bottom plate and prescribed motion for top plate, thus the cylindrical architected structure is squeezed between two plates. The ensemble and deep learning machine learning (ML) methods are used for mapping nonlinear stress-strain, the correlation between structural design parameter and the predicted energy absorption. The FEA and ML results are in conformity with experimental data. The designed structure showed tunable energy absorption capability.

abst. 1293
RIVA
Tuesday
June 23
12h10

## Impact of specimen geometry and hole preparation technique on bearing strength performance of 3D printed reinforced polymer composites


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This study investigates the influence of fiber orientation, specimen thickness, and hole preparation techniques on the bearing strength of bolted joints in 3D-printed Carbon Fibre Reinforced Polymer (CFRP) composites. Specimens were manufactured using a Markforged Two 3D printer with different layer layups (longitudinal and quasi orientation) with samples with integrated printed holes and with post-processed drilled holes using the drilling/reaming technique. ASTM D5961's double lap shear test was used to evaluate how fibre steering and continuity affect mechanical performance and failure progression. Drilled hole specimens performed slightly better in mechanical performance, achieving an average peak bearing stress 18.04% higher than their printed specimens. The strength of drilled specimen with the hole reached 402.08 MPa, compared to 321.94 MPa in the printed specimen, which is a 22.14% improvement in the strength. This was due to the lower fibre in the printed specimens using the weaker white nylon matrix with a lower fibre volume fraction (29.87%) compared to Onyx (36.36%). Failure mode analysis revealed consistent bearing failure with internal damage in printed specimens, linked to progressive and ductile failure, while drilled samples mostly showed bearing and net tension failure mode, associated with fibre disruption and abrupt net-tension cracking. These results underscore the structural advantage of preserving fibre paths through integrated printing. Computed tomography (µCT) was carried out to investigate the fibre orientation around the hole in printed samples which confirms voids/porosity cause early failure in the samples with holes printed. Optical and scanning electron microscopy was carried out to see the failure behaviour and it was noticed that failure mainly occurs due to delamination/debonding and fibre pull-out. The findings are particularly relevant to aerospace and automotive applications demanding predictable failure and lightweight, high-performance design. Overall, this study supports the use of fiber-steered printed holes to improve joint strength and reliability in CFRP components.


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abst. 1314
RIVA
Tuesday
June 23
12h30

## Process defects related failure mechanisms and of 3D-printed continuous carbon fiber-reinforced honeycombs


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3D printing of continuous carbon fiber-reinforced structures relieves molds in composite manufacturing and gives flexibility to the design of lightweight and robust honeycombs. Nevertheless, how process defects affect the failure mechanisms of 3D-printed continuous carbon fiber-reinforced honeycombs

remains undisclosed. To advance this research area, it requires a comprehensive investigation of the failure mechanisms and process defects of 3D-printed continuous carbon fiber-reinforced composite circular and auxetic honeycombs, with particular attention to the influence of stacking orientations and Poisson's ratios. In this study, continuous carbon fiber-reinforced 3D printing has been introduced to fabricate circular and auxetic honeycombs. Both in-plane and out-of-plane quasi-static compression experiments were carried out. The mechanical properties and failure mechanisms were investigated through experimental analysis and cross-section observation, from which the microscopic voids and weak interfaces were identified as the dominating factors influencing the failure modes. This study provides insights into the association between process defects and failure mechanisms of 3D-printed continuous carbon fiber-reinforced honeycombs, which offers guidance for the design of lightweight and robust composite structures.

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## A Multiscale Framework for Process Modeling in Thermoset Composites

abst. 1330
**RIVA**
Tuesday
June 23
12h50

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Manufacturing processes for thermoset composite materials involve tightly coupled thermochemical and mechanical phenomena acting across multiple length and time scales. Cure kinetics, heat transfer, resin flow, chemical shrinkage, and evolving material properties interact in complex ways during processing, leading to the development of residual stresses, geometric distortions, and curing-induced defects such as voids and microcracks. These process-induced features have a critical impact on the structural integrity and long-term performance of composite components, yet remain difficult to predict using conventional single-scale modeling approaches. This work presents a multiscale framework for process modeling in thermoset composites, in which hierarchical and concurrent multiscale modeling strategies are combined to capture the evolution of material behavior from the microscale to the structural scale. At the microscale, physics-based models are employed to describe resin cure kinetics, temperature-dependent reaction rates, chemical shrinkage, and the evolution of viscoelastic and mechanical properties during polymerization. These microscale mechanisms are upscaled to inform mesoscale descriptions of fiber–matrix interactions, ply-level anisotropy, and damage initiation while preserving sensitivity to local processing conditions. At the macroscale, the framework couples thermal, chemical, and mechanical fields to simulate manufacturing processes such as autoclave curing and out-of-autoclave processing. The proposed framework enables predictive simulation of residual stress accumulation, curing-induced distortions, and the initiation of microcracks arising from chemical shrinkage, thermal mismatch, and constrained deformation during processing. Representative numerical examples are presented to demonstrate the capability of the framework to capture the influence of processing parameters and cure cycles on stress evolution and defect formation. The results highlight the importance of accounting for multiscale interactions in thermoset composite manufacturing and illustrate the potential of the proposed framework as a virtual tool for process optimization, defect mitigation, and improved manufacturing-informed design of composite structures.

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## Topologically Variable Heterogeneous Lattice Infills: A Novel Algorithm and Effective Property Assessment

abst. 1395
**RIVA**
Tuesday
June 23
13h10

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Additive Manufacturing (AM) has significantly expanded engineering design possibilities by enabling the fabrication of complex geometries unattainable through conventional processes [1][2]. Among these, lattice structures have attracted considerable attention for their ability to achieve lightweight designs with tailored mechanical properties. In particular, heterogeneous lattices, characterized by spatial variations in unit cell topology, offer enhanced design flexibility but remain challenging to implement due to difficulties in ensuring geometric compatibility and mechanical continuity between adjacent cells [3]. Building upon previous work introducing a connectivity-preserving geometric algorithm for beam-based unit cells compatible with AM constraints, this study presents a novel geometrical algorithm for the generation of topologically variable heterogeneous lattice infills. The structures are modelled as equivalent continua with spatially varying effective properties derived from unit cell geometry, enabling accurate mechanical representation while reducing computational cost. The resulting lattice systems constitute architectured composite materials whose effective mechanical properties are obtained through asymptotic homogenisation of the underlying unit-cell topology. Assuming constant effective properties within each unit cell further improves numerical robustness and optimization convergence. The proposed workflow integrates CAD modelling (OpenCascade), adaptive meshing (Gmsh), and finite element analysis (FEniCSx) into a unified design-to-simulation pipeline. The methodology is validated through numerical simulations and experimental testing of additively manufactured demonstrator specimens, showing strong agreement between predicted and measured performance. Acknowledgements: This work is supported by MIUR, project: National Center on HPC, Big Data and Quantum Computing (ICSC), PNRR - CN1- Spoke6 (CUP: B83C22002940006), Sapienza Ateneo Progetti Grandi (CUP: B83C24007070005), and PROGETTO MUSICS - FISA-2023-00099 (CUP: B83C25000810001). References: [1] L. Cheng, J. Liu, A. C. To, "Concurrent lattice infill with feature evolution optimization for additive manufactured heat conduction design", Structural and Multidisciplinary Optimization, 58, pp. 511-535, 2018. [2] F. Ituarte, N. Kretzschmar, "Implications of lattice structures on economics and productivity of metal powder bed fusion", Additive Manufacturing, 31, 100987, 2019. [3] F. De Canio, M. Pingaro, P. Trovalusci, "Topologically-tunable heterogeneous infills for 3D printing: a lattice design algorithm", Submitted, 2026.

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## Advanced numerical techniques for composite structures and materials

### A Dual-Reciprocity Boundary Element Formulation for Two-Temperature Time-Fractional Thermoelastic Analysis of Layered Composite Shells with Cavities

abst. 1010
**Repository**

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A novel boundary element method (BEM) formulation is developed to investigate the two-temperature, time-fractional thermoelastic behavior of layered composite shells containing internal cavities under transient thermal shocks. The model integrates Caputo fractional heat conduction, representing nonlocal thermal memory, with a two-temperature framework that distinguishes conductive and thermodynamic temperatures, thereby capturing non-equilibrium heat transfer at microstructural scales. Each composite layer is characterized by distinct anisotropic thermal and elastic properties, and multi-domain coupling is rigorously enforced through interface continuity of temperature, heat flux, displacement, and traction. The governing equations are transformed into the Laplace domain and solved using dual-reciprocity BEM to eliminate domain integrals, enabling efficient and accurate simulation of complex geometries without volumetric meshing. Numerical inversion of the Laplace transform recovers the full transient response. Parametric results reveal that decreasing the fractional order $\alpha$ induces subdiffusive thermal waves and delays stress development, while increasing the two-temperature parameter bbb enhances thermal nonlocality and smooths transient gradients. Validation against analytical benchmarks confirms excellent accuracy, stability, and convergence of the formulation. The proposed approach provides a robust and computationally efficient tool for analyzing advanced composites and microstructured materials exhibiting fractional and non-equilibrium thermal behavior, offering new insight into the coupled thermomechanical response of functional layered systems subjected to high-rate thermal loading.

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### 3D static thermo-magneto-electro-elastic analyis of flat and curved structures

abst. 1032
**TIGELLIO**
Wednesday
June 24
12h10

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Nowadays, thermo-magneto-electro-elastic coupling is an unexplored phenomenon for some classes of smart materials. These cutting-edge intelligent materials can be useful for the development of advanced aerostructures for the next generation of satellites, aircraft, and space vehicles. Their main innovations and advantages lie into functioning as sensors and actuators that respond to external thermal, magnetic, electric, or mechanical loads. To enable the use of these intelligent materials in the design of innovative aerostructures for next-generation space and aeronautical vehicles, the behaviour of thermo-magneto-electro-elastic structures must be deeply investigated. To understand the static behaviour of these intelligent smart structures, a 3D thermo-magneto-electro-elastic analytical model for multilayered spherical shells is proposed. Thermo-magneto-electro-elastic full coupling is included considering the six second-order differential equations for the thermo-magneto-electro-elastic problem as a unique set of equations. The six second-order differential equations consist of: the 3D equilibrium equations, the 3D divergence equation for the magnetic induction, the 3D divergence equation for the electric displacement and the 3D Fourier heat conduction. The use of the orthogonal mixed curvilinear reference system permits to investigate the behaviour of spherical shells, plates, cylinders and cylindrical panels. The set of second-order differential equations are solved in a closed-form solution taking into account the Navier harmonic forms in the in-plane directions and the exponential matrix method in the thickness direction. To correctly evaluate the 3D behaviour of considered structures, a layer wise approach is introduced by considering interlaminar continuity conditions on displacements, magnetic potential, electric potential, temperature, transverse shear and transverse normal stresses, transverse normal magnetic induction component, transverse normal electric displacement component and transverse normal heat flux component. Some preliminary results will be presented to validate the model. Then, new results for simply supported multilayered plates, cylinders, cylindrical panels and spherical shells will be proposed for different thickness ratio (from thick to thin structures). All

the possible involved effects for this smart material structures will be shown and discussed in terms of thermo-magneto-electro-elastic coupling, curvature of structures, material layers and lamination schemes and thickness layer values.

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abst. 1043
**Repository**

## A Locking-Free Variationally Consistent Finite Element Formulation for Functionally Graded Timoshenko Curved Tapered Beams

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Functionally graded materials (FGMs) have attracted increasing interest thanks to their ability to overcome inherent limitations of laminated composites, leading to widespread use in advanced engineering applications. This has motivated extensive research on the modeling, analysis, and optimization of FGM beams, plates, and shells, with continuing efforts to develop simple, reliable and computationally efficient structural models. Complex geometries of many FGM components pose significant challenges to robust numerical modeling. While finite element methods have proven highly versatile, standard displacement-based formulations for curved Timoshenko beams typically suffer from shear-locking in slender configurations and membrane-locking when curvature increases. Common strategies, such as assembling short straight elements or resorting to hybrid-mixed formulations, either require many elements or are restricted largely to uniform cross-sections, with only limited extensions available for non-uniform geometries. This work proposes a simple, and effective finite element formulation for functionally graded Timoshenko curved tapered beams. The formulation is based on a complementary-energy-based variational setting in which the approximations satisfy all equilibrium equations in strong form, inherently eliminating both shear- and membrane-locking. The accuracy and robustness of the formulation are demonstrated through representative benchmark examples, and the obtained numerical results are thoroughly analyzed and discussed.

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abst. 1059
**TIGELLIO**
Wednesday
June 24
12h30

## Validation of analytical models for adhesive-bonded single-lap joints using a physics-informed neural network

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Recent advances in computational resources and data science have led to the rapid growth of deep learning neural networks, a class of machine learning algorithms that has gained popularity due to its practical applicability across a wide range of science and engineering fields. One prominent and emerging application of deep learning is the solution of partial differential equations (PDEs). This has led to the development of physics-informed neural networks (PINNs), which incorporate physical laws to solve the differential equations governing specific scientific problems. As PINNs have proven to be an effective approach for solving PDEs, specialized algorithms are required that embed initial and boundary conditions directly into the cost function of artificial neural networks (ANNs) through automatic differentiation, ensuring consistency with the underlying physics. The validation of analytical models in engineering mechanics is commonly performed using experimental measurements or high-fidelity numerical simulations. However, closed-form analytical solutions are available only for a limited class of idealized problems. In most practical engineering applications, the governing physics is formulated in terms of PDEs, whose exact solutions are generally unattainable due to geometric complexity, nonlinear material behavior, and coupled boundary conditions. As a result, numerical discretization techniques, most notably the finite element method, are widely employed as reference solutions for model validation.

Despite their effectiveness, such methods introduce additional modeling and discretization uncertainties and require substantial computational effort, particularly when very fine meshes or small increment sizes are needed. Recent advances in physics-informed machine learning, especially deep learning frameworks that leverage automatic differentiation, offer a promising alternative for validating and solving PDE-governed problems. By embedding physical laws directly into the learning process, these approaches enable the construction of continuous, mesh-free solutions without requiring closed-form expressions or extensive experimental datasets. Nevertheless, the systematic use of physics-informed deep learning as a rigorous validation framework for theoretical models - bridging experimental observations and classical numerical simulations - remains insufficiently explored, constituting a significant research gap. As an initial application in the field of structural adhesive joints, this study validates the PINN framework against available theoretical solutions for single-lap adhesive joints. The PINN approach is employed to predict axial stresses in the bonded adherends and the distribution of shear stresses in the adhesive layer of SLAJs under two modeling scenarios: (i) a formulation that neglects shear deformation in the adherends and (ii) an extended formulation that accounts for shear deformation in the adherends. The governing physics is described by a differential equation in which the axial stresses in the upper and lower adherends are treated as the primary variables and expressed as functions of the longitudinal coordinate along the joint. The axial stress fields are obtained by solving the differential equation subject to prescribed boundary conditions, while the remaining stress components, namely the adhesive shear stresses, are derived analytically from the axial stress solutions in the adherends. The accuracy of the proposed PINN-based methodology is evaluated through direct comparison with closed-form analytical solutions for both modeling cases, obtained using Mathematica. The excellent agreement between the PINN predictions and the analytical solutions demonstrates the validity and robustness of the proposed numerical approach. Future work will extend this framework to bonded joint configurations that incorporate bending effects, enabling the prediction of peel stresses and transverse tensile stresses.

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## A geometrically nonlinear MITC6 triangular shell formulation for laminated composite structures

abst. 1118
**TIGELLIO**
Wednesday
June 24
12h50

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This work presents geometrically nonlinear analyses of laminated composite shell structures using an efficient six-node triangular shell finite element based on the Mixed Interpolation of Tensorial Components (MITC) concept. The element combines the adaptability of triangular meshes to complex geometries with the ability of the MITC method to mitigate locking issues, aiming at providing an effective numerical tool for complex composite shells characterized by large deformations and strong anisotropy. The formulation is developed within a total Lagrangian framework and employs Reissner-Mindlin kinematics to account for transverse shear deformation in moderately thick and thin shells. Large displacements and rotations are captured by means of the covariant Green-Lagrange strain measure, while selected strain components are interpolated through an MITC-based assumed strain approach in order to effectively eliminate shear and membrane locking. An equivalent single-layer laminate constitutive model is adopted, in which the orthotropic lamina stiffnesses are transformed into the shell coordinate system and analytically integrated through the thickness to obtain extensional, bending, coupling and transverse shear stiffness matrices. Validated through several numerical examples of laminated composite shells undergoing large deformations, the MITC6 shell element demonstrates the following characteristics: effective suppression of shear and membrane locking, robustness on severely distorted triangular meshes, and superior accuracy and computational efficiency relative to other triangular elements in geometrically nonlinear composite shell analyses. The results show that the well-constructed MITC6 triangular element, combined with an anisotropic laminate constitutive model, provides a practical and reliable tool for the large-deformation analysis of complex laminated composite shells in engineering practice.

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abst. 1122
**TIGELLIO**
Wednesday
June 24
13h10

## An efficient MITC9 shell element for large-deformation analysis of laminated composite shells

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This study focuses on the geometrically nonlinear analysis of laminated composite shells using an efficient MITC9 shell formulation. The Mixed Interpolation of Tensorial Components (MITC) approach is employed to develop a nine-node quadrilateral shell element. In this formulation, selected covariant components of the Green-Lagrange strain tensor are interpolated independently at optimally positioned tying points and then projected back onto the displacement field. Explicit expressions for both direct and assumed strain-displacement matrices are derived in a local Cartesian coordinate system, incorporating transverse shear strain gradients. This formulation allows the element to maintain the standard five Reissner-Mindlin degrees of freedom per node while effectively mitigating both shear and membrane locking, even under large rotations. A robust orthotropic laminate constitutive model is established in the convected shell basis. The stiffness of each orthotropic lamina is first defined in its material coordinate system, then transformed to the shell coordinates, and subsequently analytically integrated through the thickness. This yields the classical extensional, coupling, and bending stiffness matrices, as well as the transverse shear stiffness matrix, applicable to arbitrary stacking sequences. Within the total Lagrangian framework, these laminate stiffnesses are coupled with the MITC9 kinematics, resulting in a consistent tangent stiffness matrix that separates material and geometric contributions, making it suitable for Newton-Raphson iterations in large-deformation analyses. The performance of the proposed formulation is validated through several benchmark problems involving highly anisotropic laminates and large rotations. These examples include: a semi-cylindrical shell subjected to a radial point load, a cantilever plate under end-distributed loading, a circular ring plate under edge-line loading, a free-ended cylindrical shell under symmetric tensile loading, and a perforated laminated hemispherical shell under concentrated loads. In all cases, the MITC9 element accurately reproduces reference load-displacement curves and displacement contours, demonstrates locking-free behaviour even on relatively coarse meshes, and exhibits excellent robustness with respect to mesh distortion and lay-up variations, confirming its effectiveness for nonlinear analysis of laminated composite shells.

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abst. 1138
**CIMA**
Tuesday
June 23
15h10

## Development of Flip-Chip Underfills for Advanced Chip Packaging: An Integrated Computational and Experimental Approach

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Advanced semiconductor packaging is widely applied in consumer electronics, automotive systems, industrial automation, and healthcare devices, where high integration density and reliable thermal management are required. As multiple chips are integrated into a single package, efficient heat dissipation becomes critical for long-term performance and reliability. Underfill materials are used to provide mechanical support, reduce thermomechanical stress, and improve heat transfer between the chip and substrate. However, it remains difficult to achieve high thermal conductivity together with low viscosity, electrical insulation, and low coefficient of thermal expansion (CTE). Increasing the amount of inorganic fillers generally improves thermal conductivity; however, it also leads to higher viscosity and reduced processability, which can result in void formation and stress concentration. In this work, aluminum nitride

(AlN) particles are employed as thermally conductive fillers due to their high intrinsic thermal conductivity and electrical insulating behavior. A spherical-like bimodal core–shell filler structure is prepared by coating larger AlN particles with smaller AlN particles using suitable coupling agents. Different size ratios and filler volume fractions are fabricated to improve packing density and dispersion in the epoxy matrix. The bimodal filler configuration allows higher filler loading while maintaining relatively low viscosity. Thermal conductivity, viscosity, elastic modulus, electrical resistivity, and CTE of the fabricated underfill composites are measured. The microstructure and filler distribution are analyzed to understand the packing behavior of the bimodal system. The effect of filler size ratio and volume fraction on the overall composite properties is evaluated. At filler volume fractions of 45–50%, the developed underfill composites show thermal conductivities in the range of 2.3–2.7 W/m·K while maintaining viscosities between 1.94 and 7.49 Pa·s. Compared with conventional commercial underfills and previously reported epoxy-based systems, these results demonstrate a clear improvement in both thermal and rheological performance. Our results indicate that the proposed bimodal core–shell AlN filler architecture provides a practical and scalable route for the development of next-generation underfill materials, enabling efficient thermal management in advanced semiconductor packaging without compromising manufacturability or long-term reliability. This work was supported by the National Research Foundation of Korea (NRF) through the National RD Program, funded by the Ministry of Science and ICT (RS-2023-00260461).
Keywords: Epoxy-based composites, underfill materials, flip-chip, semiconductor, thermal conductivity

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## Higher order Haar wavelet method approach for high strain rate response of composite structures

abst. 1166
**RIVA**
Friday
June 26
10h20

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The high strain rate response of thin composite beams/plates subjected to impulsive loading is studied using a higher-order Haar wavelet method. The composite structures are subjected to a transient force applied either at the free end or at the midpoint. Emphasis is placed on the dynamic deformation behavior under high strain rate conditions. The study provides insight into the dynamic performance of thin composite structures subjected to impulsive loads, which is relevant to impact-resistant and lightweight structural applications. Fractional damping is incorporated into the analysis, and Caputo fractional derivatives are employed to model the governing fractional differential equations. The solution procedure is based on the separation of variables, solution of the spatial equations using beam bending formulations, solving the time-fractional equations using the higher-order Haar wavelet method (HOHWM). The influence of fractional damping on the dynamic response is analyzed in detail.

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## Z-Pin Reinforcement for Improved Tensile Strength in Stepped Co-CuredComposite Joints

abst. 1175
**Repository**

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In applications involving thin composite structures, co-curing is widely preferred over mechanical fastening techniques as it improves joint load-bearing capacity and induces a more uniform stress distribution over the bonded region. Nevertheless, the inherent low transverse strength of fiber-reinforced laminated materials and the high peel and shear stresses arising at joint edges made co-cured composite joints highly to delamination. Among the techniques proposed to enhance the delamination resistance of laminated composites, z-pinning—which consists of inserting thin metallic or fibrous pins through the thickness of an uncured laminate—emerged as a promising approach. Z-pinning has proven effective in

improving the structural performance of various joint configurations, although limited studies focused on the effect of pins with unconventional shapes. Compared to conventional straight configurations, U-shaped pins may establish additional load transfer paths between adherends while further reducing stress concentrations at joint edges. Furthermore, most of the existing studies examined reinforcing patterns involving comprehensive pinning throughout the whole overlap region, leading to high pin densities that may degrade the in-plane tensile properties of the composite laminate. Therefore, this study examines the quasi-static performance and damage progression of stepped-lap composite joints selectively reinforced with conventional and U-shaped metal z-pins. Manufactured with a cross-ply layup, joints were bonded through an overlap length of 40 mm. Before curing, selected panels were selectively reinforced with stainless steel z-pins, which were inserted into pre-punched holes aligned in four rows straddling the joint line and positioned 5 mm from the joint edges. Unpinned and pinned joints were vacuum-bagged and co-cured in an autoclave. Coupon specimens 20 mm in width were eventually cut to perform quasi-static tensile tests. Experimental findings indicate that debonding, initiating at the joint edges and propagating along the joint interface until complete adherend separation, governs ultimate failure in both unpinned and pinned configurations. To gain deeper insight into damage mechanisms, experimental tests were analyzed using multiple methodologies to characterize damage initiation and progression throughout the loading history. Moreover, a finite element model of unpinned and pinned joints was subsequently developed employing cohesive damage formulations to capture both joint and pin-laminate debonding phenomena. Numerical predictions demonstrate favorable agreement with experimental observations regarding ultimate strength, load-displacement behavior, and debonding crack evolution. The proposed model successfully captures the beneficial effect of through-thickness z-pins on joint static strength and damage tolerance, demonstrating that z-pins do not delay delamination onset but rather prevent its propagation by reducing the energy release rate at the crack front.

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abst. 1181
**CIMA**
Tuesday
June 23
15h30

## Solid shell finite elements for composite structures

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This paper presents a new solid shell finite element for geometrically linear elastic plates/shells. This finite element aims at modeling both thin and thick plates/shells without any pathologies of the classical finite element approximation (shear and Poisson or thickness locking, spurious modes, etc). This new FE uses six nodes for the approximation of the three dimensional geometry. For the displacement, it is based on the classical Equivalent Single Layer (ESL) of order one using bottom and top displacements in the three directions. In order to be efficient in the field of composite modelling, Sinus fonctions and ZigZag terms are added for the two in-plane displacements. The order of the approximation for the transverse displacement is increased, adding a third unknown, avoiding Poisson locking. The transverse normal stress is included allowing use of the three-dimensional constitutive law. Final Solid shell FE are based on 7-, 9- of 11-parameters, using 6 nodes for the three dimensional geometry. The element performances are evaluated on some standard plate/shell tests, and comparisons are given with exact three-dimensional solutions for plates under mechanical and thermal loads. All results indicate that the present element is free of locking phenomenon, highly insensitive to mesh distortion, has very fast convergence properties and gives accurate results for displacements and stresses

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abst. 1205
**CIMA**
Tuesday
June 23
15h50

## Numerical Assessment of the Vibration Correlation Technique for Buckling Load Prediction of Imperfect CFRP Cylindrical Shells

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Accurate prediction of the buckling load of imperfection-sensitive composite cylindrical shells remains a challenging problem, particularly when vibration-based techniques are applied within nonlinear numerical frameworks. This study presents a numerical assessment of the Vibration Correlation Technique (VCT) for estimating the axial buckling load of carbon fiber reinforced polymer (CFRP) cylindrical shells incorporating measured midsurface imperfections. A representative set of imperfection cases (Z15–Z26), reconstructed from previous experimental measurements, is considered. The cylinders consist of a non-symmetric four-ply laminate with a [24/-24/41/-41] layup under clamped–clamped boundary conditions, with nominal height and diameter of 500 mm, and a total thickness of 0.5 mm. The numerical investigation is conducted using LS-DYNA, with particular emphasis on mesh convergence and element formulation effects relevant to vibration-based buckling prediction. Mesh convergence studies are performed by varying shell element formulations and by progressively doubling the number of elements along the circumferential direction. This strategy ensures that the nodal locations used to impose measured midsurface imperfections remain identical across meshes, enabling consistent assessment of imperfection sensitivity. Convergence is evaluated based on the critical linear buckling load and natural frequencies of perfect shells, followed by analysis of selected imperfect configurations. VCT follows predictions that are interpreted using the Arbelo characteristic chart framework, where normalized natural frequencies and loads are correlated to estimate buckling loads. The methodology shows stable and conservative buckling load estimates across varied imperfection maps while revealing sensitivities associated with model choices. The study demonstrates the applicability of VCT within an explicit finite element framework and highlights numerical aspects, including loading-rate sensitivity, that influence the stability of VCT extraction for imperfect CFRP cylindrical shells.

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## Free vibration analysis of doubly-curved laminated shells by Legendre spectral method and a higher-order shell theory

abst. 1217
**CIMA**
Tuesday
June 23
16h10

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A highly efficient pseudospectral approach is developed for the free vibration analysis of laminated shells based on Reddy's higher-order shear deformation shell theory. Kronecker products are employed to construct two-dimensional differentiation matrices, while univariate differentiation matrices are generated using Legendre polynomials. Acknowledgements: The authors acknowledge Fundação para a Ciência e a Tecnologia (FCT) for its financial support to LAETA via the project UID/50022/2025 (DOI: https://doi.org/10.54499/UID/50022/2025).

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## Nonlinear Response Analysis of Thermo-Mechanically Coupled C/SiC Composite Joint Structures

abst. 1306
**CIMA**
Tuesday
June 23
16h30

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C/SiC composites are widely used in high-temperature service structures in aerospace applications owing to their excellent high-temperature mechanical performance and stable thermochemical properties. In practical applications, complex assembled structures inevitably incorporate numerous joints to enable component fastening and load transfer. Under dynamic loading, joint interfaces exhibit pronounced nonlinearities associated with frictional contact and thermally induced expansion, which can drive preload relaxation and joint stiffness degradation. These effects substantially alter the dynamic characteristics of the assembly and complicate reliable response prediction. In this study, a typical C/SiC joint configuration is investigated using a global–local analysis framework. The joint contact region is locally refined, and nonlinear contact elements are introduced to represent interface opening/closure, microslip/sliding, and hysteretic energy dissipation. The remainder of the structure outside the contact

zone is modeled as linear, thereby achieving a practical balance between computational efficiency and predictive fidelity. In addition, a sequential thermo-mechanical coupling strategy is employed to incorporate temperature-field-induced variations in material properties, thermal mismatch effects, and preload relaxation through temperature-dependent updates of contact parameters. This framework enables nonlinear dynamic response prediction under elevated-temperature conditions. Finally, the predicted nonlinear dynamic responses are validated against thermo-mechanical experimental response data obtained from the C/SiC joint, providing methodological support for the design optimization and reliability assessment of C/SiC jointed structures.

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abst. 1311
**CIMA**
Tuesday
June 23
16h50

## Liouville-Green Analysis of Love Wave Dynamics at Spring–Membrane Interfaces in Generalised Linearly Graded Piezo-Viscoelastic Structures with Flexoelectric and Semiconductor Coupling

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This work studies guided shear horizontal Love wave propagation in two advanced electroactive layered configurations that are relevant to next generation surface acoustic wave and sensing devices. The first model consists of a distinct functionally graded piezo-visco-flexoelectric guiding layer bonded to a distinct piezo-visco-flexoelectric half space. The second model replaces flexoelectricity with semiconducting effects and considers a distinct functionally graded piezo-visco-semiconductor layer over a distinct piezo-visco-semiconductor half space. In both models, the layer and substrate are joined through an imperfect spring-membrane interface, allowing simultaneous control of interfacial compliance and interfacial inertia in a unified manner. Viscoelasticity in the layer and substrate is described using the Kelvin-Voigt constitutive model, which naturally introduces complex wavenumbers and captures frequency dependent attenuation while retaining an analytically tractable framework. A Liouville-Green (LG) asymptotic framework is developed for the coupled field equations with spatially varying material properties. Unlike conventional graded approaches that impose a single common gradation law, the present formulation introduces a generalised linear gradient which permits independent gradation of mechanical, electromechanical, dielectric and viscous parameters, enabling a flexible description of engineered gradients. This leads to a flexible and physically meaningful description of engineered gradients and enables closed form asymptotic expressions for the depth dependent wave fields. The resulting complex secular relations is obtained for Love wave modes, capturing both dispersion and attenuation due to viscoelasticity, together with the additional size sensitive contribution from flexoelectric coupling or the electro-semiconductor interaction. Parametric results demonstrate that independent grading profiles, interface stiffness and membrane effects can be tuned to control mode confinement and enhance sensitivity to material and interfacial imperfections. The proposed dual model framework and the graded LG strategy provide a first step toward systematic design of graded smart layered media for high performance waveguiding, filtering and sensing applications.

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abst. 1326
**RIVA**
Friday
June 26
10h40

## Prediction of effective properties of short-fiber composites using a novel data-driven model

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Composites reinforced with short fibres play a significant role in modern engineering applications. The effective elastic behaviour of such materials depends on the interaction of microstructural parameters, including fibre volume fraction, fibre aspect ratio, and spatial arrangement, as well as the elastic properties of the fibre and matrix phases and the characteristics of the fibre–matrix interface. Full-field homogenization approaches based on the numerical analysis of the representative volume element (RVE) can provide highly accurate predictions of effective properties but typically require substantial computational effort. In contrast, well-known mean-field homogenization models, such as the Mori–Tanaka scheme, offer excellent computational efficiency but may exhibit limited accuracy in certain cases, particularly at higher fibre volume fractions. This work introduces a model that enriches the mean-field

homogenization framework using data generated from a full-field model. In other words, the idea is to combine the physics-based basic features of the Mori–Tanaka method with data generated from full-field, RVE-based homogenization. The objective is to achieve accuracy comparable to full-field homogenization while retaining the computational efficiency characteristic of mean-field approaches. In the previous work, such a model has already been applied to analyse composites reinforced with spherical particles. Nonetheless, analysis of short-fibre composites requires a more complex model formulation, due, among other factors, to anisotropy. In this case, both the original Eshelby and strain concentration tensors are modified using a genetic algorithm to fit the model's outcome to the database. During the conference, details of the model formulation, the database generation stage, the obtained results, and prospects will be presented.

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## Mechanical Characterisation and Numerical Modelling of Continuous Basalt and Carbon Fibre Reinforced Additively Manufactured Composites for Aerospace Applications

abst. 1337
**CIMA**
Tuesday
June 23
17h10

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Additive manufacturing of fibre reinforced polymers has enabled the fabrication of composite structures with complex geometries and tailored fibre layouts offering new design possibilities for lightweight load-bearing components in aerospace applications. In particular, the integration of continuous fibres within thermoplastic matrices offers significant improvements in stiffness and strength compared to short-fibre or unreinforced printed polymers. However, the mechanical response of additively manufactured continuous fibre composites is strongly affected by process-induced features such as fibre placement, interlayer bonding, and matrix–fibre interaction, which lead to significant void formations. This is especially true for emerging reinforcement materials such as basalt fibres, whose performance in additively manufactured composites has received limited attention compared to carbon fibres. This work presents an experimental and numerical investigation of additively manufactured composites reinforced with continuous basalt and carbon fibres. Specimens are fabricated using a fused filament fabrication-based process with in-situ continuous fibre deposition. A comprehensive mechanical characterisation is carried out, including tensile, flexural, and dynamic loading conditions. The mechanical performance of basalt fibre reinforced composites is compared with carbon fibre reinforced counterparts, highlighting their differences. Based on the experimental observations, a numerical model is developed to describe the mechanical behaviour of these materials. The model incorporates the layered nature of the additively manufactured architecture and accounts for the contribution of continuous fibres, the polyamide matrix, and fibre–matrix interfaces. Homogenisation strategies are explored to capture the mechanical response. Model predictions are validated against experimental results, demonstrating the capability of the approach to reproduce the observed stiffness and failure trends. The outcomes of this study provide insight into the microstructural properties of continuous fibre reinforced additively manufactured composites and contribute to the development of predictive numerical models for their structural analysis. The comparison between basalt and carbon fibre reinforcements further supports the assessment of basalt fibres as a cost-effective and sustainable alternative for lightweight composite aerospace structures.

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## Natural Neighbor Meshless Formulation for Crack Propagation in Composite Joints

abst. 1357
**CIMA**
Tuesday
June 23
17h30

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Structural adhesive joints bonding composite material adherends are widely used in high-end industries as well as in academic research. Nevertheless, the numerical simulation of such joints is often challenging due to the intricate stress fields, the slenderness of the specimens, and the difficulty in refining the thin adhesive layer. In this work, a truly meshless technique based on natural neighbours and the Voronoï diagram is implemented to simulate crack growth in adhesive joints. The Natural Neighbours Radial Point Interpolation Method (NNRPIM) uses the Voronoï diagram to collocate the integration points and construct the corresponding shape functions over the natural neighbours, eliminating the need for a background integration mesh. Fracture propagation is then modelled by locally remeshing the crack tip nodes. Numerical results are compared against experimental data and standard Finite Element Method (FEM) simulations. The NNRPIM solutions accurately predict the experimental data at a computational cost comparable to that of the FEM.

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abst. 1366
**TIGELLIO**
Wednesday
June 24
10h00

## Simplified modeling of defects in lattice and Variable Stiffness laminates

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Modern structures are becoming increasingly customized, with geometries and material distributions designed with unprecedented degree of flexibility. A first meaningful example is given by lattice structures, whose basic geometries can be nowadays arbitrarily generated via additive manufacturing. A second example is given by Variable Stiffness (VS) laminates, where the fibers' path - hence the elastic distribution - can be shaped to meet the desired internal load path. Manufacturing techniques based on Automatic Fiber Placement (AFP) and continuous tow shearing have been proposed in this context. One crucial feature in both additive manufacturing and AFP concerns the unavoidable presence of defects in the final manufactured components [1,2]. As compared to nominally pristine configurations, imperfect lattice structures as well as VS laminates may exhibit substantial deviations with respect to their nominal counterparts in their structural response. This work illustrates a numerical strategy for allowing imperfections to be effectively introduced in lattice structures and VS laminate models. Specifically, the investigation aims at developing new numerical tools for the preliminary design, and is therefore characterized by computational efficiency and ease of modeling. In a first part, lattice structures are assessed. Typical deviations in their geometry pattern, as well as the presence of porosity are studied and included into a 1D finite element approach, where the constitutive law is inherited from refined 3D models. In the second part of the work, the modeling of imperfections is illustrated focusing on VS laminates. The proposed strategy relies on a Ritz-based method [3], where the presence of gaps and overlaps is explicitly accounted for. Both the proposed modeling strategies demonstrate the importance of appropriately including the effect of defects to obtain accurate predictions of the structural response. In turn, this effect is proven to be relevant when preliminary optimizations are carried out.
Acknowledgments: This work was carried out within the Space It Up! Project funded by the Italian Space Agency (ASI) and the Italian Ministry of University and Research (MUR) under contract No. 2024-5-E.0, CUP No. I53D24000060005. References: [1] Cao, X., Jiang, Y., Zhao, T., Wang, P., Wang, Y., Chen, Z., Li, Y., Xiao, D. and Fang, D. "Compression experiment and numerical evaluation on mechanical responses of the lattice structures with stochastic geometric defects originated from additive-manufacturing." Composites Part B: Engineering Vol. 194 (2020) [2] Dutta, S. and Zhao, W. "Buckling of variable angle tow steered laminates considering gap/overlap defects identified using innovative image processing." Composite Structures, 368, 119221 (2025). [3] Vescovini, R., Oliveri, V., Pizzi, D., Dozio, L. and Weaver, P. M. "Pre-buckling and buckling analysis of variable-stiffness, curvilinearly stiffened panels." Aerotecnica Missili Spazio, 99, 43-52 (2020).

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abst. 1414
**TIGELLIO**
Wednesday
June 24
10h40

## Unveiling Oxygen Vacancy-mediated Metastable Phase Transitions of Yttria-stabilized Zirconia and Their Roles on Thermal Transport via Neural Network Potentials

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The atomic structures of ceramics critically govern their thermal properties. However, their atomic thermal transport mechanisms are poorly understood. Here, we developed novel neural network potentials with near-DFT accuracy, enabling the precise exploration of the atomic structural evolutions in yttria-stabilized zirconia and their influence on thermal properties. It was found that the transition of zirconia is primarily driven by tilt vibrations (from monoclinic to tetragonal) and octahedral distortions (from tetragonal to cubic), while the yttrium doping and its resultant oxygen vacancy cause local stress and lattice mismatch, thereby shifting the transition temperature. As the doping concentration increases, the energy barrier between YSZ decreases, making it easier to induce phase transitions. Meanwhile, the lattice thermal conductivities (LTCs) are mainly related to low-frequency acoustic branches and exhibit size effects, but are insensitive to anisotropy. Further analysis of phonon lifetimes reveals that the yttrium doping and associated oxygen vacancies can enhance the lattice anharmonicity and defect scattering. This work provides a pioneering theoretical approach for analyzing the structure-induced thermal properties of advanced oxide ceramics.

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## Finite Element Delamination Modeling in Elastically Coupled Composite Beams

abst. 1416
**RIVA**
Friday
June 26
09h40

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The study covers fracture behavior of carbon/epoxy laminated composite beams with different stacking sequences, exhibiting elestic coupling. Two different numerical techniques available in the Abaqus CAE software were employed to model delamination processes: the virtual crack closure technique (VCCT) and surface-based cohesive zone modeling (CZM), both relying on the finite element method (FEM). The beam models were loaded in accordance with the double cantilever beam (DCB) loading scheme commonly used to determine mode I fracture properties. The compliance-based beam method (CBBM) was employed as a data reduction scheme. This method is based on the equivalent crack length concept and provides the evolution of the strain energy release rate (SERR) under predominant mode I loading, characterized with the energetical fracture toughness measure (GI) without the problematic following of crack length. Numerical results for coupled beams were confronted with experimental data. The results revealed a good agreement in the first part of the load–displacement curve. During damage propagation, the plots differed due to the fiber-bridging phenomenon occurrence in the experimental tests.

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## Microstructure-informed finite element modelling of Carbon Forged short-fibre composites: mechanical response and piezoresistive behaviour

abst. 1421
**RIVA**
Friday
June 26
09h20

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This paper presents an experimental–numerical investigation of an in-house manufactured long-chopped carbon-fibre composite (Carbon Forged/SMC-like system), with the dual aim of assessing its piezoresistive response and developing a predictive finite element (FE) model accounting for mesostructural heterogeneity. Tensile tests were performed under displacement control with full-field strain measurements via Digital Image Correlation (DIC) and simultaneous electrical esistance acquisition using a

two-probe setup. All specimens exhibited an approximately linear relationship between normalised resistance change and axial strain, with consistently positive gauge factors, supporting resistance-based load/strain monitoring with limited instrumentation. X-ray computed tomography (μ-CT) was used to extract spatial fields of local fibre volume fraction and fibre orientation tensor. These data were exploited to reconstruct the specimen mesostructure and automatically generate an LS-DYNA model based on the *CONSTRAINED_BEAM_IN_SOLID (CBIS) approach, where fibres are represented as embedded beam elements and the epoxy matrix as solid elements. The beam diameter was calibrated teratively to match the experimental stiffness, while fibre failure was enforced through a damageable constitutive description to prevent unrealistically high beam stresses. Model validation was carried out by comparing load–displacement curves, fracture loads, sectional strain profiles along the gauge length, and fracture patterns. The framework reproduces the global fracture load with a mean deviation of 5.9% and captures the main spatial trends of the measured strain fields; remaining discrepancies are attributed primarily to manufacturing-induced porosity not explicitly represented in the current model.

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abst. 1423
**TIGELLIO**
Wednesday
June 24
09h40

## Physics-Informed Extreme Learning Machine for the Analysis of Laminated Composite Nanoshells

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Composite nanoshells are largely employed as load-carrying elements in advanced micro- and nano-scale systems for their excellent mechanical properties. However, their microstructural behavior remains still not completely understood, largely due to the lack of general and efficient analysis tools. Analytical solutions are limited to simple configurations, while numerical methods based on finite elements are often computationally expensive. This work presents a novel computational tool that can accurately capture the microscale effects of laminated nanoshells under arbitrary stacking sequences, boundary conditions, and geometries, with improved computational performance. The shell mathematical model is formulated within a Kirchhoff–Love strain-gradient shell theory derived using the differential geometry of surfaces. For the numerical solution, we employ a mesh-free method which combines Physics-Informed Neural Networks (PINNs) and Extreme Learning Machines (ELMs). The proposed Physics-Informed Extreme Learning Machine (PIELM) framework enables efficient solution of the higher-order partial differential equations inherent of nonlocal shell theories, alleviating the computational cost associated with mixed or higher-continuity finite element formulations. The efficiency of this tool is exploited to investigate microscale effects across different nanoshell configurations, providing new insights into their mechanical behavior. Overall, the proposed framework offers a versatile tool to support the analysis and design of composite nanoshells in micro- and nano-structures. Acknowledgements: The publication was made with funding from the Ministry of University and Research (MUR) under the FIS2 Grant, Project TOSSTO no. FIS-2023-01465, (CUP: J53C25000610001).

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abst. 1428
**RIVA**
Friday
June 26
10h00

## VCT-based buckling load prediction in unstiffened CFRP cylinders: Assessment of predictive robustness under varied imperfection maps and modifications to the Arbelo characteristic chart

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This study investigates the predictive capability of the Vibration Correlation Technique (VCT) for estimating the buckling load of unstiffened CFRP cylindrical shells subjected to axial compression. The analysis is based on a combined experimental–numerical dataset for ten cylinders (Z15–Z26),

including measured maps of mid-surface imperfections and thickness variations. In order to assess the robustness of the method under broader geometric scenarios, the numerical investigation was extended to include modified imperfection maps obtained by scaling and inversion of the original measured fields. Buckling load predictions were generated using the standard Arbelo-type characteristic chart and several alternative formulations based on different definitions of the unloaded natural frequency and the reference critical buckling load. The results show that the standard approach and its modified counterpart provide accurate and predominantly conservative predictions, even at relatively low load levels. The study further demonstrates that VCT remains stable over a wide range of imperfection amplitudes, confirming its robustness with respect to imperfection variability. Although the direction of imperfections affects local prediction behavior, the overall distributions of prediction deviations obtained for original and inverted maps remain comparable. A gradient-based analysis of the prediction accuracy proved effective for identifying anomalous cases in large datasets, particularly those associated with local buckling preceding global instability. These irregularities can often be reduced by including predictions derived from higher-order vibration modes. The results also highlight the strong sensitivity of VCT to the correct definition of the baseline natural frequency, indicating the importance of precise frequency measurement in practical applications. Overall, the findings confirm that VCT provides a reliable nondestructive framework for buckling load prediction in thin-walled composite cylinders with realistic and modified imperfection patterns. While selected modifications to the Arbelo characteristic chart may increase conservatism in specific cases, the standard formulation remains a robust and practically justified baseline for VCT-based prediction. This research was supported by the National Science Centre, Poland, under grant agreement no. UMO-2024/53/B/ST8/01594

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## Coupling of data-driven approaches integrating material and structural data for composite structures

abst. 1429
**TIGELLIO**
Wednesday
June 24
10h20

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This work presents a dual distance-minimizing data-driven algorithm for simulating composite structures comprising both solid and thin-walled components. In regions modeled with solid finite elements, stress–strain data are used to drive the simulation. For thin-walled components discretized with beam, plate, or shell elements, generalized stress–strain data (namely, normal force, bending moment, normal strain, and curvature) are employed to analyze the structural behavior. To connect non-matching meshes arising from different element types and discretization requirements, a penalty-based coupling technique is adopted to enforce displacement continuity and transfer interaction forces across interfaces between solid and structural elements. In this manner, the computational efficiency in thin-walled regions is enhanced by leveraging structural theories, while the accuracy in solid regions is preserved to capture localized stress fields. Several numerical examples are provided to validate the proposed method and demonstrate its robustness for coupling solid and structural elements within the data-driven computing paradigm.

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## An Open-Source Fluid-Structure Interaction Framework for Composite Plates

abst. 1435
**RIVA**
Friday
June 26
09h00

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Fluid-Structure interaction (FSI) in highly flexible, thin structures involves strong nonlinear coupling and large displacements. From the simulation point of view, demanding requirements exist in terms of coupling treatment and numerical stability of the resulting discretized problem. In our ongoing research, we address these issues by developing a fully open-source computational framework which is based on the partitioned coupling of a computational fluid dynamics solver and a computational structural mechanics solver, supplemented with an Arbitrary Lagrangian-Eulerian mesh motion strategy and an Interface Quasi-Newton acceleration technique. Our framework is intended to provide a robust and reproducible environment for simulating strongly coupled FSI phenomena in thin, deformable structures. In this context, this talk investigates the applicability of the proposed framework to composite structures, particularly thin, plate-like systems, where anisotropy can significantly affect the coupled dynamic response. In fact, studies on the behaviour of composite plates immersed in viscous flow suggest that orthotropy, lay-up, and stiffness tailoring can significantly impact oscillation amplitude, dominant frequency, and deformation patterns. This presentation focuses on the methodology of how a partitioned, open-source workflow originally developed for highly flexible thin plates can serve as a general computational basis for analysing composite structures interacting with viscous flows. This paves the way for future high-fidelity applications in the multiphysics analysis of composite structures.

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abst. 1439
**SANT'EFISIO**
Friday
June 26
15h30

## A lattice-based framework for damage and failure modelling in nano-silica reinforced pervious concrete

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This study presents a numerical investigation of the damage and failure behaviour of nano-silica reinforced pervious concrete, using the Lattice Discrete Element Method (LDEM). The material is discretised as a three-dimensional lattice of truss elements, enabling the simulation of crack initiation, propagation, and strain localisation in quasi-brittle systems. A key contribution of this work is the implementation of a trilinear constitutive law, introduced for the first time within the LDEM framework to reproduce the nonlinear softening response of pervious concrete. Stochastic material variability is incorporated through a Weibull-distributed random field applied to fracture energy. The numerical model is calibrated using flexural test data and validated against independent compressive and splitting tensile results. The simulations accurately reproduce both global structural response and local failure mechanisms, including crack patterns and energy dissipation, with prediction errors below 6%. The robustness of the approach is further demonstrated through its application to different loading configurations, highlighting its capability to predict the mechanical response under varying boundary conditions. The proposed framework provides an efficient and reliable numerical tool for the analysis of damage evolution and failure mechanisms in cement-based composite materials, offering significant potential to reduce experimental effort and support the design and optimisation of pervious concrete systems.

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abst. 1440
**SANT'EFISIO**
Friday
June 26
15h50

## Economic Optimal Control of Composite Material Curing Processes

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This work develops an economic optimal control framework for the curing process of thermoset composite materials in an autoclave. The process is modeled as a coupled thermo–chemical dynamical system, where the state variables are the degree of cure, the laminate temperature, and the autoclave temperature. Unlike standard industrial approaches in which the thermal cycle is prescribed a priori, the autoclave temperature is treated as a control-dependent state variable whose dynamics are governed by heating and cooling rates. The curing kinetics is described through a nonlinear autocatalytic model of Kamal–Sourour type, coupled with a lumped thermal balance that accounts for both heat exchange with the autoclave and exothermic heat generation due to the reaction. The economic formulation is constructed by introducing a running cost functional that incorporates multiple competing objectives: energy consumption, control smoothness and operational time. A terminal penalty enforces the requirement of achieving a prescribed degree of cure. The resulting optimal control problem is addressed through the dynamic programming principle, leading to a nonlinear Hamilton–Jacobi–Bellman (HJB) equation in a three-dimensional state space. The optimal feedback control is obtained analytically via minimization of the reduced Hamiltonian, yielding a projection of the gradient of the value function onto the admissible control set. From a computational perspective, the HJB equation is solved numerically using a semi-Lagrangian scheme on a discretized state space. The optimal policy is first computed backward in time and subsequently used to reconstruct the optimal curing trajectory forward in time. This approach allows the thermal profile of the autoclave to emerge endogenously from the optimization, rather than being imposed externally. Numerical experiments highlight the interplay between physical constraints and economic parameters. In particular, the results show how the optimal temperature trajectory adapts to the trade-off between energy costs, and process duration.

abst. 1047
SANT'EFISIO
Friday
June 26
14h30

## Abrasive water jet drilling of flax fibre metal laminates: effect of drilling approach on interlayer delamination and abrasive contamination

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The current study investigates the influence of two drilling approaches namely direct drilling and pre-drilling on the structural integrity, interlayer delamination and abrasive contamination of holes machined in flax fibre metal laminates (FFMLs). Abrasive water jet drilling (AWJD) process was used to create holes in the FFML by varying the water pressure (WP) 1000,3000 bars, traverse speed (TS) 20,100 mm/min, abrasive mass flow rate (AMFR) 300 g/min and standoff distance (SD) 2,4 mm. Direct drilling approach involved using AWJD process to create 5-mm holes in the FFML. Pre-drilling approach involved drilling a 3-mm hole size using a twist drill followed by enlargement of the hole to 5-mm using AWJD. The hole integrity was evaluated under scanning electron microscopy (SEM) and computerised tomography (micro-CT) scan to assess delamination, damage, fracture and failure mechanisms in the FFML. Using the direct drilling approach, the holes suffered from severe interlayer delamination and abrasive contamination. In addition, peel-up and push out delamination were observed regardless of the drilling parameters used while pre-drilling approach proved to be successful in eliminating them.

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abst. 1054
SANT'EFISIO
Friday
June 26
14h50

## Valorisation of Post-Consumer Textile Waste for High-Performance PLA Bio-composites through polyvinyl alcohol (PVA) Modification

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Each year, 80 million tonnes of textile waste are landfilled, causing significant environmental challenges. Transforming this waste into value-added composite materials supports pollution reduction, raw material conservation, and promotes circularity and sustainability in material innovation. Already, several research have been conducted on this subject, and this waste material is gaining increasing attention from the researchers with time. However, existing studies rarely address the integration of biopolymer, functionality and circularity within such systems, leaving a critical need for holistic, bio-based solutions. In this study, post-consumer textile waste (used cotton bed sheet) was employed as reinforcement in polylactic acid (PLA) matrices, with fibre surfaces modified via alkali (NaOH), polyvinyl alcohol (PVA), and NaOH-PVA combined treatments. Composites were fabricated using a stacking procedure followed by compression moulding, and systematically characterized through FTIR, density, void content, mechanical testing, SEM, DMA, TGA, and water contact angle analysis. FTIR confirmed successful chemical modification, while all composites exhibited acceptable void content (<2%) and density ( 1.31 g/cm3). Mechanical performance improved significantly after textile waste valorisation, with PVA modification yielding 16% increases both in tensile and flexural strength, compared to untreated composites. DMA results revealed higher storage modulus values for modified composites, indicating enhanced fibre–matrix interfacial bonding. TGA demonstrated improved thermal stability with modification, and water contact angle measurements confirmed superior hydrophobicity even after 90 seconds. These findings highlight the potential of chemically modified textile waste-reinforced PLA composites for non-structural and semi-structural applications in automotive, construction, and furniture sectors, contributing to circular economy strategies in composite engineering.

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## Analysis of the crashworthiness of novel flax-fibre hybrid reinforced 3D woven composites

abst. 1422
**SANT'EFISIO**
Friday
June 26
15h10

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This paper investigates the impact crashworthiness performance of novel flax-fibre reinforced three-dimensional (3D) woven composite structures through a comprehensive experimental programme. Composite panels with tailored 3D woven architectures were manufactured using a resin infusion process and subjected to crashworthiness tests. The impact response was evaluated in terms of peak load, load–displacement characteristics, absorbed energy, and post-impact damage morphology as well as the effect of impact speed. High-speed data acquisition and post-test inspections were employed to identify dominant failure mechanisms, including fibre fracture, matrix cracking, yarn pull-out, and through-thickness damage evolution. The role of 3D weaving parameters, particularly binder yarn configuration and fibre volume and weight fraction, on impact resistance and crash energy absorption was systematically assessed. Novel impact parameters were developed to more clearly display the effect of the architecture. Experimental results reveal that the presence of through-thickness reinforcement delays damage initiation, suppresses delamination, and promotes progressive crushing under impact loading. Compared with equivalent two-dimensional woven flax-fibre composites, the 3D woven specimens demonstrated improved damage tolerance and higher specific energy absorption, accompanied by more stable failure modes. The findings highlight the effectiveness of 3D woven flax-fibre composites in enhancing impact crashworthiness and support their potential application in lightweight, sustainable structural components subjected to dynamic loading conditions.

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## Mechanical Assessment of Flax Fiber Composites for Sustainable Lightweight Structures

abst. 1438
**TIGELLIO**
Wednesday
June 24
17h50

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The increasing demand for sustainable and low-impact materials is encouraging the development of alternative solutions for structural and lightweight applications. In this context, natural fiber-reinforced composites represent a promising option, as they combine reduced environmental impact, low density, and suitable mechanical properties. Among them, flax fiber composites are particularly attractive due to the renewable origin of the reinforcement and their potential use in components where stiffness, strength, and weight reduction are key design requirements. This study investigates the mechanical behaviour of flax fiber composite laminates through an integrated experimental, analytical, and numerical approach. Different laminate configurations were considered, including woven and biaxial flax reinforcements, PET core layers, bio-based epoxy resin, and rib-like reinforcement systems. Three-point bending tests were carried out to evaluate the flexural response of the specimens and to identify the main failure mechanisms. Attention was given to flexural failure, interlaminar shear effects, and delami-nation, which can significantly affect the load-bearing capacity of laminated composites. An analytical model based on Classical Laminate Plate Theory (CLPT) was developed to estimate the stress distribution through the laminate thickness under bending loads. The model allowed the mechanical contribution of each layer to be assessed and provided a preliminary interpretation of the influence of stacking sequence and material properties. In parallel, numerical simulations were performed in ANSYS ACP to reproduce the experimental bending configuration and obtain a more detailed evaluation of the in-plane stress distribution. The comparison between experimental observations, analytical predictions, and numerical results showed a consistent qualitative agreement in terms of stress trends and failure

behaviour. However, some quantitative differences highlighted the limitations of classical laminate assumptions, especially the neglect of interlaminar shear stresses and the hypothesis of perfect bonding between layers. These aspects are particularly relevant for natural fiber composites, where material variability, manufacturing process, and local reinforcement configuration can influence the structural response. Overall, the proposed methodology provides a useful framework for the preliminary assessment and optimization of flax fiber composite laminates. The results support the development of predictive tools for bio-based composites and contribute to their possible application in sustainable lightweight structural components.

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## Improvement of sound absorption characteristics of honeycomb sandwich panel with heterogeneous micro perforations using numerical analysis

abst. 1087
**Repository**

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This study presents a systematic optimization approach for enhancing the broadband sound absorption performance of micro-perforated honeycomb sandwich panels through controlled grading of perforation diameters and strategic perforation distribution. While previous research has explored heterogeneous micro-perforations with randomly distributed diameter ratios, the critical role of occupancy rates for each perforation diameter in achieving optimal absorption bandwidth has been overlooked. A coupled COMSOL Multiphysics-MATLAB optimization framework was developed using LiveLinkTM to sequentially determine optimal occupancy rates for each perforation diameter. The optimization algorithm targeted perfect absorption at specific resonance frequencies, automatically adjusting occupancy rates for each perforation diameter. Finite element analysis (FEA) employing thermoviscous acoustics was performed to evaluate absorption characteristics across 500-2200 Hz. Results demonstrate that optimized occupancy rates (i.e. 18, 13.5, 8, 5.5 and 3 percentage for perforation radii 0.5-1.1 mm) achieves a bandwidth of 1100 Hz at 0.8 absorption coefficient (990-2050 Hz range), representing a 120 percentage improvement over randomly distributed configurations reported in literature (at absorption coefficient 0.8 with 500 Hz bandwidth). The optimized design exhibits critical coupling of resonant peaks through constructive interference, producing smooth broadband absorption rather than isolated peaks. A larger panel configuration (14 cm x 14 cm) demonstrated 190 Hz bandwidth at 0.8 absorption in the lower frequency range (310-500 Hz). This work establishes that systematic optimization of occupancy rates is essential for maximizing absorption bandwidth in heterogeneous micro-perforated acoustic absorbers.

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## Symplectic Contact Analysis of Finite-Sized Media

abst. 1364
**RIVA**
Friday
June 26
11h30

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Most contact analyses are conducted based on the half-space assumption. However, in practical material characterization, the relative spatial positioning between the indenters and the specimens significantly influences the accuracy of predicting fundamental material properties. To address this issue, this report introduces the symplectic analysis into contact mechanics, establishing a symplectic approach for three-dimensional contact problems in finite-sized media. A series of explicit analytical solutions for various contact problems are derived, which can be further extended to multi-field coupling scenarios. For finite-sized layered media, the Saint-Venant solution is derived via the semi-inverse method, and the Papkovich-Neuber type solutions in sub-symplectic representation are formulated for the three-dimensional symplectic contact analysis. The validity of the layered Hamiltonian transformation under two types of indentation scenarios is rigorously proven. Considering the inherent boundary nonlinearity of contact problems, this report introduces the Cantor pairing diagram to devise a strategy for determining the contact area based on the symplectic method (which also accommodates the consideration of adhesive contact). The proposed theoretical models and analytical solutions have been validated against finite element simulations, confirming their accuracy and effectiveness. By incorporating boundary effects and interface effects, this report comparatively analyzes the influence of factors such as indenter position and modulus distribution on indentation curves, alongside comparative analysis with traditional Hertzian contact solutions, which establishes a theoretical foundation for developing physically plausible contact models.

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abst. 1367
**RIVA**
Friday
June 26
11h50

## Structural analysis of variable stiffness laminated composite sandwich plates using refined zig-zag theory and Spectral Chebyshev method

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This work presents the structural and vibration analysis of sandwich panels with variable stiffness composite (VSC) face sheets and a compliant soft core. Equivalent single-layer (ESL) theory fails to accurately capture interlaminar stress continuity and transverse shear effects in sandwich structures. To overcome this limitation, this study uses the Refined Zig-Zag Theory (RZT), which ensures accurate layerwise kinematics without increasing the number of primary variables significantly. The governing equations are derived via Hamilton's principle and solved using Spectral Chebyshev (SC) technique which provides high-order accuracy and rapid convergence with significantly fewer degrees of freedom compared to conventional finite element formulations. Displacements, stress distributions, and fundamental frequencies are evaluated under different core to face sheet thickness ratios, stacking sequences, and boundary conditions. The accuracy of the proposed formulation is further validated through comparisons with finite element results. The results demonstrate the influence of stiffness tailoring on bending and vibration characteristics and provide benchmark solutions for VSC sandwich structures.

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abst. 1374
**RIVA**
Friday
June 26
12h10

## Miura-ori as a structural sandwich core: comparing fold-core sandwich plates by simulation and experiments

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The present work evaluates the load-bearing capacity of sandwich panels with Miura-ori fold-cores by benchmarking their stiffness and flexural rigidity against three widely used core concepts: corrugated sheet, honeycomb, and foam. Miura-ori and related tessellations form a well-established design space for lightweight cellular structures, and prior studies have clarified how geometric parameters (and, for sheet-based realizations, material orientation) govern linear stress and stability of Miura structures and the mechanics of fold-line formation during folding [1-3]. To enable an unbiased comparison, we construct representative unit cells such that the dimensions and relative density are identical across the four core families. The base material is modeled as elastic and isotropic, and the initial assessment is restricted to geometrically linear response. Virtual three-point bending and compression tests are conducted on square sandwich patches to extract problem-specific flexural rigidities and the corresponding in-plane and across-thickness stiffness measures. A subsequent parametric study varies the Miura opening angle to identify designs maximizing normalized stiffness relative to a unit-cell dimensions and density-matched honeycomb reference, consistent with the need for fair comparisons. To further quantify the merit of Miura-ori beyond the linear regime, single- and multi-layer corrugated cores are compared with their Miura counterparts in large-deformation three-point bending and compression, with emphasis on load-displacement response. In the linear regime, the Miura-ori responses are verified against the homogenized plate-based framework of Li et al. (2026) [4], and the overall trends are validated by dedicated experiments. References: [1] Kankkunen, T., Niiranen, J., Kouko, J., Palmu, M., Peltonen, K. (2022). Parametric linear finite element stress and stability analysis of isotropic and orthotropic self-supporting Miura-ori structures. Mechanics of Advanced Materials and Structures, 29(27), 5808-5822. https://doi.org/10.1080/15376494.2021.1965679 [2] Kankkunen, T., Niiranen, J. (2025). Folding pristine paper to an origami structure - materially and geometrically nonlinear finite element analysis. European Journal of Mechanics / A Solids, 112, 105674. https://doi.org/10.1016/j.euromechsol.2025.105674 [3] Kouko, J., Kankkunen, T., Palmu, M., Niiranen, J., Peltonen, K. (2023). Practical folding meets measurable paper properties. Materialia, 31, 101871. https://doi.org/10.1016/j.mtla.2023.101871 [4] Li, X., Jamalimehr, A., Legrand, M., Pasini, D. (2026). Homogenization framework for rigid and non-rigid foldable origami metamaterials. Journal of the Mechanics and Physics of Solids, 209, 106519. https://doi.org/10.1016/j.jmps.2026.106519

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## Beam, plate and shell theories

### Laminate Plate with Non-Symmetric Lay-Up under In-Plane Cyclic Loading

abst. 1021
**TIGELLIO**
Thursday
June 25
12h10

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The analitycal equation for thin laminate plate with extension-bending mechanical copuling have been derived. The clasical laminate plate theory have been consider, three parametric deflection function have been assuemd. The problem was solved assuming non-zero damping coefficient. The equation was derived amploying the Galerkin method. Derived equation allows to analyse the plate behawior in case of in-plane harmonic load. The exemplary cases have been solved using FEM sotware. The comparison between both solution i.e., analitycal and numerical have been used to designate the necesity in assumption plate deflection function with more than two parameters. It was faound that the plate bahaviour subjected to dynamic harmonic load differes from the case of static one. Additionally, it was prove that having analitycal solution it is possible in very fast way analyse plate behaviour for thousends parameters distinguish the conditio leading to non-stable behaviour.

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### Shear effects in transversely-isotropic beams with annular cross-sections

abst. 1007
**SANT'EFISIO**
Tuesday
June 23
12h10

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This presentation analyzes the response of bars with disc-shaped or ring-shaped cross-sections to transverse forces. The bars are made of transversely isotropic materials in which the principal axes of the material and the beam are aligned. An exact elasticity solution for the internal three-dimensional problem is explained in detail, and all strain, stress, and displacement components for circular and annular cross-sections that are simple enough to be used as hand formulas are provided and visualized using area and line diagrams. For a selection of unidirectional fiber-reinforced plastics and an isotropic material, a parameter study shows deviations of material strength models for the load-equivalent shear stress from the exact solution and investigates the influence of shear on beam deflection and failure mode. The introduction provides a brief overview of theories on the bending of beams with rectangular cross-sections and explains that the existing theory for members with disc-shaped cross-sections is a material strength model that does not satisfy the homogeneous natural boundary conditions. Therefore, a new theory is required. The theory proposes displacement fields that are linearly combined from so-called macro strains, which originate from thin-beam theory with unknown displacements and are derived using a consistent elasticity approach. Due to the circular shapes of the problem domain and its boundary, the theory is described in cylindrical coordinates and derived using the static approach, in which the stresses are primary solutions and the displacements are secondary solutions. The necessary basic equations include the equilibrium and compatibility conditions for the stress constraints, the transverse isotropic material law for determining the strains, and the kinematic relations for integrating the displacements from the strains. The presentation explains the primary solution approach and the process of general and adjusted stresses in detail. The transverse shear stress distributions that balance the external force are compared with those of the strength-of-materials model, highlighting the limitations of the latter. Stress, strain, and displacement solutions, including the deformation function, are presented with equations as well as surface and line diagrams. The parameter study considers a range of typical unidirectional fiber-reinforced composites and focuses on strength aspects, using Hashin's failure criteria to distinguish between fiber failure and failure between fibers. Specifically, it deals with the minimum beam lengths L at which fiber failure occurs due to the bending moment at the clamping point before failure due to shear force occurs. The presentation ends with literature references, conclusion, and acknowledgments. Points not included in the presentation, namely integration of the displacements from the strains, derivation of the proprietary strength-of-materials model for ring-shaped cross-sections, quantification of its errors, and the influence of elasticity constants on the deflections of the center line of the beam, can be found in the conference proceedings.

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abst. 1012
SANT'EFISIO
Tuesday
June 23
12h30

## A finite element model for buckling of laminated beam-type structures

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This work presents an improved shear-deformable beam formulation for the stability analysis of laminated composite beam-type structures with thin-walled cross-sections. Each wall of the cross-section is assumed to be a thin, symmetric, balanced, or unbalanced angle-ply laminate. The equilibrium equations for a straight beam element are derived using the principle of virtual work within the framework of the updated Lagrangian formulation, Hooke's law, and a nonlinear displacement field of the thin-walled cross-section that accounts for restrained warping and large rotation effects. Stress resultants are evaluated using the Timoshenko–Ehrenfest beam theory for bending and a modified Vlasov theory for torsion. The couplings between stress resultants and deflections, which arise from unbalanced laminates and imply interactions between normal and shear stress resultants, are taken into account. In addition, the coupling between shear forces is considered—an important aspect for unsymmetric cross-sections where the principal axes and principal shear axes do not coincide. Shear locking is prevented by applying Hermitian cubic interpolation functions for deflections and twist rotations, together with associated quadratic functions for slopes and warping. The effectiveness of the proposed geometrically nonlinear shear-deformable beam formulation is validated through benchmark test problems.

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abst. 1155
TIGELLIO
Thursday
June 25
12h30

## Hamilton's formulation-based weak form physics-informed Gaussian Process Regression for free vibration response of cracked helicoidal laminated spherical shell panels

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The free vibration analysis of cracked laminated shell structures is complicated by the combined effects of geometric curvature, material anisotropy, helicoidal stacking sequences, and displacement discontinuities induced by cracks. In this work, a Hamilton's formulation-based weak form physics-informed Gaussian Process Regression (PI-GPR) framework is developed to study the free vibration response of cracked helicoidal laminated spherical shell panels. The governing equations are derived using Hamilton's principle, yielding a weak-form representation that naturally enforces boundary conditions and accommodates crack-induced kinematic discontinuities without the need for explicit enrichment or remeshing strategies. High-fidelity numerical data generated from higher-order shell theory are used to train the Gaussian Process model, while the weak-form physical constraints are embedded directly into the learning process. This physics-informed integration significantly enhances prediction accuracy and robustness, particularly in data-scarce regimes. The proposed framework accurately predicts natural frequencies and mode shapes over a wide range of crack lengths, crack locations, helicoidal fiber rotation schemes, and geometric parameters, with excellent agreement against reference solutions at a fraction of the computational cost. Parametric studies reveal the strong coupling between crack severity and helicoidal architecture on the dynamic stiffness and vibration characteristics of spherical shell panels. The proposed PI-GPR approach provides a reliable and efficient surrogate for vibration analysis of damaged bio-inspired laminated shell structures and is well suited for design, optimization, and uncertainty-aware applications.

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abst. 1194
SANT'EFISIO
Tuesday
June 23
13h10

## Multifield analysis of anisotropic doubly-curved shells of arbitrary shape with higher-order theories

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This work presents a refined two-dimensional higher-order Equivalent Layer-Wise (ELW) formulation for the multifield analysis of doubly-curved shell structures with holes and material discontinuities, composed of generally anisotropic media [1]. The formulation is expressed in principal coordinates and employs a higher-order through-the-thickness expansion of the multifield unknowns, allowing the direct prescription of electric and magnetic potentials, as well as temperature and moisture concentration, on the shell bounding surfaces [2]. The model incorporates the coupled effects of mechanical elasticity, electrostatics, magnetostatics, thermal conduction, and mass diffusion. The governing equations are derived from the Master Balance Principle under thermodynamic equilibrium conditions. Fully coupled constitutive relations are obtained via an analytical homogenization procedure based on the Mori–Tanaka scheme, accounting for interactions among the involved physical fields [3]. An isogeometric mapping of the physical domain is adopted to accommodate arbitrarily shaped geometries, and the formulation is implemented within the Finite Element Method (FEM) framework. Post-processing is performed using a patch-based recovery technique [4] to reconstruct primary and secondary multifield variables throughout the doubly-curved solid. The accuracy and robustness of the proposed formulation are demonstrated through systematic comparisons with three-dimensional finite element reference solutions and semi-analytical Navier-type solutions [5]. Parametric studies further quantify the influence of multifield coupling effects on the structural response. References: [1] F. Tornabene, Hygro-Thermo-Magneto-Electro-Elastic Theory of Anisotropic Doubly-Curved Shells, Esculapio, (2023). [2] F. Tornabene, M. Viscoti, and R. Dimitri. Hygro-thermal coupling effect on the magneto-mechanical response of curved laminated structures. Composite Structures, Vol. 370, p. 119329, 2025. [3] F. Tornabene, M. Viscoti, R. Dimitri and T. Rabczuck. Thermo-magneto-mechanical analysis of curved laminated structures with arbitrary variation of the material properties and novel recovery procedure. Engineering Analysis with Boundary Elements, Vol. 176, p. 106232, 2025. [4] F. Tornabene, M. Viscoti and R. Dimitri. Innovative recovery procedure applied to the static solution of anisotropic doubly-curved shells with holes and irregular shape. Thin-Walled Structures, Vol. 218 (C), p. 114126, 2025. [5] F. Tornabene, M. Viscoti and R. Dimitri. Magneto-Electro-Elastic Analysis of Doubly-Curved Shells: Higher-Order Equivalent Layer-Wise Formulation. Computer Modeling in Engineering and Science, Vol. 142 (2), p. 1767, 2025.

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## A novel theoretical model of temperature dependent critical buckling load for metallic columns

abst. 1223
**TIGELLIO**
Thursday
June 25
12h50

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The buckling behavior of metallic columns under wide-range temperature environments has a significant impact on the safety performance of engineering structures. This work, based on the Force-Heat Equivalence Energy Density Principle (Li's Principle of Energy Equivalence), the theoretical characterization models of temperature dependent critical buckling load for stainless steel and aluminum alloy columns without fitting parameters were established, and the predicted results by the model realize a reasonable agreement with the available experimental results. Moreover, the influencing factors analysis regarding the evolution of critical buckling load with temperature were performed. This study contributes to a deeper understanding of the performance and reliability of metallic columns under operating temperature conditions, and providing an effective theoretical characterization method for convenient prediction of buckling performance of metallic columns under wide-range temperature environments.

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## Complete mode change in the far post-buckling response of laminated plates: An analytical approach

abst. 1238
**TIGELLIO**
Thursday
June 25
13h10

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This presentation is devoted to the analysis of complete mode change in the post-buckling behavior of laminated composite plates. The plate under uniaxial compression has simply supported boundary conditions. For this purpose, a comprehensive closed form equation is calculated by introducing a novel multi-term displacement function which only consists of dominant mode shapes. The von Kármán type of compatibility equation is solved and the resulting stress function, together with the assumed displacement are employed to solve the equilibrium equations of thin-walled plates within the framework of classical theory. By incorporating different initial imperfection patterns, all possible equilibrium paths are traced. The method is more efficient than numerical arc-length methods to find snapping conditions. Comparison of the analytical post-buckling curves with those of commercial finite element analysis reveals the existence of multiple bifurcation points in the equilibrium path, which they are not visible in the numerical methods. By conducting some parametric analysis, it is shown that there are some factors such as aspect ratio and layer arrangement which are effective to have earlier mode change.

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abst. 1349
**RIVA**
Friday
June 26
15h30

## A quadrilateral curved shell element with pseudo-curvatures and the discrete shear projection method

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This study presents a quadrilateral curved shell element, named Q4Ys20, with 20 degrees of freedom. The element was developed based on the first-order shear deformation theory of Reissner-Mindlin-Naghdi to analyse isotropic and laminated composite shells. It uses a linear approximation for displacement fields and pseudo-normals to obtain the full C0 continuity of the 3D geometry. The pseudo-normals are then used for the pseudo-curvatures in the bending energy. The pseudo-curvature geometrically couples the membrane with bending behaviours. The Q420 element passes the bending patch test, has no spurious energy modes, and demonstrates accurate solutions across established benchmark tests for isotropic and laminated composite shell structures. Numerical results indicate that the proposed element offers accuracy comparable to well-established elements like MITC4, MITC4+, and DKQ24.

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abst. 1378
**RIVA**
Friday
June 26
15h10

## Homogenization of heterogeneous morphoelastic thick Reissner-Mindlin plate with finite-strain deformation when the thickness and the size of the in plane heterogeneities are of the same order of magnitude

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In this work, we propose a new two-scale finite-strain thin plate theory for highly heterogeneous thick plates described by a repetitive periodic microstructure. For this type of theory, two scales exist, the macroscopic one is linked to the entire plate and the microscopic one is linked to the size of the heterogeneity. We consider the case when the plate thickness is comparable to in-plane heterogeneities. Then we obtain the nonlinear homogenized model by performing simultaneously both the homogenization and the reduction of the initial three-dimensional plate problem to a two-dimensional one. The constitutive law of each material is assumed to be of non linear elastic quasi-incompressible law with growth which is used for biological plate for example leaves of plants. The total displacement field is assumed to be the sum of the macroscopic part of the displacement and a microscopic one. For thick plate, Reissner-Mindlin model is commonly used in Engineering. It is the main novelty of this current work. Then the macroscopic part of the displacement field is completely defined by the displacement

field of the reference undeformed mid-surface and the director vector field , which is necessarily of unit length and not orthogonal to the deformed mid-plane of the plate. So it takes into account of the effect of transverse shears and the inextensibility of the normal fiber. It is analogous to the Timoshenko beam model which takes into account the effect of transverse shears for thick beam. Then the potential energy the variational formulation and the strong formulation of the macroscopic mechanical problem can then be established. The microscopic displacement satisfies a microscopic problem which is carefully constructed. The homogenization is obtained by considering the equivalence between the global macroscopic work of internal forces and the local microscopic one.

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## Generalized Beam Theory for buckling analysis of thin-Walled Composite Beams

abst. 1432
**SANT'EFISIO**
Tuesday
June 23
12h50

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The use of composite materials in structural applications is steadily increasing, yet their complex mechanical behavior poses significant challenges for engineers worldwide. Conventional theories often struggle to accurately capture the in-plane response of thin-walled composite members under buckling loads. This paper presents an original software implementation based on the Generalized Beam Theory (GBT), which models thin-walled composite beams as linear elements while preserving high precision in their in-plane distortion and cross-sectional deformation. The proposed GBT-based tool is applied to perform buckling analyses on classical thin-walled composite profiles, such as C-shapes and I-beams, commonly used in civil engineering. Results from the software are validated against well-established analytical and finite element methods, demonstrating excellent agreement in critical buckling loads and deformation modes. This validated approach provides a reliable foundation for extending GBT to more complex problems involving composite structures, enabling efficient preliminary design and optimization in engineering practice.

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## Composite structures and materials

abst. 1014
**CIMA**
Tuesday
June 23
12h10

### Environmental Aging and Freeze-Induced Damage in Post-Impact Aerospace-Grade Carbon/Epoxy Composites

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This study investigates the combined influence of hygrothermal conditioning and freeze exposure on the structural degradation of post-impact aerospace-grade carbon fibre reinforced polymer (CFRP) laminates. Plain-weave carbon/epoxy composites with a stacking sequence of [(45/45)/(0/90)]s were conditioned for moisture absorption in accordance with ASTM D5229, in both pristine and low-velocity impact-damaged conditions, until reaching equilibrium moisture content. Subsequently, the specimens were subjected to freeze exposure at 80 °C. Gravimetric analysis was employed to quantify diffusion kinetics and equilibrium moisture uptake, while X-ray computed tomography (CT), scanning electron microscopy (SEM), and ultrasonic C-scan imaging provided detailed three-dimensional characterisation of internal damage, including delamination and matrix cracking induced by impact and environmental exposure. The synergistic effects of moisture, elevated temperature (80 °C, 90% RH), and subsequent freezing were evaluated to assess the evolution of microstructural damage in both pristine and impacted laminates. Finite element simulations incorporating temperature- and moisture-dependent material degradation, thermal expansion, and cohesive zone modelling were used to predict the residual compressive strength after impact (CAI). The results demonstrate that impact damage accelerates moisture diffusion and promotes microcrack propagation, leading to a reduction in CAI strength. Freeze exposure further degrades fibre–matrix interfaces and interlaminar bonding through differential thermal contraction of absorbed moisture. These findings highlight the importance of accounting for coupled environmental and mechanical damage mechanisms when evaluating the long-term durability and structural integrity of aerospace-grade CFRP components.

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abst. 1016
**CIMA**
Tuesday
June 23
12h50

### Thermal Cycling Induced Degradation of CFRP Laminates under Supersonic Flight Conditions

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Carbon fibre reinforced polymer (CFRP) laminates are increasingly adopted in next-generation supersonic aircraft due to their exceptional specific stiffness, strength, and thermal stability. However, during high-altitude and high-speed flight, these structures are subjected to repeated and extreme thermal excursions—ranging from sub-zero temperatures at altitude ( 55 °C) to aerodynamic heating near +150 °C—posing significant durability challenges. The mismatch in coefficients of thermal expansion between carbon fibres and polymer matrices generates cyclic interfacial stresses, driving progressive microcracking, fibre–matrix debonding, and residual stress accumulation. While numerous studies have characterised hygrothermal ageing and single-temperature exposure, comparatively fewer have examined the cumulative effects of repeated thermal cycling representative of supersonic flight environments. Existing investigations reveal complex and sometimes contradictory trends in stiffness and strength evolution, with damage mechanisms and property degradation highly dependent on laminate architecture, resin chemistry, and exposure history. This study addresses these knowledge gaps through an extensive experimental evaluation of aerospace-grade CFRP laminates exposed to cyclic thermal loading between 55 °C and +150 °C. The investigation systematically quantifies the evolution of microstructural damage using X-ray computed tomography (XCT) and correlates these observations with changes in tensile, compressive, open-hole tension (OHT), and open-hole compression (OHC) performance across multiple cycle intervals. Results provide new insight into the coupling between thermally induced microdamage and residual mechanical performance, highlighting the early-stage accumulation of microcracks as

the dominant driver of property degradation. The findings contribute to the development of predictive durability models and inform qualification frameworks for reusable composite structures operating under the severe and cyclic thermal environments of supersonic and spaceflight applications.

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## Advanced Layup Strategies for Damage-Tolerant and Cost-Effective CFRPs Suitable for Large Aerospace Structures

abst. 1020
**CIMA**
Tuesday
June 23
13h10

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Aircraft components experience complex loading conditions such as high-cycle fatigue, adverse environmental effects, and foreign object damage at low altitudes. Consequently, novel layup design strategies are essential for developing robust, lightweight structures with high integrity, addressing the brittleness and limited impact resistance of conventional aerospace designs. Recently, alternative microstructural concepts, such as bio-inspired and double-double layups, have been introduced to enhance the damage tolerance of carbon fibre-reinforced polymers (CFRPs), thereby improving structural efficiency and reducing fuel consumption. Conventional aircraft designs often involve assembling multiple large components, increasing manufacturing complexity, time, and cost. In contrast, integrated one-piece structures produced through co-curing and bonding offer a viable alternative, simplifying production and improving performance. This study investigates the integration of alternative design principles – bio-inspired and double-double – with automated dry fibre placement (DFP) and resin transfer moulding (RTM) to enable the manufacture of large-scale, damage-tolerant CFRP components. Recent advancements in automated manufacturing allow efficient implementation of non-conventional layups and microstructural designs that significantly enhance mechanical performance in aerospace applications. A bio-inspired helicoidal design is applied to develop CFRP laminates with improved damage tolerance while remaining compatible with large-scale manufacturing. Double-double designs further reduce manufacturing time and cost without compromising performance. The laminates are produced using DFP and RTM and tested under mechanical loading conditions, including buckling, low-velocity impact (LVI), and compression-after-impact (CAI) to assess stability relative to baseline configurations. Both bio-inspired and double-double layups are designed as buckling-matched laminates using D-matrix equivalence for fair comparison. Pitch angles are varied through the laminate thickness, based on preliminary finite element analysis, to determine the optimal configuration. Using DFP, aerospace-grade carbon fibre tapes are laid with controlled orientation. After deposition, injection and curing, the laminates are then demoulded and cut into specimens for testing in accordance with ASTM standards, and results will be presented at the conference.

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## Fracture of Graded Aluminum Matrix Composites: Experiment and Phase-Field Modeling

abst. 1026
**SANT'EFISIO**
Thursday
June 25
10h00

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Multilayered metal–ceramic composites constitute a class of functionally graded materials defined by discrete variations in composition across their thickness. These advanced structural systems can be tailored to meet specific performance requirements. Aluminum-matrix composites, in particular, are highly attractive due to their low density, high thermal conductivity, enhanced specific strength, and the relatively low cost of their constituent phases. A detailed assessment of their fracture properties and failure mechanisms is essential for expanding their use in engineering applications. This work presents an integrated experimental and numerical study of fracture in vertically and transversely graded AlSi12–AlO composites. Multilayered bulk disks with volume fractions of 10, 20, and 30 percent AlO are manufactured via powder metallurgy. Single-edge V-notched beam (SEVNB) specimens and round compact tension specimens are extracted and tested under four-point bending and tension, respectively. The experiments are supported by phase-field fracture simulations, in which the length-scale parameter is calibrated by fitting numerically predicted fracture loads to the measured values. The calibrated model is then used to investigate the influence of layer stacking sequence on the load–displacement response and crack trajectory. The results indicate that the stacking sequence has a significant impact on the peak load, post-peak behavior, and crack propagation path. Moreover, the phase-field simulations successfully capture experimentally observed features such as crack arrest, crack branching, and crack deflection within the graded layered structure.

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abst. 1063
SANT'EFISIO
Wednesday
June 24
16h10

## Integrated design of flame retardancy, smoke suppression and structure of carbon fiber reinforced vinyl ester resin composites through intercalation of nanofiber membranes

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Nanofiber flame-retardant membranes (FPm) are prepared from polyether sulfone (PES) and pentaerythritol phosphate ester (PEPA) by electrospinning technique and inserted in the interlayer of carbon fiber reinforced vinyl ester resin (CF/VER) composites. The FPm can improve the flame-retardancy and smoke suppression of the CF/VER composites by promoting the charring of interlayer structure and form a barrier layer. The thickness of the FPm and the flame-retardant performance of the composites are positive correlation. At a FPm's thickness of 50 m, the limiting oxygen index (LOI) and UL-94 ratings of the CF/VER composites reached 33.5 % and V-1, respectively. The total heat release (THR) and total smoke release (TSP) are reduced by 26.4 % and 30.4 %, respectively. Due to the interlayer enhancement effect of FPm, the mechanical strength and interlaminar fracture toughness of CF/VER composites are also improved. Especially, when the thickness of FPm is 30 m, the mode I interlaminar fracture toughness (GIC) of the CF/VER composite increased by 17.4 %. while the flexural strength, interlayer shear strength (ILSS), mode II interlaminar fracture toughness (GIIC) and storage modulus (E') are all enhanced.

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abst. 1075
SANT'EFISIO
Wednesday
June 24
16h30

## Buckling analysis of thin-walled FG composite beam type structures under thermo-mechanical loads

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This research investigates the buckling behavior of a functionally graded Euler-Bernoulli beam under thermo-mechanical loads using an upgraded geometric nonlinear algorithm, THINWALL FG. The algorithm utilizes a 1D numerical model based on a spatial beam finite element approach, considering small deformations and large rotations. For nonlinear analysis, the updated Lagrangian (UL) incremental

formulation is implemented using the principle of virtual works. The focus of the model is on studying stability issues arising from varying temperature conditions. The study explores composite materials, particularly functionally graded materials, and assumes three types of temperature distributions across the beam wall thickness: uniform, linear, and nonlinear. Temperature-dependent material properties varying only in the thickness direction using the power-law function. The model allows for determining the load level leading to unstable deformation forms. Under different boundary conditions, power-law index values, and FG distributions, critical values of temperatures are determined, as well as the non-linear response of beam structures. Comparative analysis is conducted with existing literature and shell finite element models, demonstrating key differences. The proposed algorithm significantly advances the existing research in the stability analysis of thin-walled structures.

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## Assessment of the long-term behaviour of timber-concrete composite floors

abst. 1082
**SANT'EFISIO**
Wednesday
June 24
16h50

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The combination of timber and concrete for the development of composite cross-sections in the design of floor slabs has demonstrated enormous benefits. Timber brings lightness, flexibility and sustainability to these systems, and concrete provides rigidity, continuity, the possibility of designing rigid joints and an improvement in acoustic and fire performance. The goal is to design solutions in which concrete has a reduced presence, with a very thin layer on top of the section. Numerous studies and proposals have been made regarding different types of shear connections and cross-section designs. Timber and concrete share the characteristic of creep deformation, also strongly influenced by the temperature and humidity conditions in service, which makes it extremely difficult to determine their long-term behaviour. The most common studies and reference standards (EC-5 CEN/TS 19103;2021) establish an analysis of this long-term behaviour that must take into account a combination of factors affecting the two materials and the connection system. These methodologies, based on the effective modulus, determine three corrections to the elastic and shear moduli of each component. In addition, they establish a single exposure environment condition in terms of humidity-temperature, which does not correspond to conventional situations characterised by a changing environment. Based on different configurations, our research team has developed long-term testing campaigns under changing environmental conditions, corresponding to outdoor exposure and therefore subject to seasonal climate variations, establishing a new simplified methodology. The solutions tested comprise composite pieces consisting of a laminated wood web and a reinforced concrete top slab, using glued perforated steel sheets as a connection joint; a second mixed solution with a double T-section, a laminated wood lower section and birch plywood webs, with direct connection to the upper concrete slab by means of perforations in the webs; and a third solution with a double T-section with a lower flange and CLT webs that uses the system of perforations in the webs as a means of connection with the upper concrete slab. In all cases, lengths compatible with the typical use of these systems are adopted, ranging from 6.00 to 9.00 m, with permanent loads compatible with residential uses. These elements have been kept in uncontrolled exposure conditions for periods of up to 1,000 days, with periodic monitoring of deformation and environmental conditions of humidity and temperature. Experimental analysis has revealed the influence of the stiffness of the slabs that make up the cross-section on the deflection of the floors and on the increases and decreases in creep deformation over time. This analysis has led to the development of an analytical approach that allows for the long-term determination of a component's deflection based on the ambient temperature and humidity history in which it has been installed. Based on these results, a methodology is proposed that is capable of predictively establishing long-term behaviour, taking into account the initial stiffness of the piece and the cyclic component variations that environmental changes generate in the assembly, obtaining very closed relationships between measured and estimated results in all cases

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abst. 1085
TIGELLIO
Tuesday
June 23
17h30

## SPH-FE Analysis of Bird Strike Damage in Bio-Inspired Helicoidal Laminated Composites: Effect of Impact Location

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Laminated composites are employed in the construction of diverse structures across civil, automotive, aerospace, marine, and military sectors, since the mechanical characteristics of laminated structures may be altered by adjusting the ply angle and thickness of each layer. The primary issue with classic laminated composites, is their brittleness; they possess significant strength but may fracture abruptly upon impact. However, bionispired materials, on the other hand, are both strong and tough. Therefore, this prooceding focuses on the damage behavior of bio-inspired helicoidal laminated composite plates with hole and explores how the damage response varies based on the location of impact. A hybrid Smoothed Particle Hydrodynamics (SPH) - Finite Element (FE) modeling approach methodology is used in Abaqus. The comparison of the damage response of bio-inspired helicoidal configurations with those for conventional laminated composite plates is presented. The birds strike the center and close to the edge of the plate. The Hashin damage criteria is applied to evaluate damage modes, including fiber fracture in tension/compression and matrix rupture, under these challenging impact conditions within the laminate's structure. Validation of the literature studies for the accuracy of the present numerical model. To measure the localized energy absorption behavior at the plate edge and center, strain energy analysis was carried out. Research results demonstrated that Bio-inspired laminated composite shows higher strain energy dissipatiation capacity.

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abst. 1090
SANT'EFISIO
Wednesday
June 24
17h10

## A comparative assessment of the drop-weight impact damage tolerance in bio-based composite laminate sandwich structures under various weathering conditions

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Fibre-reinforced sandwich composites are widely used in offshore energy and marine sectors as a preferred material in primary structural components due to their excellent mechanical performance and lightweight characteristics. However, they are susceptible to impact damage that can occur both during manufacturing and maintenance as well as during service. In this work, the performance of a sustainable alternative to glass-fibre reinforced sandwich composite laminates is investigated under drop-weight impact with the influence of various weathering conditions, under controlled humidity and temperature. The damage propagation and evolution is further explored using non-destructive testing techniques, such as X-Ray computed tomography (XCT) and microscopic analysis.

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abst. 1094
SANT'EFISIO
Wednesday
June 24
18h10

## Investigation of the shock attenuation capabilities of full-composite sandwich panels

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Explosions, whether accidental or intentional, impacts, collisions, and road accidents represent scenarios where a structure can be subjected to dynamic loading, jeopardizing its integrity and the safety of people and equipment within it. In this context, this work aims to develop and evaluate the performance of

full-thermoplastic reinforced fibers composite sandwich panels. To this end, a solvent-based process for manufacturing sandwich panels including corrugated laminated composites with a thermoplastic matrix reinforced by continuous fibers, has been developed. Two materials are considered: PLA and ABS. The preliminary obtained results, for quasi-static and low speed impact loadings, are promising and demonstrate the good performance of the developed materials.

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## Design and Detailing of Stiffened Composite plates with Integral Longitudinal and Transverse Stiffeners

abst. 1096
**Repository**

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Plates are efficient structural members for carrying both in-plane and out-of-plane loads. The provision of stiffeners enhances the out-of-plane stiffness and post-buckling strength of plates without significantly increasing their total weight. Stiffened steel plates are widely used in ship decks and offshore oil platforms, where they are predominantly subjected to combined in-plane and out-of-plane loading. Owing to their high strength-to-weight ratio, high stiffness-to-weight ratio, and excellent corrosion resistance, stiffened composite plates present a viable alternative to stiffened steel plates. The design of stiffened plates subjected to in-plane axial loads primarily aims to prevent the local buckling of both the plate and the stiffeners prior to reaching the ultimate strength. In this study, a design procedure is developed considering general ranges of plate slenderness ratios and column slenderness ratios for stiffened composite plates with integrally fabricated longitudinal and transverse stiffeners. The proposed procedure addresses the determination of preliminary dimensions, minimum plate thickness, maximum stiffener depth, number of laminate layers, thickness of individual layers, and the corresponding laminate lay-up sequence.

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## Numerical investigation of masonry arches strengthened with nonwoven flax-based cementitious laminates

abst. 1107
**SANT'EFISIO**
Wednesday
June 24
17h30

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Masonry arches represent a fundamental structural typology in existing and historical constructions, often requiring strengthening solutions that are compatible with the original materials while improving structural performance. Cementitious composite systems have been widely investigated for masonry strengthening; however, the use of nonwoven natural fiber textiles in cementitious strengthening systems remains largely unexplored as a sustainable alternative for masonry strengthening. This contribution presents a numerical study on masonry arches strengthened with a nonwoven flax-based cementitious laminate, developed in close connection with an experimental investigation on full-scale masonry arches. A reference unreinforced arch and strengthened configurations are considered to evaluate the influence of the nonwoven composite system on the structural response of the arch. The numerical framework is based on finite element modeling of masonry arches, accounting for the geometry, material properties, and strengthening configuration. The numerical analyses aim to reproduce the mechanical behavior observed in experimental tests, with particular attention to the global response of the arch under loading. The results support a numerical–experimental comparison, providing insight into the effectiveness of nonwoven flax-based cementitious composites for masonry arch strengthening. This work contributes to the assessment of bio-based composite systems for structural rehabilitation and sustainable construction applications.

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abst. 1116
SANT'EFISIO
Thursday
June 25
13h10

## Structural Assessment of Composite Laminates with Holes Integrated During Layup Using Continuous Fiber Deposition

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Holes and cut-outs in fiber reinforced polymer composites represent one of the most critical structural features, as they interrupt the continuity of the reinforcement and force the load to redistribute around the geometric discontinuity. This redistribution produces non-uniform and highly concentrated stress fields that can be severe in composite laminates, where the load carrying capability depends strongly on the local fiber direction. Even small openings can therefore initiate matrix cracking, promote delamination, and significantly reduce the ultimate strength of the component. In conventional composite manufacturing, holes are typically created through drilling or trimming operations, which cut load bearing fibers and may generate machining related defects. In addition to the structural problems, these operations increase process time and material waste, often making drilled holes a governing factor for both structural performance and manufacturing efficiency. However, despite their practical relevance, there is limited understanding of how continuous fiber reinforcement around an opening influences local stress fields and failure mechanisms in laminates that remain free of fiber discontinuities. This work investigates an alternative fiber reinforced composite polymers manufacturing strategy that integrates the hole directly during layup, avoiding any post machining or drilling. The concept relies on a continuous fiber deposition technology called IFP (Infinite Fiber Placement) developed by Holy Technologies GmbH and made available for the present research. The process enables the manufacturing of laminates by placing a single uninterrupted dry roving fiber along programmed trajectories, allowing controlled redirection of the reinforcement around the opening while preserving the full fiber continuity and avoiding any fiber interruption. This capability not only maintains the structural integrity of the reinforcement but also allows multiple local reinforcement strategies. Since the system deposits a single continuous roving, and no drilling is necessary, the fiber path can be guided around the hole in different configurations, giving the freedom to tailor the local architecture to the expected load redistribution. This level of control is not attainable with traditional laminate manufacturing and offers new opportunities for optimizing regions containing geometric discontinuities. The resulting preform is consolidated through resin transfer molding in a closed mold system. An additional characteristic of the process is the use of a fully dissolvable epoxy resin that allows complete recovery of the continuous uninterrupted fiber at the end of life. Because the reinforcement is deposited as an uninterrupted roving filament, the reclaimed fiber can be recovered without geometric discontinuities and size reduction, and reused with minimal performance loss. Although recyclability is not the primary focus of this work, this characteristic reinforces the technological relevance of maintaining fiber continuity and contributes to improved material efficiency for future composite applications. In this study, specimens produced with integrated holes were manufactured using the continuous fiber deposition process and compared with conventional laminates in which the hole was manufactured by a standard drilling operation. The mechanical characterization focuses on stress and deformation redistribution around the opening, the initiation and evolution of damage, and the resulting structural response under tensile loading. Microstructural observations were also conducted to correlate failure mechanisms with the local fiber architecture and with the presence or absence of reinforcement continuity. The obtained results indicate that integrating the hole during layup can modify the local load redistribution and influence the onset and progression of damage. The study highlights the potential of continuous fiber architectures to improve the structural response around geometric discontinuities and improve the material usage efficiency. Furthermore, the study provides a first framework for developing design strategies for composite laminates with locally tailored reinforcement paths.

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abst. 1131
SANT'EFISIO
Wednesday
June 24
15h10

## Prediction and Enhancement of Impregnation Quality in Wet Filament Winding through Impregnation Pressure Control

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Carbon Fiber Reinforced Plastics (CFRPs) are widely used in aerospace, automotive, and energy structures because they provide high strength and stiffness at low weight and resist corrosion. Wet filament winding is commonly adopted since it is fast, cost-efficient, and can place continuous fibers along the required path with good repeatability. It is especially suitable for cylindrical and axisymmetric parts where fiber angle control is critical. A key difficulty in wet filament winding is that the thermoset resin keeps curing during the process. As curing progresses, the resin viscosity gradually increases. This viscosity rise is unavoidable, and it increases the flow resistance against resin impregnation into the small pores inside a fiber tow. When the flow becomes limited, dry regions and voids can appear, and impregnation can vary from layer to layer even if the machine settings are unchanged. A condition that produces good impregnation at the beginning of winding can become insufficient later, so the process benefits from control strategies that adapt to the changing flow resistance rather than relying on fixed processing parameters. In this study, we propose a process control method to improve impregnation in wet filament winding. First, a cure kinetics model is used to predict how resin viscosity evolves in real time under the winding conditions. Based on this prediction, we use a mechanism-based model that connects the driving pressure at the drum-tow interface to resin impregnation into the tow. The framework includes a viscosity-adaptive tension control strategy to maintain sufficient driving pressure for impregnation as the resin viscosity increases. Also, consider hydrodynamic pressure generated by relative motion between the tow and the drum, which can add an additional driving force for resin flow. The main focus is on compensating for the gradual loss of impregnation efficiency caused by viscosity increase and on assessing whether hydrodynamic pressure can support impregnation without simply increasing the tensile load carried by the fibers. To validate the proposed impregnation mechanisms, tow-level specimens collected during the winding process were analyzed by cross-sectional imaging to quantify the distributions of fiber, resin, and void fractions and compare them with the simulation trends. In addition, resin saturation was evaluated to check how much of the available pore space was filled with resin. The results show that viscosity-adaptive tension control improves fiber volume fraction uniformity and reduces void content compared with constant tension conditions. In addition, the relative-motion condition increases resin saturation, indicating improved impregnation while keeping the fiber tension unchanged. Overall, this work connects rheological changes to impregnation behavior in wet filament winding and proposes an effective route for improving impregnation consistency throughout the process. The combined use of viscosity-tension control and hydrodynamic pressure not only compensates for flow limitations due to the viscosity increases but also leads to enhanced impregnation quality and more reliable mechanical performance in wet-wound composite structures.

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## High-stability electromagnetic wave absorbing metasurface for deformable lattice structures

abst. 1144
**SANT'EFISIO**
Wednesday
June 24
15h30

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With the escalating demand for structure-function integration in aerospace, high-end equipment, and other cutting-edge fields, advanced structural materials that synergistically combine exceptional mechanical properties with tailored physical functionalities have emerged as a research frontier. Against this backdrop, lattice structures have garnered extensive attention due to their superior lightweight characteristics, high specific strength/stiffness, and remarkable designability. Through deliberate engineering of their unit cell configurations and spatial arrangements, lattice structures can achieve specialized mechanical functionalities—such as negative Poisson's ratio and multi-stage energy absorption—that are unattainable with conventional bulk materials. Among these, deformable lattice structures (also referred to as mechanical metamaterials) can undergo controlled large deformations in response to external stimuli, enabling transformative applications including adaptive morphing structures and flexible robotics. This further expands the application scope of lattice structures and holds significant strategic implications for realizing active deformation, dynamic response, and smart skin technologies in aerospace devices. Integrating electromagnetic wave absorption functionality into lattice structures represents a critical pathway to achieving structural stealth, which enables aircraft platforms to reduce their radar cross-section (RCS) while preserving robust mechanical load-bearing capacity. However, prevailing strategies for implementing wave absorption in lattice structures—such as direct doping with magnetic or dielectric absorbing fillers—often compromise the mechanical integrity of the structure, leading to increased brittleness of the matrix material and degraded interfacial strength, thereby deviating from the core objective of structure-function integration. Moreover, for practical deployment, the polarization stability of absorption performance is paramount: the structure must maintain consistent and efficient absorption when electromagnetic waves are incident at varying polarization angles. This poses a formidable challenge for lattice structures, which typically feature complex three-dimensional geometries. Notably, for deformable lattice structures, their geometric configurations change drastically before and after deformation, making it a central unresolved issue to ensure high and stable absorption performance throughout large-scale deformation processes. Three primary challenges hinder the realization of high-performance, stable electromagnetic wave absorption in deformable lattice structures: First, limited design space. The solid fraction of lattice structures is typically very low, leaving minimal effective physical space for integrating wave-absorbing functional units. This severely constrains traditional absorption schemes that rely on thick lossy materials or intricate resonant structures. Second, complex polarization stability design. Most deformable lattice structures exhibit three-dimensional asymmetry, and their inherent structural anisotropy readily causes absorption performance to fluctuate significantly with the polarization direction of incident waves, making it extremely difficult to achieve wide-angle, polarization-insensitive absorption responses. Third, stringent deformation adaptability requirements. Deformable structures undergo substantial, non-linear changes in unit shape, spatial orientation, and relative positions between their initial and deformed states, which directly alter their electromagnetic response characteristics. Conventional "static" absorption designs are ill-suited to this dynamic, multi-state electromagnetic environment, making it a highly challenging goal to ensure stable absorption performance throughout the deformation process. To address these challenges, this paper proposes and demonstrates an electromagnetic metasurface-based approach to endow deformable lattice structures with high-stability electromagnetic wave absorption capabilities without compromising their mechanical properties. The core of this strategy is to abandon bulk matrix doping and instead utilize the laser-induced graphene (LIG) technique to directly fabricate patterned graphene metasurface layers in situ on the surfaces of lattice structure components. This process requires no additional adhesives or complex post-treatment; the resulting lightweight graphene layer forms a robust bond with the substrate, adds negligible weight, and has a minimal impact on the structure's mechanical strength and deformability. To validate the feasibility of this approach, we selected representative lattice structures, designed the pattern distribution of the graphene metasurface by using the optimization method, and fabricated integrated LIG metasurface samples via multi-material additive manufacturing. Experimental results show that the as-fabricated samples achieved over 90% broadband absorption efficiency within the target frequency band in the undeformed state, with excellent stability under both TE- and TM-polarized wave incidence. More importantly, when the structure underwent large tensile deformation, only minor shifts in the absorption center frequency and bandwidth were observed, and the absorption performance remained highly stable throughout the deformation process. These findings fully demonstrate the effectiveness and advancement of the proposed metasurface design method in addressing the electromagnetic performance stability of deformable structures. This research provides a versatile, efficient, and mechanically benign design and manufacturing paradigm for integrating electromagnetic functionalities into deformable lattice structures and broader classes of flexible/reconfigurable mechanical metamaterials. It significantly advances the development of structure-function integration toward dynamic and intelligent applications.

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## Transforming 3D-Printed Anisotropic Modules into Mechanically-Enhanced Isotropic Metamaterials

abst. 1160
**SANT'EFISIO**
Wednesday
June 24
09h40

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Structural materials for engineering applications often operate under forces from multiple directions, demanding isotropic mechanical performance. Mechanical metamaterials (MMs) exhibit high designability in mechanical properties, and their topology-based designs have enabled the realization of nearly isotropic mechanical responses in theory. However, most MMs are fabricated via additive manufacturing processes, where the layer-by-layer deposition introduces materials anisotropy that limits the actual performance obtained. Inspired by Kong-Ming Locks, this work proposes an orientation-controlled assembly strategy that transforms anisotropic 3D-printed modules into mechanically-enhanced isotropic metamaterials. The MM architecture is decomposed into modular planar components (printed with filaments aligned to its principal load-bearing direction); the components are then mechanically assembled to a macroscopic MM, thereby altering the deposition orientation along critical loading paths and enhancing isotropy. Experiments and finite element simulations are conducted to evaluate the mechanical performance under quasi-static, dynamic impact, and cyclic fatigue loads. The near-isotropic mechanical responses are achieved in assembled MMs: compared with integrated MMs, their anisotropy level is reduced by 94.3%, while stiffness, strength, failure strain, and energy absorption increase by 9.3%, 50.0%, 59.1%, and 155.5%, respectively. The proposed strategy provides a route to overcome AM-induced anisotropy and enables scalable manufacturing of high-performance, isotropic metamaterials for complex service environments.

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## A Hybrid Biomimetic Suture and Nacre Strategy for Balancing Strength and Toughness in Architected Composites

abst. 1162
**SANT'EFISIO**
Wednesday
June 24
10h00

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Balancing strength and toughness is a central challenge in the design of architectured composites. In this study, we present a dual-biomimetic strategy that integrates bone-like sutured interfaces within a nacre-inspired brick-and-mortar framework (NS-Hier). Specimens were fabricated using multi-material SLA printing and evaluated under quasi-static uniaxial tension and three-point bending. The results demonstrate that NS-Hier achieves superior mechanical synergy compared with single biomimetic designs. Under tension, NS-Hier exhibits an average stiffness of 428 MPa and strength of 5.2 MPa, surpassing nacre-like and 2D-suture structures. More importantly, toughness of NS-Hier structure reaches 185 mJ, representing a 2.5-fold increase over nacre-like and a 1.5-fold increase over 2D-suture specimens. Fracture analysis confirms that the sutured geometry enforces crack deflection, branching, and bridging, while the brick-and-mortar layers enable progressive sliding and energy dissipation. Meanwhile, the role of suture curvature depth (h) on the regulation of structural performance was discussed, where optimal values achieve the best compromise between stiffness and toughness. Overall, this dual-biomimetic design reconciles the classical stiffness–toughness trade-off and offers a scalable route toward damage-tolerant architected composites

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abst. 1168
**SANT'EFISIO**
Thursday
June 25
10h20

## Computational Study of the Coupled Electromechanical Behavior of a Piezoelectric Cantilever Beam

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This work presents a detailed numerical investigation of a smart composite cantilever beam integrated with a piezoelectric layer, focusing on its coupled sensing and actuation behavior. The structure consists of carbon fiber–reinforced polymer (CFRP) laminate with a symmetric stacking sequence, onto which a surface-bonded piezoelectric (PZT) layer is attached to serve simultaneously as a sensor and an actuator. The coupled electromechanical response of the system is formulated within the framework of linear 3-D piezoelasticity under static loading conditions. For the sensing analysis, a prescribed transverse displacement is applied at the free end of the cantilever beam, and the induced electric potential and electric field distributions within the piezoelectric layer are evaluated. Conversely, in the actuation analysis, an electric voltage is imposed across the PZT layer, and the resulting structural response, characterized by the transverse deflection of the beam's outer surface, is obtained. All simulations are conducted using a coupled-field finite element formulation implemented in the ADINA software environment, ensuring accurate representation of the mechanical-electrical coupling effects within the smart composite structure. As a surrogate machine learning approach Gaussian process regression (GPR), artificial neural networks (ANNs), support vector regression (SVR) are used, based on the coupled electromechanical numerical simulation to predict vibrational responses. As validation, the physics-informed neural network, (PINN) is applied to recognize the effective coupling parameter.
Acknowledgment: The research was supported by projects VEGA 1/0307/23 and VEGA 1/0642/24 of Scientific Grant Agency of the Ministry of Education, Research, Development and Youth of the Slovak Republic and the authors extend their acknowledgement to the financial support of the European Union under the REFRESH-Research Excellence For REgion Sustainability and High-tech Industries project number CZ.10.03.01/00/22_003/0000048 via the Operational Programme Just Transition.

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abst. 1172
**CIMA**
Friday
June 26
15h30

## Theoretical Modeling of Bio-Composites for Sustainable Construction Components

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The construction sector increasingly demands sustainable materials to lower carbon emissions and utilize agricultural waste. Bio-composites from natural fibers and polymers offer viable solutions through their renewability, low weight, and lower environmental footprint relative to conventional options. These bio-composites suit non-load-bearing elements such as partition walls and cladding. They provide balanced strength for service loads, good thermal and acoustic insulation, and easy manufacturability, fostering eco-friendly buildings that meet sustainability goals without losing performance or aesthetics. This work introduces a theoretical modeling approach to forecast elastic properties of bio-composites for non-load-bearing construction components. By estimating key parameters like elastic modulus and density enables early structural viability checks, linking material development to real-world construction needs.

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abst. 1191
**RIVA**
Thursday
June 25
16h50

## Investigation of Interfacial Bonding in Zr-Based Metallic Glass/PA6-GF30 Sandwich Composites Manufactured by Injection Molding

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Metallic glasses exhibit remarkable properties compared to crystalline metals due to their amorphous structure. These include high strength and hardness, as well as a high elastic strain limit. Conversely, they exhibit low toughness and a high susceptibility to brittle fracture, making them less suitable as monolithic structural components. For this reason, metallic glasses are increasingly used as a reinforcing phase in hybrid materials to compensate for their brittleness. n this contribution, a sandwich composition consisting of Zr-based metallic glass face sheets and a PA6-GF30 (Polyamide 6, 30% glass fiber reinforced) core is manufactured. The metallic glass is processed by injection molding. To enhance the interfacial bonding, the metallic glass surfaces are laser-structured prior to composite manufacturing. A systematic parameter study is conducted to modify the micro- and nanoscale surface structures while maintaining the amorphous structure of the metallic glass. The resulting surface morphologies are characterized using optical and scanning microscopy, and X-ray diffraction (XRD) measurements are employed to verify the retention of the amorphous structure after laser treatment. Subsequently, the sandwich composites are produced in a single-step injection molding process in which the PP core is molded directly onto the structured metallic glass face sheets. The interfacial shear strength is evaluated using an edge shear test. This processing route offers a scalable approach for manufacturing high-performance, lightweight sandwich composites based on metallic glass face sheets.

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## Studying the Effect of Pre-stress on the Response Robustness of Shallow Composite Arches Subject to Large Deformations

abst. 1193
**RIVA**
Thursday
June 25
17h10

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Recent advances in engineering design have spurred interest in exploiting compliant structural components. This is reflected in many industries such as Aerospace (winglets), Renewable Energy (trailing edges of turbine blades), and Space (deployable systems, including booms and sails). The inclusion of composite materials further increases the potential of compliant design by coupling anisotropic tailoring with geometric non-linearity, offering the potential to optimise performance further. However, despite the potential benefits of these compliant composite structures (or systems), there remains an ongoing challenge to experimentally validate their performance, particularly under complex load patterns. Furthermore, the well-known distribution of composite material's mechanical properties (due to effects such as material areal weight, fibre straightness, and manufacturing-induced variances) presents a significant additional challenge when aiming to harness these non-linear structural systems. To enable a wider industrial uptake of these compliant systems, it is essential to ensure the expected response is "Right-First Time", which requires robust designs and a framework for experimental validation. To continue progress towards meeting this challenge, this study presents insight into the effects of pre-stress on the compliant behaviour of shallow composite arches, combining numerical simulation with targeted experimental validation. Through a parametric exploration of key system variables, metrics that capture the design's robustness can be developed, providing the designer with greater confidence in achieving the desired behaviour. The parametric study quantifies the deviation of experimentally observed responses from the idealised behaviour of compliant composite arches, providing insight into the system's underlying physics by quantifying the extent of variation between the two. In doing so, the contributions from composite material variability (to minimise them) can be isolated from the desired effects of tuneable design parameters. The anticipated impact of variations of arch geometry and stiffness is shown to be significantly affected by pre-stress in the system. Specifically, mechanical and thermal stresses can be accounted for by considering both manufacturing-induced stresses (e.g., due to thermal mismatches between laminate layers) and boundary-induced stresses during arch positioning. The idealised behaviour of the arch is obtained using 2D-shell Finite Element Analysis, which permits modification of the boundary-induced pre-stress. This alters the arch's initial equilibrium position and can be aligned accurately with experimental observations. By comparing these tuned virtual experiments to physical observations, an envelope can be defined that captures expected parameter-led

variation and material variability. From this envelope, a notional robustness index is developed, identifying parametrisations with increased reliability demonstrated across several configurations/qualitative responses. Lastly, experimental observations highlight the importance of environmental factors and viscoelastic effects for accurately predicting responses, providing a roadmap for further work (that is, to develop approaches that account for their contributions rather than applying rigid exclusionary boundaries). The work presented confirms a validated pathway for engineering of robust, tailorable, compliant composite arches, providing guidance on tuning stiffness and prestress to reliably elicit the designer's desired behaviour. It supports the development of a broader framework for large-deformation testing in general and characterisation of composite structures that is typically beyond the scope of traditional off-the-shelf mechanical testing machines.

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abst. 1232
**CIMA**
Friday
June 26
14h30

## Investigation of Mechanical and tribological properties of Epoxy reinforced with short carbon fibres and ZTA ceramic particles.

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Drilling operations in the oil and gas industry are conducted under some of the harshest service conditions, where casing and drill pipes and tool joints (DP-TJ) materials are exposed to severe mechanical wear, corrosive environments, and extreme temperatures. The increasing demand for deeper wells and directional drilling has intensified casing failures, primarily caused by the continuous wear imposed by drill pipes and tool joints. These operational challenges highlight the necessity for advanced materials with superior wear resistance to preserve structural integrity and sustain drilling efficiency. One way to improve the wear resistance of the casing pipe and its service life is to develop a hybrid epoxy-based composite lining with improved wear resistance and a lower friction coefficient. This research work aims to develop a hybrid epoxy composite lining with improved wear resistance. The epoxy matrix is reinforced with wear-resistant ceramic fillers, zirconia-toughened alumina, along with the addition of friction-reducing fillers such as short carbon fiber. ZTA particles enhance the wear resistance due to their exceptional hardness and thermal stability, while short carbon fibers may enhance the lining's wear-resistant behavior via possible improvement in thermal dissipation and friction reduction. Hybrid composites synthesized using different combinations of fiber (10, 15, 20 wt%) and ZTA at 10 wt% are being investigated under dry conditions employing wear rate tests. The wear mechanism will be examined using analysis of the wear track microstructure and wear debris using a scanning electron microscope. Figure 1 shows the Shore D hardness for neat epoxy, and it is a composite. Keywords: Epoxy-based composites lining, short fiber, ceramic reinforcements, hardness, wear rate, friction coefficient.

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abst. 1246
**CIMA**
Friday
June 26
14h50

## Comparison of Wear Behaviour of Two Epoxy Composite Casing Linings

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In oil and gas well drilling, wear between the casing material and the hardened drill pipe tool joint (DP-TJ) is an inevitable issue that can, in severe regimes, result in deformed or even collapsed casings. The present study compares the wear behaviour of two epoxy based composites (A B) to be used as lining for steel or GFRP casings in oil and gas well drilling. Both linings are composed of a short-glass-fibre (SFG) reinforced epoxy matrix. The primary fillers of composite A included silicon carbide (SiC), aluminium oxide (Al2O3), and calcium carbonate (CaCO3), resulting in an average shore D hardness of 83.8. Composite B was modified by hard micro-spherical ceramic fillers (zirconia and fly ash). The fly-ash consists predominantly of SiO, AlO, and alumino-silicate phases. The average shore D hardness of composite B was 87.8. Wear tests performed, under dry conditions, using real casings and DP-TJ revealed that the wear behaviour of both materials was highly dependent on the applied side load and rotational speed of DP-TJ. The results showed that, under low to moderate speed (65-115 RPM) and side load (500 N), the average specific wear rate (K) for both composites was below 3.0x 10 MPa-1. However, under high wear conditions, K of composite A showed a drastic increase to above 50× 10 MPa-1 at 700 N and 154 rpm while that of composite B remained below 13× 10 MPa[1]. Microscopic analyses of worn surfaces revealed that at 65 RPM, adhesive wear is the predominant mechanism under all side loads. As the rotational speed increases a combination of abrasive and adhesive wear mechanisms with some matrix cracking are observed. High side loads resulted in excessive adhesive wear and delamination for composite A while the presence of zironia and flyash improved composite wear. Flyash particles enhanced wear resistance by filling cracks and surface voids. Keywords: casing wear, epoxy based com-posite linings, short-glass-fiber, zirconia, flyash

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## Technological aspects of manufacturing metallic coatings using the „cold spray" method on a FRP epoxy composite substrate with a pre-impregnated interlayer

abst. 1248
**Repository**

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Coatings applied to fibre-reinforced polymer matrix composites play an important role in giving the surface functional properties such as protection against impact, scratching and high temperatures, or enabling electrical conductivity or acting as a shield against electromagnetic interference. In these studies, one of the modern, advanced coating application methods, known as „cold spray", was used. It is mainly applied to metal parts, and its use on polymers is a major challenge due to the high speed of the metal powder and the need to heat the gas. This makes it impossible to deposit metal directly onto the FRP surface due to erosion and substrate softness. Therefore, the study presented several different pre-impregnated interlayers that allow metal to be deposited using the „cold spray" method or even to build thicker coatings. Pre-impregnated interlayers are a separate, original product that is added to the composite during its curing in an autoclave or vacuum infusion. It is flexible and can be used on curved surfaces. The study presents both technological issues and the results of laboratory tests of FRP composites with „cold spray" metal coatings. Metal powders such as aluminium, nickel, copper, zinc and tin were used for spraying, to which alumina was also added for technological reasons. Adhesion, tensile and flexural tests have shown that pre-impregnated interlayers can be used in practice as a material enabling the application of metal using the „cold spray" method.

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## Sustainable Hybrid Epoxy Composites Reinforced with Hemp and Interknitted Carbon–Kevlar Fabrics

abst. 1255
**Repository**

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The growing demand for sustainable high-performance composites has driven the development of hybrid systems that integrate natural and synthetic reinforcements. This study focuses on the fabrication and systematic characterization of hemp fiber–reinforced epoxy hybrid laminates incorporating interknitted carbon–Kevlar fabrics to assess the impact of stacking sequence on mechanical, interlaminar, and viscoelastic properties. The laminates were produced by hand lay-up and curing, with various configurations of carbon–Kevlar (C/K) and hemp (H) layers, including fully synthetic, hybrid, and fully hemp systems. Tensile testing indicated that the fully Carbon–Kevlar laminate exhibited the highest strength (295 MPa) and modulus (3.85 GPa), whereas hybrid laminates such as C/K–H–C/K–H maintained moderate tensile strength (153 MPa) with enhanced strain tolerance compared to hemp-only laminates (50 MPa). Flexural testing underscored the critical influence of stacking sequence, with sandwich-type configurations (C/K–H–H–C/K) achieving high maximum flexural stress (477 MPa) and load-bearing capacity, surpassing several symmetric designs. Interlaminar shear strength (ILSS) results demonstrated that alternating hybrids (C/K–H–C/K–H) achieved high maximum loads (69 N) and ILSS values (793 MPa), comparable to fully synthetic laminates, indicating effective interfacial stress transfer. Dynamic mechanical analysis and Cole–Cole plots revealed that incorporating hemp increased damping and viscoelastic heterogeneity, particularly in alternating hybrid configurations, which correlated with enhanced damage tolerance observed in flexural and ILSS tests. Scanning electron microscopy (SEM) of fractured surfaces corroborated the experimental findings by revealing fiber pull-out, matrix cracking, and interfacial failure mechanisms consistent with the observed macroscopic behavior. The findings highlight Carbon–Kevlar and hemp hybrid composite with the optimal stacking sequences, effectively balancing mechanical performance, energy dissipation, and sustainability.

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abst. 1280
SANT'EFISIO
Wednesday
June 24
10h20

## Dynamic crushing failure mechanism and energy absorption of natural bamboos under impact load

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The axial crushing behavior of natural bamboos with various growth ages under quasi-static and impact loads was experimentally investigated in this study. First, the macro- and micro- structural features of bamboo were observed, and the tensile mechanical properties of bamboo materials were measured. And then the typical crushing responses and deformation/failure patterns of dynamically-loaded bamboos were presented, compared with those under quasi-static load. Whereafter, the strain field distribution and energy absorption characteristics of bamboo culms were analyzed, and the crashworthiness of tested bamboo culms under impact load was evaluated. Finally, the energy absorption capacity of bamboo culms was compared with typical metallic circular tubes (made of Q235 steel and AA6061-T6 aluminum alloy) and other widely-used engineering materials/structures. The results indicate that the brittle fracture is the dominant failure mode of bamboo culms, which includes the splitting mode for internodal specimens and the bulging mode for nodal specimens. The nodal bamboo culms have a superior energy absorption capacity and crashworthiness compared to internodal bamboo culms, attributed to the dense distribution of vascular bundles and high anti-split strength of bamboo nodes.

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abst. 1284
CIMA
Tuesday
June 23
12h30

## Influence of manufacturing parameters on the selected properties of carbon fiber composite laminates

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Carbon fiber composite laminates are extensively used in high-performance engineering applications due to their exceptional strength-to-weight ratio and mechanical performance. The quality and structural integrity of these laminates strongly depend on the manufacturing process. This study examines the influence of selected process parameters, specifically process pressure (0–0.5 MPa) and laminate thickness (1–8 mm), on the structural integrity of carbon fiber composite laminates. Samples were fabricated under controlled laboratory conditions to ensure reproducibility. Their structural integrity was assessed using non-destructive testing (NDT) methods, including visual inspection and ultrasonic evaluation, as well as X-ray computed tomography (CT), enabling detailed analysis of internal defects and porosity distribution. The results highlight the importance of optimizing manufacturing parameters to achieve high-quality carbon fiber composite laminates and provide valuable guidance for their industrial application.

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## Repair process and performance evaluation of functional honeycomb structure

abst. 1286
**SANT'EFISIO**
Thursday
June 25
10h40

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The mechanical property and wave-absorbing property of the functional honeycomb structure (FHS) will decrease after being damaged to a certain extent, but the traditional composite repair process can not satisfy the recovery requirements of wave-absorbing property. In this paper, the foaming adhesive film with wave-absorbing property is innovatively introduced into the repair process of FHS, and the material parameters and repair process parameters are optimized to improve the recovery rate of wave-absorbing property of the repaired structure, which is finally verified by experimental and numerical simulation results. The results show that the mechanical property of the FHS can be effectively restored, while the reflection loss and effective wave-absorbing bandwidth can be restored to the level of the intact structure, and the wave-absorbing performance in some frequency bands exceeds that of the intact structure, thus providing references for the repair process of the functional composite structure.

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## Reducing Computational Costs for the Simulation of Large Composite Structures: A Laminate-Based Elasto-Plastic Approach

abst. 1287
**SANT'EFISIO**
Wednesday
June 24
10h40

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The non-linear simulation of large fibre-reinforced polymer (FRP) structures remains a major challenge, as detailed ply-based modelling leads to excessive numerical effort. As a result, nonlinear effects are often only investigated in detailed analyses – for example, by simulating specific details using submodelling or as part of multiscale methods – while structural analyses of large components are usually limited to linear-elastic material descriptions due to the enormous computational effort involved. This contribution focuses on the development of a novel material model specifically aimed at the efficient representation of non-linear laminate behaviour in large FRP structures. Instead of modelling individual plies, the proposed approach homogenises the non-linear response at the laminate level. The material behaviour is formulated using an orthotropic invariant-based plasticity model combined with a non-associated flow rule, enabling the description of characteristic non-linear effects while maintaining computational efficiency. A secondary aspect of the model development is to keep the experimental characterisation effort based on the unidirectional layer. All laminate material parameters are derived exclusively from unidirectional (UD) coupon tests. Through a homogenisation procedure, both linear and non-linear laminate properties are obtained without the need for laminate-specific testing. The material model is implemented as a user-defined subroutine in ABAQUS/Explicit. In order to demonstrate the robustness and applicability of the model for larger FRP structures, validation is carried out systematically on three levels. This contribution presents the results of the first two stages, in which simulations are

compared with experimental data from UD and multilayer coupons as well as with investigations on open-hole and filled-hole specimens. These comparisons show that the developed model is capable of accurately reproducing the nonlinear laminate response and local effects of load redistribution. The third step towards complete validation is still pending: this involves numerically simulating a full-scale crash test of a glider that has already been carried out experimentally. Successful comparison between this large-scale experimental crash data and the simulation will provide conclusive proof of the model's suitability for analysing complex FRP structures under real crash conditions.

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abst. 1336
SANT'EFISIO
Thursday
June 25
12h10

## Diluents-modified epoxy composites

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The objective of this study was to compare the mechanical properties of epoxy composites modified with diluents. The study investigated epoxy composites made from three epoxy resins based on bisphenol A, a polyamide curing agent, and four types of diluents: toluene, xylene, acetone, and white spirit. The epoxy composites were subjected to a static tensile test (in compliance with ISO 527-1) and a compression test (in compliance with ISO 604). Obtained results demonstrate that the addition of diluents to epoxy compositions affects their mechanical properties. Depending on the diluent used, its content and the selected epoxy resin, it is possible to produce epoxy composites with the desired mechanical properties.

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abst. 1344
SANT'EFISIO
Wednesday
June 24
15h50

## Laminated bamboo – concrete composite slab with combined notch and screw connections

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Bamboo is seen as a terrific material for many uses, including structures, as it promotes sustainability by reducing reliance on virgin materials. In an effort to leverage abundant indigenous bamboo resources and align with sustainable development principles, this paper introduces bamboo-concrete panels with three distinct connection methods. This study contrasts experimental data with theoretical values of screw-connected bamboo-concrete composite slab panels. The maximum bending capacity of screw-connected panels exceeds that of notch-screw-connected panels by 4% to 12%, and is 3 to 4.2 times that of notch-connected panels, indicating superior performance. Furthermore, the study reveals that bamboo-concrete composite structures with the highest load capacity primarily experience tensile fractures in bamboo fibers at the bottom of the slab and concrete rupture beneath the loading point. It is noteworthy that the bending capacity of bamboo-concrete composite panels diminishes with an increase in the thickness of the bamboo panels.

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abst. 1346
SANT'EFISIO
Thursday
June 25
12h50

## Failure scenario of a hybrid composite–metal structure joined by induction and resistance welding under restricted bearing loading

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This work investigates the failure scenario of a hybrid composite/metallic structure assembled using induction and resistance welding, based on extensively instrumented bearing tests. Thermoplastic composite materials have attracted growing interest in the aerospace industry due to their specific mechanical properties, weldability, and potential recyclability. Their integration into complex aeronautical substructures requires the development of novel joining techniques such as induction and resistance welding. When applied to load-transfer interfaces, these techniques are likely to significantly influence the failure mechanisms of composite structures. Understanding damage mechanisms in large-scale structures under quasi-static loading requires dedicated testing procedures and extensive instrumentation, which remain scarcely documented in the literature. Experimental campaigns involving complex loading conditions and heavy instrumentation in large, intricate, and costly aeronautical structures therefore demand rigorous test preparation, which is rarely addressed in detail in existing studies. The demonstrator investigated in this study is a composite structure designed to connect hydrogen tanks to the fuselage of next-generation aircraft. It is designed and manufactured through a collaboration between DLR, NLR and Airbus within the framework of the FASTER-H2 project under Clean Aviation (project number 101101978). DLR manufactures the composite components and performs resistance welding, whereas NLR performs induction welding. The demonstrator consists of an assembly of carbon-fibre-reinforced thermoplastic components and Z-shaped aluminium alloy parts, joined by adhesive bonding, bolted connections, and composite welding techniques (induction and resistance welding). The device is a safety mechanism conceived to exhibit controlled bearing failure during crash events. One of the key features of this design is a novel pin assembly that favours the progression of bearing failure within the interface between two composite parts of the demonstrator. The objective of this study is to characterise the failure scenario of the demonstrator in a configuration where bearing propagation is limited. Mechanical tests are performed at Jéricho, ONERA's mechanical testing platform dedicated to structural experiments, under quasi-static displacement-controlled loading. To investigate the role of composite welds in the failure scenario, the original pin assembly conceived by DLR is replaced by two simplified alternative configurations. The first uses a modified pin device, while the second combines the modified pin device with the addition of washers. In practice, these configurations limit bearing damage propagation and promote catastrophic failure of the demonstrator. The tests are instrumented using six optical cameras for stereo digital image correlation. Camera positioning is defined through a preliminary study combining numerical simulations and 3D modelling using Blender. The experimental setup enables a detailed characterisation of the demonstrator failure scenario. The test preparation and instrumentation allow the failure scenarios of both specimens to be analysed. For the configuration with the modified pin device, although bearing is observed, several damage mechanisms develop away from the pin, including adhesive joint debonding, partial failure of bolted connections, and delamination in welded regions. For the configuration combining the modified pin device with washers, bearing propagation is arrested, leading to catastrophic failure of the demonstrator and damage mechanisms similar to those observed in the first configuration.

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## Thermo-Mechanical and Electrical Properties of Glass Fiber Reinforced Acrylic Elium/Graphene Composite Laminates

abst. 1352
**RIVA**
Thursday
June 25
16h30

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Glass fiber reinforced thermoplastic composite structures based on Elium acrylic resin modified with graphene nanoplatelets were developed to enhance mechanical performance while providing multifunctional properties. In this study, composite laminates were manufactured using liquid thermoplastic

Elium resin incorporating different graphene contents and reinforced with glass fibers. The microstructure of the composites was investigated using scanning electron microscopy (SEM), revealing good fiber impregnation and satisfactory graphene dispersion within the polymer matrix at optimized concentrations. Mechanical behavior was evaluated through tensile and impact tests to characterize the structural response of the laminates under both static and dynamic loading conditions. The results show that graphene incorporation improves composite stiffness and mechanical strength, while also enhancing tensile performance. Thermal analyses performed using DMA, TGA, and DSC demonstrate improved thermomechanical stability and restricted polymer chain mobility in graphene-modified composites. Furthermore, electrical conductivity measurements reveal the formation of conductive pathways within the material, confirming the multifunctional potential of these composites. The combined improvements in mechanical, thermal, and electrical properties highlight the suitability of graphene-modified Elium-based composite structures for lightweight and high-performance engineering applications where both structural integrity and functional performance are required.

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abst. 1356
SANT'EFISIO
Wednesday
June 24
17h50

## Ribbing Without Tooling: Printing Thermoplastic Ribs on Thermoset Skins via Printable Interphases

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Lightweight composite panels rely on local ribbing to increase bending stiffness and buckling resistance. However, conventional thermoset manufacturing necessitates complex tooling and imposes strict geometric constraints, such as demolding draft angles, which severely limit shape freedom. Direct material extrusion of molten thermoplastics onto cured epoxies could eliminate these constraints, but this approach is fundamentally hindered by chemical incompatibility, low surface energy, and limited chain interdiffusion at the interface. To overcome this barrier, this research investigates the concept of a printable interphase: a co-cured thermoplastic film designed to render the thermoset surface weldable. The study examines how the thermal activation required to achieve sufficient polymer mobility for welding competes against the thermal degradation limits of the underlying epoxy matrix. To isolate these mechanisms, both high-temperature and low-temperature interphase systems were evaluated on an epoxy prepreg baseline. Single-lap-shear testing and thermal analysis demonstrated that joint performance is strictly governed by a coupled thermal process window. If the thermal input is too low, interfacial mobility remains inadequate, preventing the formation of a stable weld. Conversely, excessive thermal dwell times degrade the near-surface thermoset matrix or destabilize the interphase. When processed within the defined limits, the printed multi-material joints successfully match or exceed the baseline shear strength of the reference thermoset skin. To demonstrate the value of this approach, a helicopter door demonstrator from the LIGHT project was used as an application context. This establishes a novel process chain for carbon fiber reinforced polymer parts, where a thermoplastic film is integrated globally or locally into the thermoset layup. After consolidation, the component surface becomes directly printable, decoupling feature formation from thermoset flow limitations and removing the need for dedicated multi-part molds. By eliminating demolding draft angles entirely, direct printing allows for structurally optimized, draft-free ribbing. For a specific load-introduction subcomponent, this draft-free design reduced the estimated component mass by approximately 30%. Analytical models confirm that this geometric freedom yields cross-sectional mass savings of 5–22% for typical draft angles of 1–5°, with the benefit accumulating further in three-dimensional rib networks. Ultimately, printable interphases introduce a new architectural degree of freedom for load-aligned, multifunctional composite structures — with direct relevance to certification-compatible manufacturing routes where preformed thermoplastic inserts can substitute direct printing where throughput or process stability demands it.

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## Analysis of single and doubly curved Kevlar epoxy composite shell structures of various curvatures subjected to high velocity impact at elevated temperature

abst. 1392
**Repository**

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Curved composite shells are widely employed in defense and aerospace applications due to their lightweight and good mechanical performance. In this research, the single curved Kevlar epoxy composite shell (SCKECS) and doubly curved Kevlar epoxy composite shell (DCKECS) structures of four distinct central curvature heights of 2.5, 5, 7.5 and 10 mm were fabricated using the vacuum-assisted resin transfer method. The curved composite shell structures were impacted with a spherical projectile using single-stage gas gun at various impact energies at ambient and elevated temperature of 393 K, followed by surface indentation measurements and ultrasonic testing. At ambient temperature, geometric stiffness was predominant: dent diameters decreased as curvature height increased, thereby confirming enhanced impact resistance with increased curvature. The DCKECS structure exhibited biaxial resistance and shown almost uniform delamination pattern, in contrast to the unidirectional hoop effects seen in the SCKECS structure, which exhibited increased delamination along the transversely constrained edges due to shear concentration. The rubbery state of epoxy at 393 K drastically changed the delamination trend for the SCKECS structure, resulting in the complete disappearance of transverse damage, but interlaminar damage in the DCKECS increased due to biaxial stress distribution. The sample impacted under 48 J at 393 K resulted in projectile rebound through rubbery matrix energy dissipation and free fiber sliding. This findings points out the curvature and temperature interactions on the high velocity impact characteristics of SCKECS and DCKECS structures, which will help designers to create durable high-impact structures for real-world situations.

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## Microwave-Selective Curing of Outer Continuous Reinforcement Shell for Bent GFRP rebars

abst. 1404
**SANT'EFISIO**
Thursday
June 25
12h30

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Glass fiber reinforced polymer (GFRP) rebars are increasingly adopted to reduce steel corrosion in reinforced concrete; however, bent portions remain mechanically vulnerable due to stress concentration and residual deformation. Conventional oven or furnace curing limits the implementation of designable stiffness-gradient structures. We propose a bent-GFRP rebar architecture featuring an outer continuous reinforcement shell selectively formed on the tensile-side surface of the bent region. A thin shell composed of a thermoset resin containing chopped carbon fiber as a microwave susceptor at 0.2 - 2.0 wt.%, is applied by coating, followed by localized microwave irradiation. Multilayer shells with graded susceptor content and degree of cure are employed to realize a functionally graded core-shell structure, in which the outer layer attains higher stiffness while the inner layer retains relative toughness; surface protrusions can be introduced to preserve mechanical interlock with concrete. Local microwave curing is conducted at 2.45 GHz under an input power of 300 to 1500 W with closed-loop temperature control maintained at 120 to 180 °C, which increased the outer-shell glass transition temperature by 5 to 20 °C and improved the local elastic modulus by around 10%, resulting in an enhancement of at least 15% in overall bending stiffness of the bent portion compared with uniformly cured GFRP rebars. These results demonstrate that microwave-driven selective shell reinforcement provides a scalable route to mechanically robust bent GFRP rebars, overcoming a critical hurdle to full steel replacement by enabling steel-like performance in bent regions and thus expediting the broader deployment of GFRP rebars in building and civil infrastructure.

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abst. 1431
SANT'EFISIO
Thursday
June 25
09h40

## Advanced Methods for Thermal Buckling Analysis of Higher-Order Composite Laminates

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Recent developments in composite structures with enhanced mechanical performance have made it possible to achieve an improved strength-to-weight ratio, which is particularly valuable in demanding applications such as civil and aerospace engineering. Although higher-order theories provide an accurate representation of these structures, their implementation is often complicated due to the large number of involved variables. To simplify the formulation, internal constraints are imposed; however, these constraints can introduce difficulties in numerical approaches like the finite element method (FEM), often necessitating higher-order interpolation functions. Motivated by these challenges in finite element modeling of constrained composite systems, this study investigates the thermal buckling response of higher-order graphene platelet-reinforced composite (GPLRC) plates. Internal constraints within higher-order plate theories are enforced using the Lagrange Multiplier Method (LMM) and the Penalty Method (PM). These approaches eliminate the need for interpolating displacement fields with higher-order continuity requirements, allowing the use of standard C Lagrange shape functions. As a result, they facilitate simpler formulations, maintain a well-defined weak form, ensure compatibility with conventional FEM software, and avoid unnecessary complexity within classical finite element frameworks. The governing equations for the GPLRC laminated plate are formulated based on the General Third-order Shear Deformation Theory (GTSDT). The effective material properties of the laminate are evaluated using the Halpin–Tsai model in combination with the rule of mixtures. Additionally, four distinct GPL distribution patterns through the thickness are examined to assess their influence on the buckling behavior of the laminate. A comprehensive comparison between LMM and PM is carried out by varying parameters such as mesh density, GPL weight fraction, and geometric characteristics. The results confirm the accuracy and efficiency of both constraint enforcement techniques in FEM-based thermal buckling analysis of composite plates. Overall, this work establishes a reliable and efficient framework for analyzing complex composite structures, supporting practical implementation in computational mechanics applications.

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abst. 1388
CIMA
Friday
June 26
15h10

## Machine Learning-Based Classification of UV-Induced Surface Degradation in Carbon Fibre Composites Using Augmented SEM Datasets

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Carbon fibre reinforced polymer (CFRP) composites are increasingly employed in aerospace, automotive, and civil infrastructure applications, where long-term exposure to ultraviolet (UV) radiation can lead to progressive surface degradation and compromised structural performance. In this study, CFRP samples were subjected to accelerated UV exposure under controlled laboratory conditions to investigate the effects of prolonged irradiation on surface morphology and defect evolution. Both UV-exposed and unexposed specimens were examined using high-pressure and low-pressure scanning electron microscopy (SEM), enabling a comparative assessment of surface features and the acquisition of high-quality image datasets. SEM analysis revealed clear evidence of UV-induced surface damage in exposed samples, including fibre exposure, matrix cracking, void formation, and the presence of microparticles. Based on these observations, the SEM image dataset was labelled and categorised into four defect classes: fibres, matrix cracks, microparticles, and voids. To address the challenge of limited experimental data, an initial dataset of 58 SEM images was expanded using extensive data augmentation strategies, generating datasets at 5×, 10×, and 20× scales. Transfer learning was employed to train a machine learning

model for automated defect identification and classification. Model performance was evaluated across all four dataset configurations. The baseline model trained on the original dataset achieved a validation accuracy of 72.73%. With the introduction of data augmentation, performance improved significantly, reaching 91.18% for the 5× dataset and further increasing to 98.71% for the 20× augmented dataset. These results demonstrate a strong positive correlation between dataset diversity and classification accuracy, which highlight the effectiveness of combining transfer learning with systematic data augmentation for small, experimentally derived image datasets. Nonetheless, manual inspection of SEM micrographs often suffers from variability in defect interpretation, limited reproducibility, and practical constraints specifically when large image volumes are analysed. By automating defect classification, the proposed machine learning-based framework minimises human bias while improving inspection accuracy, enabling reliable early-stage damage detection and condition monitoring that support timely preventive maintenance and extend the service life of CFRP structures operating under extreme environmental conditions.

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## Composite structures in civil engineering

abst. 1029
**RIVA**
Thursday
June 25
10h40

### Mechanical behaviour of BFRP- confined coal reject concrete columns under eccentric compression

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This study examines the mechanical response of coal reject concrete composite columns confined with basalt fiber-reinforced polymer (BFRP) under eccentric compression. A total of twelve cylindrical specimens with a constant diameter of 150 mm and a height of 300 mm were fabricated and tested to investigate the influence of eccentric values (i.e., 0 mm , 25 mm, 50 mm and 75 mm). Experimental results revealed a notable reduction in ultimate load capacity with the increased eccentricity. The failure mechanism transitions from compressive-dominated failure under concentric loading to a combined tensile-compressive mode under eccentric conditions. Moreover, BFRP confinement was found to mitigate the inherent brittleness of coal reject concrete, significantly improving ductility and deformation compatibility. Moreover, larger eccentricities led to increased lateral deflection and uneven confinement distribution, resulting in pronounced stress concentration within the compression zone of the core concrete. These findings offer practical insights for the structural use of coal reject concrete and inform the design of composite members for underground mines where the eccentric compression situation is a normal issue.

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abst. 1036
**RIVA**
Thursday
June 25
10h00

### Structural Performance of a hybrid FRP bridge girder with wind turbine blade type Vestas V-66 and non-conventional concrete

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In the wind energy sector, about 2.5 million tons of composite materials are used, mainly placed in wind turbine blades. The first generation of turbines is just ending its life after about 20 years of operation and is successively replaced with modern turbines. By 2025, about 14 thousand blades will be withdrawn from use, which corresponds to 40 - 60 thousand tons of composite materials. Therefore, numerous research and development works are currently being carried out to develop various methods of recycling decommissioned blades, including those enabling their reuse. Among the most effective of these is product recycling, which involves minor and low-energy processing of materials to create a new product—in this case, a hybrid girder made from a Vestas V-66 wind turbine blade and unconventional concrete. A single Vestas V-66 wind turbine blade, from which the composite FRP girder section is obtained, has a total length of approximately 30 m and a height of 1460 – 2750 mm and is made of E-glass fibers and an epoxy resin matrix. Both the bridge deck and cross members are made of unconventional concrete class C35/45, in which 5% by weight of the coarse aggregate is replaced with crushed propeller chips with a fraction of up to 3 cm to increase recycling potential. Before attempting to implement these girders in the construction of bridge spans (road bridges and footbridges), experimental testing of a fully-fledged prototype hybrid girder was conducted to assess the ultimate load-bearing capacity, fatigue life, and dynamic characteristics. The hybrid girder shown, approximately 9 m long and 1.5 m wide, consists of a GFRP composite shell with a near-rectangular cross-section, bonded to concrete using bolted connectors to ensure a permanent bond between the two parts. The total height of the girder (girder and slab) is 70–145 cm, and the height of both crossbeams is approximately 140 cm, measured from the bottom of the deck slab. The deck slab is connected to the box beams using M-20 class 8.8 steel bolts, bolted to the top flange of the beam with two nuts and a tightening torque of 300 Nm. It has a minimum thickness of 1.5 m. 21 cm and is made of concrete reinforced with GFRP bars. The girders can withstand the live loads of the LM-1 model and a pedestrian load of 5.0 kN/m$^2$ in accordance with the PN-EN 1991-2 standard. The paper presents the results of experimental tests: static and dynamic of a hybrid girder made of a fragment of a Vestas V-66 wind turbine blade and unconventional concrete. The hybrid girder was developed as part of

the research and development project entitled: "WTBridge" – Hybrid girder made of recycled wind turbine blades and unconventional concrete for the construction and modernization of bridge structures equipped with fiber optic sensors for monitoring the structure, as part of the LIDER XIII competition financed by the National Center for Research and Development (project no. 0031/L-13/2022).

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## A Conceptual Framework for Integrating Structural and Environmental Factors in Composite Pavement Performance Assessment

abst. 1038

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Composite pavement systems behave through the combined action of multiple layers and are influenced by environmental and loading conditions throughout their lifetime. Understanding this behavior requires approaches that can incorporate diverse sources of information without relying solely on simplified assumptions. This paper introduces a broad conceptual framework for examining how structural configurations, climatic patterns, and traffic histories relate to pavement performance. The aim is to establish the groundwork for future studies that may employ advanced analytical or data-driven techniques. This preliminary formulation provides a general perspective on how different factors interact within composite pavement systems and highlights the need for integrated approaches in performance assessment.

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## Tensegrity-Based Design of Deployable Solar Roofs

abst. 1046
**RIVA**
Wednesday
June 24
10h00

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This paper explores the mechanical response and energy-production potential of a novel deployable tensegrity roof incorporating photovoltaic panels with autonomous sun-orientation capabilities. The proposed system exhibits robust structural performance when subjected to wind and earthquake excitations, while simultaneously increasing the efficiency of solar-energy capture. Originating from a recently introduced architectural concept for stadium roofs, the solution is applicable to both newly constructed and existing sports facilities. The investigation first focuses on the kinematic characteristics and mechanical behavior of a single adaptive unit, which constitutes the basic component of the roofing system. Owing to its flexible geometry, this unit can be combined to form multiple roof layouts with varying architectural configurations. The methodology integrates analytical formulations describing the deployment and motion of the module with numerical simulations aimed at evaluating its dynamic response and load-bearing capacity. These analyses account for different levels of cable prestressing, as well as the effects of wind and seismic actions. The results demonstrate that the proposed tensegrity-based roof provides dependable resistance against environmental loads. In addition, the ability to independently orient each module leads to a marked improvement in the overall efficiency of solar-energy collection.

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## Analytical design proposal of steel timber composite beams

abst. 1050
**TIGELLIO**
Friday
June 26
10h00

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Achieving carbon neutrality in the construction sector requires the adoption of sustainable practices and the use of renewable, recyclable, and reusable materials. Steel–timber composite (STC) structures represent a promising solution by combining the strength and recyclability of steel with the sustainability and versatility of timber. These systems offer advantages such as enhanced structural efficiency, design flexibility, and aesthetic appeal, making them suitable for a wide range of applications from low-rise to high-rise buildings and infrastructure projects. However, the design of STC flooring systems remains insufficiently addressed, as no standards, codes, or technical guidelines currently exist for STC beams with either laminated veneer lumber (LVL) or cross laminated timber (CLT) slabs. To bridge this gap, ongoing research and the ECCS TC11/WG6 initiative aim to establish preliminary design considerations based on analytical and experimental findings, focusing on short-term structural behavior at ambient temperature and dry indoor conditions. This paper presents a comparative study of two design approaches—the strain-limited design method and the -method for mechanically jointed timber beams according to EN 1995-1-1 Annex B—of composite beams with timber slabs. The comparison is supported by experimental data from STC beams with LVL and CLT panels, providing insights into the accuracy and applicability of each method for future design guidelines.

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abst. 1071
**RIVA**
Wednesday
June 24
09h40

## Evaluation of Eurocode 4 model for slender Circular Concrete-Filled Steel Columns

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This paper studies the behavior of slender circular concrete-filled tubular (CFT) columns under concentric axial load. A total of 939 experimental test, summarized from bibliography, have been analyzed and their ultimate load has been compared with actual design code in Europe, Eurocode 4. The effect of the slenderness, sectional aspect ratio (local buckling factor) and the strength of materials, has been investigated to understand the behavior of axially load columns. In base of this study, the validation of the current Eurocode 4 in applications with high strength materials and tubes with thin-walled sections has been probed.

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abst. 1101
**Repository**

## Preliminary Evaluation and Statistical Modelling of Hybrid Fiber-Reinforced High-Performance Concrete

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This study presents preliminary experimental and analytical investigations of high-performance concrete (HPC) reinforced with hybrid fibers of different types and proportions. The aim is to identify fiber combinations that enhance both strength and ductility while maintaining good workability and compactness. Eight HPC mixtures containing steel, polypropylene, and basalt fibers were prepared and tested at 28 days for compressive, splitting tensile, and flexural strength, modulus of elasticity, and ultrasonic pulse velocity (UPV). Statistical correlation and regression analyses were used to describe interrelations between density, porosity, and mechanical properties. Preliminary results indicate significant synergistic effects of hybrid fibers, leading to improved post-cracking behavior and fracture energy. The proposed material models enable prediction of mechanical performance as a function of fiber composition and microstructural parameters. These findings provide a quantitative basis for selecting four optimal fiber configurations for subsequent structural-scale beam testing.

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## Long-Term Mechanical and NDT Assessment of Hybrid-Fiber HPCC: Balanced Flow, Strength, and Fracture Energy

abst. 1102
**TIGELLIO**
Friday
June 26
10h20

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Adding fibers is a widely adopted route to enhance the tensile response of concrete, yet fiber type and hybridization can degrade workability and alter post-cracking mechanisms. This work evaluates the influence of steel (ST50), polypropylene (PP40), basalt (B12), and glass (G18) fibers (alone and in double-fiber hybrids) on the fresh behavior and structural response of HPCC. Eight mixes were produced: four single-fiber and four hybrids at a total Vf = 3% with a 2:1 fiber ratio. Slump was measured on fresh mixes. Hardened properties included compressive and splitting tensile strengths, and three-point bending on notched prisms (span 600 mm; effective ligament hsp = 90 mm). Flexural behavior was analyzed per EN 14651 (CMOD-controlled) to obtain fLOP, fR,1. . . 4, feq,2, feq,3. The work-of-fracture was integrated from load–deflection curves to compute GF. Basalt fibers produced the strongest loss of flow, often eliminating spread. Steel + PP and steel + glass preserved flow. Compressive strength spanned  61–98 MPa, with flowable steel-containing hybrids highest. Flexural results exposed a robust ranking of hybrids: G18+ST50 > B12+ST50 > PP40+ST50 > B12+PP40. The glass–steel hybrid achieved the top residual/equivalent strengths and GF  9.04 N/mm, indicating a long, stable bridging zone; basalt–steel reached GF  6.61 N/mm; PP–steel remained ductile but with lower sustained loads (GF  3.50 N/mm); basalt–PP was least effective (GF  2.42 N/mm). Single-fiber concretes followed the same material logic (glass  steel ≫ PP > basalt). For serviceability-driven HPCC (crack-width control, impact/fatigue), glass + steel is recommended at Vf = 3%. Basalt + steel is viable with workability control. PP + steel is appropriate when ductility and compressive/splitting strength are prioritized. The results provide design-level evidence that fiber synergy and length/modulus complementarity govern residual capacity and fracture energy in HPCC.

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## Analysis of the Concrete Filled Steel Tubular Members Subjected to Bearing Forces

abst. 1134
**TIGELLIO**
Friday
June 26
10h40

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Steel tubular members subjected to localized bearing forces and bending are vulnerable to local crushing, sidewall instability, and premature loss of load-carrying capacity. These effects are particularly pronounced in members affected by manufacturing-induced imperfections, such as residual stress and welding defects. This study investigates strengthening strategies for steel tubular members while explicitly addressing the influence of fabrication technology on structural performance. The research program is divided into two main groups of specimens. The first group consists of cold-formed square hollow sections, including empty sections and concrete-filled sections. The second group comprises robotic welded box sections, including empty welded sections, welded sections with concrete infill. All welded box specimens were manufactured using robotized welding process welding with solid wire, which ensures high geometric accuracy, uniform weld quality, and repeatable thermal input. The robotic welding procedure was specifically selected to minimize residual stress, eliminate common welding imperfections, and reduce variability in material behaviour. As a result, the welded specimens provide a reliable basis for isolating the structural effects of bearing forces, bending, and strengthening measures without distortion from uncontrolled fabrication defects. The investigation combines analytical modelling, nonlinear finite element analysis, and experimental testing. Finite element models incorporate bilinear steel behaviour with strain hardening and nonlinear concrete compression, enabling the study of stress redistribution and local instability under lateral compression. The experimental program includes lateral compression tests to examine local crushing behaviour. Results demonstrate that empty cold-formed and welded box sections are governed by early local sidewall deformation. Concrete infill significantly enhances stiffness and resistance by stabilising the steel walls and delaying crushing. The study confirms that advanced fabrication technology combined with composite action and mechanical strengthening provides a robust strategy for improving the performance of steel tubular members subjected to localized bearing forces.

abst. 1163
**RIVA**
Wednesday
June 24
10h20

## Analysis Theory and Engineering Applications of Steel-Concrete Composite Lattice Tower Structures for Large Wind Turbines

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Wind energy has become a cornerstone of China's renewable energy strategy, aligning with the country's goals of building a resource-efficient and environmentally friendly society. Expanding wind power capacity is crucial for enhancing energy production technologies and driving industrial innovation. To improve wind energy capture and increase generation efficiency, it is essential to develop taller towers with longer blades, particularly for low-wind-speed areas. However, traditional steel towers face challenges such as resonance risks due to the overlap of natural and operational frequencies, insufficient lateral stiffness causing excessive top displacement and fatigue issues, and limited load-bearing capacity leading to potential local instabilities. Recently, hybrid towers have emerged as a solution but still suffer from safety redundancy, poor fatigue performance, and construction quality concerns. To address these limitations, this study proposes a novel steel-concrete composite structure: the prestressed concrete filled steel tubular lattice tower. This innovative design combines the high load-bearing capacity of steel-concrete composites with environmental benefits, ease of transportation, and reduced land use. Despite its advantages, there remains a lack of comprehensive research on the static performance of individual components and key joints, such as transition segments and KK joints, under various loading conditions. This study investigates the static behavior of these components and the overall structure under compression, bending, shear, and torsion, examining failure modes and load-bearing capacity variations. Based on the findings, design formulas and optimization methods are proposed for practical engineering applications, ultimately contributing to the development of a mature and reliable wind tower system, while also providing valuable guidance for the application of composite structures in civil engineering.

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abst. 1200
**RIVA**
Wednesday
June 24
12h50

## Finite element modeling of bridge columns made of concrete-filled FRP tubes

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Concrete-filled FRP tubes (CFFTs) with inclined fiber orientations exhibit pronounced nonlinear behavior due to matrix cracking, fiber-matrix debonding, and shear deformation, making their finite element (FE) analysis challenging. Additionally, many material models in the literature involve nonphysical or experimentally unidentifiable parameters. This study employs LS-DYNA to analytically investigate the lateral force–displacement response of bridge columns made with $\pm 55°$ filament-wound CFFTs. Confined concrete was modeled using MAT159, the FRP shell using MAT54 with Chang–Chang failure criteria, and internal reinforcement using MAT24. Nonphysical and experimentally unidentifiable parameters were calibrated through metamodel-based parametric optimization in LS-OPT, using the global force–displacement response as the comparison metric against experimental data from the literature. A control reinforced concrete (RC) column was also analyzed for comparison. Simulation results showed excellent agreement with experiments, with peak load discrepancies within 5%, and demonstrated that CFFT columns outperform the control RC columns in lateral load resistance. This work presents one of the first fully optimized and experimentally validated LS-DYNA modeling frameworks for inclined-fiber CFFT bridge columns, providing a robust tool for future design, assessment, and reliability studies.

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## An Analytical Solution for the Buckling of FG Sandwich Beams Based on the Timoshenko Beam Theory Resting on an Orthotropic Pasternak Foundation

abst. 1201
**RIVA**
Wednesday
June 24
10h40

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This study aims to investigate the buckling behavior of a three-layered sandwich beam resting on an orthotropic Pasternak elastic foundation within the framework of Timoshenko beam theory. In the structural model being examined, the core layer of the beam is made of a homogeneous material. In contrast, the upper and lower surface layers are composed of functionally graded materials whose mechanical properties change continuously in the thickness direction according to a power-law distribution. This study presents, for the first time in the literature, the incorporation of orthotropic behavior into the Pasternak foundation model for the buckling analysis of thick sandwich beams by integrating the direction-dependent shear stiffness characteristics of the foundation into the governing formulations. The equations governing the buckling of the thick sandwich beam are derived using the principle of minimum total potential energy. By imposing simply supported boundary conditions, the governing equilibrium equations are transformed into an eigenvalue problem via Navier expansions, yielding closed-form expressions for the buckling loads. A detailed parametric study is conducted to examine the effects of the material gradation index, face-to-core thickness ratio, foundation stiffness parameters, foundation orthotropy, and beam slenderness on the buckling response. The results obtained comprehensively reveal the effects of orthotropic foundation parameters, the material gradient index in the surface layers, and the sandwich geometry on buckling resistance. This study provides a notable contribution to the literature for buckling analyses of advanced composite structures considering soil foundation-structure interaction. Acknowledgements: This study was supported by Bursa Uludag University Research Projects Coordination Office under the Grant Number FGA-2026-2816. The authors thank to BUU BAP Unit for their supports.

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## Numerical Determination of the Transverse Shear Correction Factor in BubbleDeck Slabs Using Cross-Sectional Averaging

abst. 1202
**RIVA**
Wednesday
June 24
12h10

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Plates with periodically distributed spherical voids, commonly known as BubbleDeck slabs, are increasingly used in building structures due to their reduced self-weight and efficient material utilization. However, the presence of voids leads to a highly non-uniform transverse shear stress distribution across the slab thickness, making classical assumptions adopted in first-order shear deformation theories questionable. In particular, the commonly used constant shear correction factor, derived for homogeneous and solid cross-sections, may result in inaccurate predictions of shear stiffness and deflections. This paper presents a numerical methodology for determining the transverse shear correction factor for BubbleDeck-type slabs based on a detailed cross-sectional analysis. The approach relies on three-dimensional finite element simulations of representative slab segments, from which actual shear stress distributions are obtained. Multiple cross-sections are extracted at characteristic locations with respect to the void geometry, including sections passing through void centers, ligament regions, and solid concrete zones. For each cross-section, the effective shear correction factor is evaluated using an energy-equivalence principle between the three-dimensional stress state and the corresponding two-dimensional plate model. The resulting shear correction factors exhibit significant spatial variability along the slab length and thickness, reflecting the strong influence of void positioning and concrete ligaments. To enable practical application in plate and shell models, a homogenized shear correction factor is proposed, obtained by weighted averaging of local values over a representative volume element. The study demonstrates that the effective shear correction factor for BubbleDeck slabs deviates markedly from classical values

and depends on void diameter, slab thickness, and void spacing. The proposed methodology provides a rational and physically consistent way to incorporate the effect of voids into simplified plate models, improving the accuracy of global structural analyses without increasing computational cost. The results may be directly used in numerical simulations of BubbleDeck slabs and similar voided concrete plates, and they offer guidance for future developments in homogenized plate theories for non-standard cross-sections.

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abst. 1228
**RIVA**
Wednesday
June 24
12h30

## Experimental Study on the Instability of FRP Pultruded Profile Curved Beams Under Tunnel Large Deformation Connecting rod Failure Conditions

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In the construction of highway tunnels, steel is generally selected as the material for the initial support arch frame. However, characteristics such as its heavy weight and susceptibility to corrosion have become major obstacles affecting both the construction speed and service life of highway tunnels. I-beams made of fiber-reinforced polymer (FRP) through the pultrusion process can effectively replace steel in the initial support of highway tunnels. To investigate the instability characteristics of pultruded profile curved beams under the failure of large deformation connecting rods in tunnels, this paper conducted relevant experimental studies. The failure mode of out-of-plane instability in pultruded sections was analyzed. A three-dimensional refined finite element model for out-of-plane instability was established based on an orthotropic constitutive model. Additionally, formulas were proposed to calculate the ultimate displacement and bearing capacity of pultruded profile sections under load-induced out-of-plane instability. The results indicate that: (1) The out-of-plane instability failure mode of pultruded profile curved beams follows an "S"-shaped pattern, with the failure occurring at the connection between the flange plate and web plate at the arch foot. (2) The ultimate bearing capacity for out-of-plane instability of pultruded profile sections gradually decreases as the span-to-height ratio decreases. The failure mode shifts progressively from the mid-span to the connection between the flange plate and web plate at the arch foot as the span-to-height ratio decreases. (3) In the initial support of highway tunnels, the span-to-height ratio of each pultruded profile arch frame should not be less than 5 to ensure the out-of-plane stability of pultruded profile curved beams in cases of connecting rod failure.

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abst. 1230
**TIGELLIO**
Friday
June 26
09h00

## Experimental Study on Axial Compression of Wind turbine Steel Tower with Dimple Tolerances

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Thin-walled circular steel turbines are widely used in the tapered steel towers of wind turbines. When dimple tolerances are present, local instability can easily occur, leading to a reduction in the load-bearing capacity of the tower. In this paper, axial compression loading tests were conducted on two specimens to investigate the influence of dimple tolerances on the local stability of wind turbine steel towers. The test results show that dimple tolerances have a significant impact on tower stability, and this impact increases with the severity of the dimple tolerances. The failure mode primarily involves wrinkling that originates at the dimple and extends circumferentially around the dimple edge. Eurocode predictions for the axial capacity of dimple-damaged towers are conservative: the predicted value is 9.38 % lower than the test result. Therefore, the effect of dimple tolerances on tower stability should be given serious consideration in actual engineering applications.

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abst. 1231
**TIGELLIO**
Friday
June 26
09h20

## Experimental Study on the Static Performance of Multiplanar Thin-Walled Circular Concrete-Filled Steel Tubular KK Joints.

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In order to investigate the influence of concrete filling in the joint area on the mechanical performance of KK-shaped spatial intersecting joints, this study designed two comparative specimens: a KK-shaped intersecting joint specimen with concrete filling in the joint area and an empty steel tube KK-shaped intersecting joint specimen. The test employed a loading method where the ends of the four branch tubes were hinged, and an axial tensile force was applied to the ends of the main tube to obtain the failure modes, bearing capacity, and load-displacement curves of the specimens. The experimental results show that the empty steel tube specimen mainly exhibited plastic failure in the main tube area near the compressed branch tube, while after concrete filling, the failure mode of the joint shifted to punching shear failure of the main tube near the tensioned branch tube. This indicates that internal concrete filling can effectively improve the mechanical performance of the joint. Finally, the test results were compared with the calculation formula for the punching shear failure bearing capacity of empty steel tube intersecting joints in current codes and existing research on KK-shaped concrete-filled steel tube spatial intersecting joints. It was found that the bearing capacity calculation formulas proposed by the codes and existing studies are relatively conservative.

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## Data-Driven Assessment of the Seismic Behavior of FRP-Strengthened Steel Bridge Piers

abst. 1304
**TIGELLIO**
Friday
June 26
09h40

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Local buckling of steel plates is one of the dominant failure modes of steel bridge piers under strong seismic loading. However, simple and effective reinforcement techniques for steel bridge piers with inadequate seismic performance remain limited. Owing to its high strength-to-weight ratio and ease of installation, bonded fiber-reinforced polymer (FRP) reinforcement has emerged as a practical alternative to traditional welded or bolted steel plate strengthening. Accordingly, this study investigates the seismic performance of FRP-reinforced rectangular steel bridge piers, aiming to support the development and application of composite material strengthening technologies for steel bridge piers. Interface bonding tests under combined normal and shear loading were first conducted to validate a finite element model capable of predicting bond interface failure. Based on the validated model, the buckling behavior of typical steel bridge piers was analyzed, and a channel-shaped FRP reinforcement scheme was proposed. Reinforcement efficiency was then evaluated under varying structural parameters, including width-to-thickness ratio, slenderness ratio, and axial compression ratio, enabling the identification of appropriate reinforcement materials and design dimensions. Machine learning techniques were subsequently employed to classify adhesive failure modes and to predict post-reinforcement performance indicators through regression analysis. Based on the analytical results, a database comprising 160 classification samples and 105 regression samples was established, incorporating structural parameters and reinforcement dimensions, and a predictive evaluation framework for the seismic performance of FRP-reinforced steel bridge piers was developed. The results indicate that channel-shaped FRP plates with vertically oriented fibers and flange lengths equal to one-third of the pier web length provide the most effective reinforcement, achieving efficiency improvements ranging from 1.36% to 16.83%. Among the trained machine learning models, XGBoost demonstrated the highest predictive accuracy. The classification model achieved an accuracy of 93.8% on the test set, while the regression models for bearing capacity, ductility limit displacement, bearing capacity improvement ratio, and ductility improvement ratio yielded $R^2$ and MAPE values of 0.975 and 0.86%, 0.974 and 3.48%, 0.941 and 9.92%, and 0.914 and 21.19%, respectively. All models exhibited stable performance under random sample validation. Furthermore, SHAP analysis revealed that the width-to-thickness ratio and the axial tensile stiffness ratio of the reinforcement material are the primary factors influencing bond interface failure, whereas the slenderness ratio and reinforcement dimensions mainly govern reinforcement efficiency.

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## Development of a new FRP sandwich deck panel for bridge redecking

abst. 1353
**RIVA**
Thursday
June 25
09h40

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A new sandwich deck panel made of FRP composites was developed for upgrading the existing bridge over the Narew River in Bronowo. The bridge features a 10-span layout with a total length of 140.10 m and a width of 5.20 m. Each span is simply supported, with spans of 12.0 and 15.0 m. The spans consist of four rolled-steel girders cross-braced with C-sections. A timber deck was laid on a steel grid. Due to the poor condition of the timber deck, the bridge's load capacity was limited to 5 tonnes. To increase this to 15 tonnes, the bridge is slated for modernisation, including replacing the deteriorated timber deck with a durable new deck plate and strengthening the steel girders. To avoid adding dead weight to the spans and limiting the range of girder strengthening, it was decided to use a lightweight, durable FRP composite deck. The deck panels are designed to carry a single vehicle weighing 16 tonnes. A numerical model of the panel created in the SOFiSTiK environment was used for the design. Six characteristic panel laminates were isolated in the model and modelled using finite shell elements in three-dimensional space. The strength analysis of the laminates was carried out using the maximum stress criterion. Material parameters, material safety factors, and conversion factors (including long-term effects) are taken from the CEN/TS 19101 standard. The deck panels are made of a composite material based on polyester resin reinforced with glass fibres. The panels measure 0.15 x 3.00 x 5.20 metres. They feature a sandwich structure, with outer laminates covering a ribbed core of 42 kg/m³ PUR foam. Two types of fabric were used for laminate reinforcement: a bidirectional 0/90 fabric with an asymmetrical fibre arrangement and a weight of 1250 g/m², and a bidirectional fabric $\pm 45°$ with a symmetrical fibre arrangement and a weight of 800 g/m². The core ribs are laminates arranged perpendicular to each other. The panels were manufactured using the VARTM vacuum infusion method. Along the bridge spans, the panels were attached to the steel girders with special connectors, although these did not ensure proper cooperation between the panels and the girders. To evaluate the deck's load-bearing capacity and rigidity, a strength test was conducted on the panel prototype. In static tests, the deck panel was tested in a simply-supported setup with a span of 4.80 m, subjected to both symmetrical and asymmetrical loads in the form of four patch loads simulating actual vehicle wheels, with a maximum combined load of $4 \times 310 = 1240$ kN. During these static tests, the panel displacements and the strains of selected composites were measured. Strains were recorded using optical reflectometers equipped with DFOS fibre-optic technology. After static loading, the prototype underwent dynamic testing using a modal hammer. Under static load, the panel behaved elastically up to approximately 700 kN, after which local damage developed, indicated by "crackling" and a reduction in panel stiffness. However, the panel was not compromised at the maximum load. The highest strength of the composites, reaching 98% of the design material strength, was observed in the ribs. The maximum deflection under the characteristic load was 1/465 L, and the natural vibration frequency was measured at 14.4 Hz. These values confirmed the panel's required load-bearing capacity, stiffness, and dynamic properties. The research findings were also used to validate the panel's numerical model, which achieved a 93% correlation. Following the bridge modernisation, proof-load tests were carried out on the bridge spans under both static and dynamic loads. During these tests, deflections of the main girders and strains in the panel laminates were measured using fibre-optic sensors. The observed deflections reached up to 84% of the design values, while the composite strains were approximately 91% of the design values. During the dynamic tests, two natural frequencies of the span structure were identified: 2.6 Hz and 14.8 Hz. Despite the lightweight design, the deck panels showed no signs of excitation during the dynamic tests. In summary, the design work and static and dynamic tests carried out in the laboratory and on the bridge structure confirmed that the new type of FRP composite panel can be used to modernise road bridges.

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abst. 1426
**RIVA**
Wednesday
June 24
13h10

## Axial and Eccentric Compressive Behavior of Stiffened Cruciform Steel Concrete Composite Columns

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This study investigates the axial and eccentric compressive behavior of a stiffened cruciform steel concrete composite column, which is easy to fabricate and assemble and can be used as a central column in high rise buildings. The proposed member makes efficient use of the steel tube and infilled concrete, while the angle stiffeners enhance confinement and delay local buckling, thereby improving

strength and ductility. Fourteen specimens were tested under axial compression and twelve under eccentric compression to examine the failure phenomena, mechanical performance, and failure modes. The main parameters included stiffener spacing, stiffener size and arrangement, load eccentricity, loading angle, and slenderness ratio. Test results showed that shear failure occurred in the stub specimens, whereas the medium and long specimens primarily exhibited bending failure. The results indicate that increasing the stiffener spacing, slenderness ratio, or load eccentricity, as well as reducing the stiffener size, decreases the compressive capacity. The stiffener arrangement had a limited effect, while the loading angle had a considerable influence on the compressive capacity. A finite element (FE) model was developed in ABAQUS and validated against the test results, showing good agreement in predicting both axial and eccentric responses. A comprehensive parametric study was then conducted to evaluate the effects of the width to thickness ratio, stiffener spacing and thickness, steel and concrete strengths, loading angle, and slenderness ratio. Based on the FE results and comparisons with existing design codes, simplified design equations are proposed to predict the axial and eccentric compressive capacities of stiffened cruciform composite columns. The proposed formulas can be used for practical design and engineering applications.

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## Composites in concrete-based structures

abst. 1044
**TIGELLIO**
Thursday
June 25
09h40

### Flexural Behaviors of High-Performance Fiber-Reinforced Cementitious Composite Panels with Steel, CFRP, and Steel-FRP Composite Bars

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High-performance fiber-reinforced cementitious composites (HPFRCC) enable thin, durable and lightweight prefabricated panels, while their flexural response is controlled by the coupled effects of matrix tensile behavior, reinforcement constitutive law and sectional form. This study synthesizes two complementary experimental programs on one-way HPFRCC panels to clarify matrix-reinforcement interaction in solid and hollow sections. Solid panels (40-mm thick) and prefabricated hollow panels (60-mm thick with longitudinal voids) were fabricated using ultra-high-performance concrete (UHPC), ultra-high-strength engineered cementitious composite (UHS-ECC) and lightweight ECC (LW-ECC), and reinforced with steel bars, CFRP bars and steel-FRP composite (SFC) bars. A stiffness-equivalent reinforcement design was adopted to achieve comparable initial rigidity across reinforcement systems. All specimens were tested under four-point bending. Full-field digital image correlation was used to quantify crack initiation, crack spacing, strain localization and crack-width evolution. A sectional analysis for solid panels and a calibrated nonlinear finite element model for hollow panels were employed to interpret failure mechanisms and to extend the results through parametric studies. For UHPC, the reinforcement system governed the strength-ductility balance. In solid UHPC panels, peak load increased from 16.96 kN with steel to 20.27 kN with CFRP (19%) and to 30.3 kN with SFC (79%). In hollow UHPC panels, peak load increased from 42.5 kN with steel to 61.4 kN with CFRP (44.5%) and to 75.2 kN with SFC (77.0%). CFRP increased capacity but led to more abrupt post-peak softening associated with its linear-elastic behavior, whereas SFC bars mitigated brittleness and improved post-peak stability through staged engagement of the steel core and the FRP component. Matrix selection primarily governed cracking and serviceability. Digital image correlation showed crack localization in UHPC and distributed multiple cracking in ECC matrices, resulting in slower crack-width growth and enhanced deformation capacity. For example, steel-reinforced UHS-ECC and LW-ECC hollow panels reached peak deflections of 34.2 mm and 44.3 mm, respectively, while retaining load-carrying capacity after peak. The highest flexural toughness was obtained when ECC matrices were combined with SFC bars, reflecting stable multiple cracking and sustained strain hardening in the tension zone. The numerical models reproduced key response points with errors generally below 10%. Parametric analyses indicated that reducing void diameter provided limited gains once a sufficient compression zone was maintained, whereas increasing CFRP reinforcement ratio improved crack stabilization and deformation capacity more effectively. The combined evidence provides practical guidance for lightweight modular slab and panel systems, highlighting ECC matrices for crack control and SFC reinforcement for achieving high flexural capacity with improved pseudo-ductility.

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abst. 1247
**TIGELLIO**
Thursday
June 25
10h00

### Effects of composite action between EA10 pavement and OSD on stress at fatigue details considering temperature variation

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In order to study the effects of pavement temperature change on the stress and fatigue of rib-to-deck (RD) detail, the steel box girder of the Shuangliu Yangtze River Bridge with a main span of 1430 meters was selected to carry out the investigation. After establishing a finite element model of the OSD with epoxy asphalt (EA) concrete pavement, the OSD under different transverse wheel loads, as well as different temperatures of the deck pavement was considered. The stress of RD details was obtained and fatigue performance was evaluated. The research indicates that for the OSD structure with EA pavement, each single axle in the fatigue vehicle can produce an obvious and individual stress peak in the RD details, and the number of stress cycles generated by a passing truck is equal to the number of truck axles. The stress of RD details directly below the wheel load is large, and these far away from

the wheel load is significantly reduced, indicating significant stress local effects. The stress range on the RD deck plate side is extremely sensitive to the change of pavement temperature, which increases almost linearly with the increase of pavement temperature, and the increase being most significant directly below the wheel load. The stress range at 60℃ can reach more than three times that of 0℃, while stress range on the RD rib side also increases with the increase of pavement temperature, but it is far less significant than the deck plate side, and its stress level is lower than that on the deck plate side. For the integrated design of the OSD with EA pavement in this bridge, even if the pavement temperature reaches 60℃, the estimated stress range at RD details is lower than the fatigue cut-off stress range of the details, so the OSD in this bridge has sufficient fatigue resistance.

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## Influence of Component Ratio Variation on Mechanical Performance of Epoxy Anchoring Composites

abst. 1294
**TIGELLIO**
Thursday
June 25
10h20


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Chemical anchors based on two-component epoxy systems are widely employed for structural fastening in composite and concrete assemblies, yet the relationship between resin–hardener ratio and mechanical performance remains insufficiently quantified. This study investigates how controlled modifications to the mixing ratios of components A (epoxy resin) and B (amine hardener) influence key material strength properties relevant to anchoring applications. A series of epoxy formulations were prepared with systematic variation in stoichiometric balance, followed by curing under standardized conditions. Mechanical characterization - tensile, compression, and material hardness -was performed to evaluate performance trends and identify deviation thresholds from optimal curing chemistry. Complementary analysis by scanning electron microscopy (SEM) provided insight into crosslink density and microstructural failure mechanisms. Results reveal a pronounced sensitivity of strength properties to component ratio, with both resin-rich and hardener-rich compositions exhibiting premature brittle failure and suboptimal interfacial adhesion. The findings underline the importance of stoichiometric control for reliability in composite anchoring systems and offer a foundation for predictive modelling of epoxy-based composite interfaces. This work bridges practical anchor design with composite materials science by linking molecular-level formulation effects to macroscale mechanical behaviour.


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## Influence of Perforation Distribution in Internal CFRP Tubes on the Compressive Strength and Deformability of Concrete Elements

abst. 1338
**TIGELLIO**
Thursday
June 25
10h40


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Fiber Reinforced Polymer (FRP) profiles starting to be an alternative or additive to conventional steel reinforcement in concrete-composite elements. Internal CFRP tubes provide excellent protection against corrosion and enhance structural durability. However, the performance of these elements is frequently limited by the smooth surface of the composite, which prevents an adequate bond with the concrete. To address this issue, this research investigates the effect of incorporating diverse perforation patterns into the CFRP tube walls. The study aims to determine how layout of these openings influence the mechanical response and the bond efficiency of the reinforced members. This study examines the impact of different perforation arrangements on the compressive strength and deformability of concrete elements. The research compares several distinct layouts to determine how the positioning of the openings affects the stress transfer between the concrete and the composite tube. All specimens were prepared using self-compacting concrete (SCC) and internal CFRP tubes with varying wall thicknesses. The experimental program focused on evaluating the load-bearing capacity and strain characteristics to identify the most effective arrangement of perforations for structural stability. The spatial arrangement

of the perforations is a key parameter affecting the mechanical behavior of the reinforced element. In this study, patterns featuring diagonal and symmetrical arrangements were compared, maintaining identical geometry of individual openings across all specimens to isolate the effect of their distribution. The analysis focused on how these specific layouts influence the compressive strength, the level of cooperation between the composite tube and the concrete core, and the resulting deformability of the element. The results indicate that the layout of the openings significantly alters the stress distribution, where certain arrangements provide more uniform interaction while others lead to localized effects. These findings provide a basis for optimizing the distribution of perforations to maximize the efficiency of internal CFRP reinforcement.

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## Composites in innovative applications

### A Machine-Learning Framework for Non-Destructive Defect Identification in Composite Materials

abst. 1076
**RIVA**
Wednesday
June 24
15h30

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Composite materials are widely used for marine applications due to their high strength-to-weight ratio and corrosion resistance. However, their use is often constrained by microstructural defects, crack formation and the lack of automated non-destructive inspection processes in the industry. This work introduces a novel framework derived from recent advances in data-driven image mechanics (D2IM) (Soar et al., 2024) by combining machine learning, optical microscopy, X-ray computed tomography (XCT) and mechanical testing for automated identification and classification of defects in composites. Optical microscopy and XCT are used to capture two- and three-dimensional image data, enabling the identification of microstructural defects such as porosity and crack formation across multiple scales. These datasets are then used to train convolutional neural networks (CNNs) for image classification, with the aim of correlating microstructural characteristics with material quality indicators. Our preliminary results confirm the potential of defect detection and classification from two-dimensional image datasets achieved using the machine learning model. The proposed workflow for data acquisition, reconstruction, post-processing and model training will be presented along with early observations on defect morphology. Future work will focus on validation through mechanical testing and the use of XCT, with the objective to develop a robust, non-destructive quality inspection tool for industrial use.

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### Application of honeycomb-based composites in the support structures used in offshore renewable energy infrastructure

abst. 1109
**RIVA**
Wednesday
June 24
15h50

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The development of offshore renewable energy infrastructure has been developing fast progressing from on-shore to off-shore large-scale structures. The evolution of offshore energy harvesting has resulted in a multitude of designs for submerged or partially submerged systems. Most of these energy systems are either support structures for offshore wind and tidal turbines or critical infrastructure. These submerged large-scale structures must be certified to be reliable for a long lifetime in the harsh oceanic environment. In the case of a tidal stream turbine, a large-scale structure, for example MeyGen, of around 26m tall, with a mass of over 190 tonnes, installed at a depth of 31m under the sea will be required to remain in service for more than 25 years [1]. As the structure of the turbine itself is complex, involving nonlinear interactions with the fluid as well as aquatic life, the materials to be used must satisfy a wide range of requirements. In this work the authors are concentrating on investigation of the support structure of the tidal stream turbine, focusing on an implementation of novel materials for this area, and prioritising the sustainability and reliability of the material to be used. Due to their high strength-to-weight ratio aluminium honeycomb panels have proved to be successful in a large number of applications in the aerospace industry. At the same time it is hard to overestimate the importance of the development of Thermoplastic Polyurethane (TPU) applications, due to its recyclability, non-toxicity and excellent wear resistance. There have been a few studies in the open literature demonstrating very low levels of properties degradation of TPU samples that are undergoing ageing during immersion in sea water for long periods of time [2]. These studies demonstrate the feasibility of potential applications of TPU materials in the seawater environment. Although there are results on aging of TPU samples in seawater, to the best authors' knowledge, there has been no research done on the wet, saltwater, erosion of TPU samples used as a protective coating for aluminium honeycomb panels. Therefore, this work is dedicated to the assessment of performance of composite sample composed of TPU coating and an aluminium honeycomb panel. The experimental study involved wet erosion test of the sample in the saltwater solution, performed for a number of impingement angles in order to address the fact that peak erosion rate for ductile materials [3] and metals is different. Analysis of the samples is focused on the extent of wear in the TPU coating as well as on evaluation of any deformation or damage within the main honeycomb panel due to the erosion process. For analysis of the honeycomb panel's performance an assessment of the deformation within the honeycomb as well as water ingress and adhesive failures were also undertaken. Therefore, the results represent new and novel insights into the feasibility of the application of a composite material consisting of an aluminium panel and a TPU coating. This work provides an essential stepping stone for the possible application of both honeycomb panels and TPU materials in offshore renewable power structures subjected to harsh oceanic environment. The study highlights the benefits and potential pitfalls of the implementation of these materials. The authors would like to acknowledge the financial support for this work through CoTide Engineering and Physical Sciences Research Council grant EP/X03903X/1. References: [1] MeyGen Project Description. https://marine.gov.scot (accessed on 17/12/25). [2] P. Davies, G. Evrard. Accelerated ageing of polyurethanes for marine applications. Polymer Degradation and Stability 92 (2007) 1455-1464. [3] N. Zhang et al. Thickness effect on particle erosion resistance of thermoplastic polyurethane coating on steel substrate. Wear 303 (2013) 49–55

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abst. 1121
**RIVA**
Wednesday
June 24
16h10

## Decoupling Mechanical Robustness and Ionic Conductivity in Structural Batteries via a Honeycomb-Cored Gel Polymer Electrolyte

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With the accelerating electrification of automotive and aerospace systems, structural batteries that simultaneously provide load-bearing capability and electrochemical energy storage have attracted significant attention as next-generation multifunctional energy systems. Unlike internal combustion engine–based power systems, lithium-ion batteries exhibit significantly lower gravimetric and volumetric energy densities, making system-level weight reduction a critical challenge, particularly in mobility-driven applications. In this context, structural batteries have emerged as a promising strategy to offset the intrinsic energy density limitations of lithium-based energy storage by enabling energy-storing components to directly contribute to load bearing, thereby improving overall system efficiency. Conventional approaches to structural batteries have largely focused on integrating battery cells into external structural components, which inherently restricts the achievable energy density and limits multifunctionality at the material level. To address this limitation, recent studies have explored gel polymer electrolytes (GPEs), composed of polymer matrices swollen with conductive liquids, enabling individual battery components to simultaneously fulfill mechanical and electrochemical roles. However, GPE-based structural batteries suffer from a fundamental trade-off; increasing the solid fraction of the polymer network improves mechanical stiffness and dimensional stability but inevitably reduces ionic conductivity by restricting ion transport pathways. This intrinsic compromise remains a major obstacle to the realization of high-performance structural batteries. In this work, we propose a honeycomb-cored GPE as a structural–electrochemical decoupling strategy. In this design, the honeycomb structure bears the majority of external mechanical loads, while the internal cavities are filled with a high-conductivity GPE, providing continuous ion transport pathways and effectively preventing electrolyte leakage. Honeycomb-cored GPE enables the independent optimization of mechanical integrity and electrochemical performance within a single electrolyte system. To validate this concept, honeycomb-cored batteries incorporating either liquid electrolytes or GPEs were fabricated and systematically evaluated in terms of electrochemical and mechanical performance. Experimental results revealed that liquid-electrolyte-filled honeycomb structures are susceptible to internal short circuits due to lithium metal deformation under compressive loading. In contrast, the honeycomb-cored GPE effectively suppressed short-circuit behavior by mechanically constraining deformation while maintaining stable ionic conduction. Furthermore, the honeycomb-cored GPE electrolyte exhibited superior mechanical properties alongside high ionic conductivity, demonstrating that structural stability and electrochemical performance can be simultaneously achieved within a single electrolyte architecture. These findings validate the effectiveness of honeycomb reinforcement as a design strategy for decoupling mechanical and electrochemical requirements in structural batteries. This work provides a scalable and versatile framework for the development of high-performance multifunctional energy storage systems, particularly for applications requiring both mechanical load-bearing capability and reliable energy storage. Acknowledgements: This research was supported by the Nano Material Technology Development Program through the National Research Foundation of Korea (NRF) funded by Ministry of Science and ICT (No. RS-2024-00450477).

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## MXene-reduced graphene oxide composite carbon felt electrode for enhanced performance in vanadium redox flow batteries

abst. 1141
**RIVA**
Wednesday
June 24
16h30

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Vanadium redox flow batteries (VRFBs) are attractive systems for large-scale energy storage due to their high efficiency, safety, and long cycling stability. However, their practical application is limited by slow redox kinetics at the electrode–electrolyte interface. In this work, MXene-reduced graphene oxide (MXene-rGO) composites are used to modify carbon felt (CF) electrodes to enhance electrochemical reaction rates. The MXene-rGO/CF electrodes are fabricated by a hydrothermal method at synthesis temperatures of 130°C, 150°C, 170°C, and 180°C for 8 h, and their electrochemical performance is systematically evaluated. Among the samples, the MXene-rGO/CF electrode prepared at 150°C shows the best performance and cycling stability. At a current density of 100 mA/cm2, this electrode achieves energy and voltage efficiencies of 85% and 86%, respectively, and maintains stable operation over 120 charge-discharge cycles. These results indicate that hydrothermal temperature strongly influences the structure and performance of MXene-rGO/CF composites, providing an effective strategy for developing durable, high-performance electrodes for VRFB applications.

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## Development of Advanced Electrodes for Enhanced Performance in Vanadium Redox Flow Batteries

abst. 1143
**RIVA**
Wednesday
June 24
15h10

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Vanadium redox flow batteries (VRFBs) are considered as one of the most promising component of energy storage system due to their long cycle life, high safety, and unlimited scalability of power and energy. However, their performance is strongly limited by sluggish redox kinetics and poor electrochemical activity of conventional carbon felt electrodes. In this study, a high-performance carbon felt composite electrode is developed to enhance electrochemical activity and reaction kinetics in VRFB systems. The composite electrode is fabricated by using borophene material into the carbon felt, which results in high electrochemical activity, and reduced charge-transfer resistance. Comprehensive structural, physicochemical, and electrochemical characterizations confirm the formation of a borophene material on the surface of the carbon fiber. As a result, the modified electrode exhibits significantly enhanced vanadium redox reaction kinetics, leading to higher voltage efficiency, energy efficiency, and rate capability as compared to bare carbon felt electrodes. VRFB charge/discharge test shows that the composite electrode gives superior cycling stability and reduced polarization losses under practical operating conditions. These results highlight the critical role of electrode structural engineering in overcoming kinetic limitations and provide an effective pathway toward high-efficiency and durable VRFB systems for grid-scale energy storage applications.

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abst. 1204
**RIVA**
Wednesday
June 24
17h50

## High performance rice husk ash (RHA) and alkali-activated system on reinforcement durability

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Renewable material selection and product evaluations towards the rebar corrosion resistance mechanisms have been readily progressing in the recent past for different applications. Rice husk ash (RHA) is such a promising material that can be used and assured in corrosion-resistant properties and control corrosion activities in different applications. In this research approach, focus was given to developing a new corrosion-resistant board while controlling the manufacturing parameters with very little free carbon. The conductive matrix resulting from this process is advancing the barrier formulations towards the rust formations while contributing as a dense protective shield for different ratios of material combinations of inorganic binders. Specified ratios have made it remarkable to control the heat flow with cement, geopolymer, and alkali-activated systems. The results emphasize more impact of corrosion resistance can be increased by controlling binder, RHA, and alkali-activated slag combination ratios. As RHA is being utilized as a by-product of the agricultural industry for the new approach, the process lowers greenhouse gas generation while securing the supportive principles of the circular economy.

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abst. 1372
**RIVA**
Wednesday
June 24
17h10

## Controlling biofouling growth on offshore steel structures using graphene-modified cementitious coatings

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Marine biofouling causes serious operational challenges and economic losses in offshore infrastructure. This study develops a novel thin-layer graphene-modified cementitious composite coating (GCC) applied on steel surfaces for controlling biofouling growth on offshore steel structures. Graphene nanoplatelets (GNPs) were incorporated at 0, 0.1, 0.3, and 0.5 wt.% dosages to investigate their influence on coating microstructure and antibiofouling performance. Microstructural characteristics were systematically examined using scanning electron microscopy (SEM), X-ray diffraction (XRD), and mercury intrusion porosimetry (MIP), together with surface roughness measurements. A short-term (48 h) laboratory-based bacterial adhesion and viability assay using Pseudomonas species was conducted via fluorescence staining to quantify early-stage biofilm formation. The results show that graphene incorporation markedly improves biofouling resistance, with 0.3 wt. % graphene identified as the optimal level. At this dosage, nearly 100% suppression of microbial coverage was achieved compared with the control samples. The enhanced antibiofouling performance is ascribed to the intrinsic antimicrobial properties of graphene, acting through contact-active and physicochemical interactions at the cell-surface interface, as well as to graphene-induced microstructural densification and surface homogenisation, which reduce surface bioreceptivity and inhibit initial microbial attachment. This work provides a new strategy for developing biocide-free and cost-effective antibiofouling coatings that contribute to improved long-term durability and extended service life of marine steel structures.

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abst. 1382
**RIVA**
Wednesday
June 24
17h30

## Exploring interfacial fracture behaviour in composite structural supercapacitors through combined experimental and modelling approaches

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Structural supercapacitors (SSCs) represent a promising multifunctional solution for lightweight transport systems, as they can simultaneously bear mechanical loads and store electrical energy. However, their development is limited by the mechanical–electrochemical trade-off inherent to polymer electrolytes and by the complex behavior of the electrode–electrolyte interface, which governs both charge transport and fracture mechanisms. This work presents an experimental and numerical investigation of the fracture response of SSCs based on two polymer matrices—an epoxy system (Matrix A) and an epoxy modified with AlO nanoparticles and an ionic liquid (Matrix B)—combined with unidirectional carbon fibers, either unmodified or coated with graphene nanoplatelets (GNP). Four different laminates were manufactured using a VARIM process following a [0] stacking sequence. Single-edge-notched beam (SENT) specimens were machined and tested under three-point bending inside a SEM to capture in-situ crack initiation, propagation and microstructural failure mechanisms. All materials exhibited an initial linear response followed by crack onset at the notch tip, with subsequent fiber-matrix debonding and large-scale bridging phenomena. Matrix A laminates showed higher stiffness and fracture toughness, whereas Matrix B systems displayed greater ductility but significantly reduced rigidity due to the presence of the ionic liquid. The addition of GNP improved interfacial adhesion but also reduced the apparent fracture toughness by limiting fiber bridging, which is a major contributor to energy dissipation in unidirectional composites. Porosity strongly influenced failure behavior, particularly in Matrix A + GNP laminates, where high resin viscosity hindered fiber impregnation and led to defect-driven crack deviation and local delamination. A micromechanical embedded-cell finite-element model was developed in ABAQUS to replicate the fracture process zone. The model incorporates realistic fiber distributions, cohesive elements to represent interfacial debonding, and homogenized material properties corrected for porosity. Numerical predictions showed strong agreement with experimental load–displacement responses, stiffness values, and crack propagation patterns, confirming the suitability of this approach for studying interface-dominated fracture in SSCs. This combined experimental–computational framework provides new insights into the role of the interface, resin viscosity, porosity and reinforcement modification on fracture mechanisms in SSCs. The results highlight the need for improved manufacturing control and tailored interface engineering to balance mechanical integrity with electrochemical performance in next-generation multifunctional composite energy-storage systems.

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## Improved Electrochemical Performance of Carbon Felt Electrodes via Polyaniline-MXene Modification in Vanadium Redox Flow Batteries

abst. 1391
**RIVA**
Wednesday
June 24
16h50

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Low electrochemical activity and limited mass transport constrain the performance of electrodes in vanadium redox flow batteries (VRFBs). Here, carbon felt is modified with a polyaniline-MXene composite layer to simultaneously enhance interfacial electron transfer and ion transport. The interconnected structure formed by conductive MXene sheets and the polyaniline matrix provides efficient electron pathways and improves electrolyte access within the porous electrode, reducing transport limitations and increasing the utilization of active sites. Protonated nitrogen sites in polyaniline function as active centers for the VO2+/VO2+ redox reaction, while MXene surface terminations interact favorably with vanadium species, stabilizing reaction intermediates without compromising reversibility. Full-cell electrochemical impedance spectroscopy shows that the modified electrode exhibits a significantly lower charge-transfer resistance (Rct = 0.45 $cm^2$) than pristine carbon felt (Rct = 7.5 $cm^2$). In full-cell operation, the modified electrode achieves an energy efficiency of 84.5% at 100 mA $cm^2$, which is 4.5% higher than that of the unmodified electrode, and maintains stable cycling over 150 cycles. These results confirm that surface modification is an effective strategy for improving carbon felt electrodes in VRFBs.

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# Delamination, damage, fracture, failure and durability of composites

abst. 1017
**CIMA**
Wednesday
June 24
12h10

## A computational model for progressive failure analysis of a fibre reinforced polymer composite laminate

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Fibre Reinforced Polymer (FRP) composite inherits the beneficial characteristics of its constituents that offer exceptional material properties. Their superior strength/weight and stiffness/weight ratios has led to widespread use in weight sensitive applications such as aerospace, automotive, marine, civil engineering structures, wind turbine blades, sporting tools, and other high-performance components. Despite their proven reliability, the behaviour of FRP composites is not yet well understood, which limits the exploitation of their full potential. The anisotropic and heterogenous nature of the material system gives rise to complex failure mechanisms at the ply level (intralaminar failure) as well as at the interlaminar level (delamination failure) along with their coupling, making accurate modelling of FRP laminated composites challenging. An attempt has been made to develop a computational model capable of predicting the progressive failure of FRP composite laminates accurately with a good degree of computational efficiency. To address the ply level failure, which is the focus of this study, a physically based constitutive model in meso-scale is formulated to capture intralaminar failure mechanisms such as fibre rupture, fibre kinking, matrix cracking, and fibre-matrix debonding. Unlike most existing models in the literature, that consider only damage effects, the present study has accounted for both damage and plasticity of the polymer matrix to provide a more realistic representation of the material behaviour. The damage variables are used to represent stiffness degradation, while the plasticity is incorporated to capture the permanent deformations. Three damage variables are defined to accommodate fibre rupture or micro-buckling under longitudinal tension or compression, matrix cracking under transverse stresses, and fibre-matrix debonding under longitudinal shear stresses. A smooth closed-form single yield function with a non-associative flow rule is used for plasticity, which is implemented using an implicit stress return algorithm. A higher order sub-laminate model is developed for implementing the ply failure model within a finite element modelling framework for simulating the intralaminar failure efficiently. The sub-lamination modelling scheme accommodates more than one physical layers of a multi-layered laminate within a sub-laminate (a mathematical layer) to represent the whole laminate with fewer mathematical layers stacked one over the other, which provides flexibility to balance between accuracy and computational efficiency as desired. Modelling laminates using conventional plate/shell elements offers a good degree of computational efficiency but are less accurate and have difficulty in simulating delamination at any arbitrary planes as the nodal plane is restricted to the mid-plane or a specific plane. Although three-dimensional solid elements can resolve the issue, the computational cost becomes unaffordable due to the restriction imposed by the element size in the thickness direction on the in-plane element size, resulting in a very large number of elements. The proposed sub-laminate model has three reference/nodal planes, one at the mid-plane have three displacements and two rotations while the other two planes at the two external surfaces, each have three displacements like a 3D element. These provide a cubic variation of the two in-plane displacements and a quadratic variation of the transverse displacement in the thickness direction, which are expressed analytically before the finite element implementation for capturing in-plane variations of the displacements.

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abst. 1023
**CIMA**
Wednesday
June 24
12h30

## The effect of the interface on static and long-term mechanical properties at high temperatures of CF/PEEK composites

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Compared with carbon fiber reinforced thermoset composites (CFRTS), carbon fiber reinforced thermoplastic composites (CFRTP) offer the advantages of high toughness, short manufacturing cycles, recyclability, and low cost, making them widely used in the aerospace field. Due to the diverse loading conditions and harsh service environments in aerospace applications, the mechanical response and failure behavior of CFRTP under complex service conditions have attracted increasing attention from researchers [1]. Among these complex conditions, high temperature is a critical factor. For example, Xin et al. performed tensile tests at various temperatures (23–230 °C) and strain rates (0.0001–0.01 s1) and developed a multiscale model to reveal the damage evolution mechanisms of CFRTP under thermomechanical coupling [2]. The results indicate that below the glass transition temperature (Tg) of the matrix, the strain rate significantly influences CFRTP performance, whereas above Tg, temperature becomes the dominant factor, and the failure mode shifts from fiber fracture and interfacial debonding to fiber warping and matrix plastic flow. Li et al. studied the effect of temperature on the flexural creep behavior of carbon fiber-reinforced phenolic resin (CF/PF) composites [3]. Their findings show that the degradation in creep performance at elevated temperatures is mainly attributed to the increased viscoplastic strain. CFRTP is a heterogeneous material with different thermal expansion coefficients between the fiber and matrix. As temperature increases, differential expansion between the fiber and matrix leads to non-uniform deformation, inducing residual stresses at the interface and increasing the risk of crack initiation. Therefore, the interface is a key factor influencing the mechanical performance of CFRTP at high temperatures. Chang et al studied the effect of the interface on the creep and creep rupture behavior of carbon fiber-reinforced polyamide (CF/PA) composites [4]. Three types of fiber surface conditions were compared: untreated CF (UCF), electrochemically surface-treated CF (ECF), and surface-treated epoxy-sized CF (SCF). The order of static mechanical properties from highest to lowest was: ECF/PA>SCF/PA>UCF/PA. However, the order of creep rupture strength was different: SCF/PA>ECF/PA>UCF/PA. Carbon fiber reinforced polyether ether ketone (CF/PEEK) has become one of the most widely used high-performance CFRTPs, owing to the excellent long-term high-temperature service characteristics and thermal stability of PEEK. However, research on the effect of the interface on the static and long-term mechanical properties of CF/PEEK composites at high temperatures remains limited. Herein, T300 plain fabrics were subjected to de-sizing, plasma oxidation, water-based poly (amic acid) ammonium salt (PAAs) montmorillonite (MMT) sizing, preimpregnation and compression molding to form the final CF/PEEK composites. Three sample groups, including de-sized CF (DCF), PAAs-sized CF (PCF), and PAAs MMT-sized CF (PMCF), were prepared. A series of characterization techniques were employed, including dynamic mechanical analysis (DMA), high-temperature flexural tests, high-temperature short beam shear tests, short-term creep and recovery tests, and creep rupture tests were conducted. Based on these test results, the effect of the interface on the static and long-term mechanical properties of CF/PEEK composites at high temperatures, along with the underlying mechanisms, is discussed. A finite element model was established to simulate the creep rupture behavior of CF/PEEK composites with different interfaces at high temperatures. Reference: [1] Zhu, Tianqi, et al. "Damage evolution model and failure mechanism of continuous carbon fiber-reinforced thermoplastic resin matrix composite materials." Composites Science and Technology 244 (2023): 110300. [2] **n, Yuhan, et al. "Thermo–mechanical coupling effects on mechanical properties and damage evolution of continuous fiber-reinforced thermoplastic composites." Composites Part B: Engineering (2025): 112788. [3] Li, Jikang, et al. "Temperature-dependent creep damage mechanism and prediction model of fiber-reinforced phenolic resin composites." International Journal of Mechanical Sciences 278 (2024): 109477. [4] CHANG, YEOUSHIN. "The effect of the interphase/interface region on creep and creep rupture of thermoplastic composites(Ph. D. Thesis)." (1992).

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## Low-velocity impact of hybrid sandwich structure with composite foam

abst. 1033
**Repository**

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A combined numerical–experimental study was conducted to investigate the low-energy impact response of lightweight sandwich structures featuring a composite aluminum-silicon carbide foam core and fibre-reinforced composite skins adhesive to thin aluminum face sheets, extending the concept of Fibre–Laminate Metal (FLM) configurations. The experimental research involved controlled low-velocity impact (LVI) tests using instrumented impactors to quantify contact forces, absorbed energy, indentation depth, and damage morphology. Complementary finite element simulations were developed to capture progressive damage mechanisms within the foam core, delamination and matrix cracking in the composite skins, as well as plastic deformation of the aluminum layers. The integration of test data with model predictions enabled detailed validation of the numerical framework, supporting a deeper understanding of failure initiation and evolution under impact loads. The findings provide a basis for optimizing hybrid FLM-inspired sandwich structures for enhanced impact tolerance and energy absorption.

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abst. 1056
**CIMA**
Wednesday
June 24
12h50

## Effect of graphene enhancement on the degradation of the thermo-mechanical behaviour of bio-based flax-fibre reinforced composites due to moisture and UV exposure - An experimental study

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This study investigates the effects of incorporating graphene platelets on the mechanical and thermal performance of flax fibre-reinforced bio-based composites. Micron-sized graphene platelets were incorporated in a bio-based matrix via shear mixing at various concentrations (0.5-3 wt.%), which was then reinforced with woven flax 200 g/m2 in aerial density. Composite laminates were prepared using hand lay-up followed by compression moulding under optimised pressure of 5 bars. Additionally, preheating and controlled degassing were employed to achieve uniform consolidation and optimised performance of composites. In the dry condition state, mechanical testing showed that the addition of graphene improved tensile strength, stiffness and modulus of elasticity, with optimum performance of 80 MPa observed at 1-2 wt.% graphene. DSC testing demonstrated significantly enhanced glass transition temperature (Tg) with the graphene addition in the dry baseline condition. Two sets of samples were exposed to different weathering conditions: (i) water immersion at 40°C for 312 hours and, (ii) UV exposure at wavelength of 0.89w/mm and 60°C for 360 hours. The mechanical testing results of the wet and UV-exposed samples show improved durability and resistance to degradation with increased graphene content, and scanning electron microscopy (SEM) revealed that micron-sized graphene provides a refined and uniform fibre-matrix interface, leading to reduced micro void formation and enhanced structural stability among the composites. Keywords: Tensile, graphene, water immersion, UV radiation, flax fibres, bio-based composites.

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abst. 1062
**CIMA**
Wednesday
June 24
09h40

## Application of an unsupervised deep learning approach for characterization of delamination process in composite laminates

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Delamination is one of the dominant and most critical damage mechanisms in composite laminates, strongly influencing their stiffness, load-carrying capacity and failure progression. Its development is governed by the interaction of multiple micro and meso-scale processes, including matrix cracking, fiber–matrix interfacial debonding or delamination, which often evolve simultaneously during loading. Reliable identification and characterization of these mechanisms remain challenging, particularly under experimental conditions where damage processes overlap in space and time. In this context, acoustic emission (AE) offers a sensitive means for capturing transient elastic waves generated by local damage events - however, the interpretation of AE signals is hindered by their non-stationary, nonlinear and heterogeneous nature. In this study, an unsupervised deep learning framework is applied for the characterization of delamination processes in composite laminates using AE measurements acquired during double cantilever beam test. The analysis is performed using a multi-stage data processing pipeline in which conventional AE signal descriptors are first transformed into compact nonlinear latent representations by means of a stacked autoencoder. The learned representations are subsequently embedded into a low-dimensional manifold using uniform manifold approximation and projection (UMAP) to preserve neighborhood relationships within the data. Hierarchical density-based spatial clustering of applications with noise (HDBSCAN) is then employed to identify intrinsic groupings of AE events without prior labeling or assumptions regarding the number of clusters. The proposed framework enables effective separation of large AE datasets into clusters exhibiting distinct signal characteristics. Obtained outcomes indicate, that the identified clusters can be associated with matrix cracking, fiber–matrix interfacial debonding with fiber pull-out and stable delamination propagation accompanied by frictional sliding. The presented approach does not rely on empirical thresholds or labeled training datasets and provides a systematic, fully data-driven framework for AE-based analysis of delamination process in composite laminates.

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## Analysis of the influence of adhesive threads on the material and damage behavior of FRP under quasi-static loading

abst. 1078
**CIMA**
Wednesday
June 24
10h00

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The manufacturing of composite structures from fiber-reinforced polymers (FRP) requires the provision of semi-finished fiber products that meet not only application-specific requirements but also processing requirements. To this end, semi-finished products supplied in roll form have become widely established for this purpose. Such products in roll form, for example, textile fabrics, are commonly equipped with adhesive threads to ensure adequate handling and processability. These adhesive threads are usually made of temperature-resistant thermoplastics and remain in the material after FRP consolidation. As a result, they constitute inherent microstructural features that may act as initial defects within the composite and influence damage initiation and evolution under mechanical loading. However, the effect of these adhesive threads on the local stress state and the overall load-bearing capacity of FRP composites has not yet been sufficiently clarified. In particular, the influence of the geometry and spatial arrangement of the adhesive threads on the formation of inter-fiber cracks remains poorly understood, which currently limits efficient material utilization and design optimization. This contribution provides an in-depth understanding of the microscopic structure of the adhesive fibers, their statistical distribution in the FRP, and their influence on material behavior using experimental and numerical methods. Glass fiber-reinforced epoxy resin composites with different adhesive fiber arrangements are characterized in terms of damage behavior using quasi-static tensile tests and optical analysis methods. Accompanying

finite element simulations using micromechanical modelling of the adhesive filaments and the actual crack paths allow the critical fracture energies of the base material and the adhesive filaments to be determined. Subsequent mesoscopic modelling of inter-fiber fracture formation will be used to determine transfer functions depending on the defect properties, which will enable the microstructural findings to be utilized in homogenized laminate layers. The findings serve as an important basis for engineering practice in the design and dimensioning of textile-reinforced composite components.

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abst. 1147
CIMA
Thursday
June 25
13h10

## Exploring the performance of 2D and 3D models of damage initiation and progression processes on OHT and OHC strength testing of composite laminates

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This study evaluates the performance of simple three-dimensional models in describing the process of damage initiation and progression in open-hole tension (OHT) and open-hole compression (OHC) tests on composite laminates. The analyses carried out utilize Hashin's failure criteria for both classic and continuum shell elements, as well as the basic Hashin/Puck-based failure criterion for a three-dimensional stress state. OHT and OHC studies utilized three groups of laminates: quasi-isotropic (QI) [45/0/-45/90]2s, Soft [45/-45/0/45/-45/90/(45/-45)2]s, and Hard [0/45/0/90/0/-45/0/45/0/-45]s from IM7/8552 carbon fiber-reinforced polymers (CFRP). The 2D vs 3D analyses, based on experimental results, demonstrate that 3D elements are more suitable for analyzing open-hole strength, and 3D results appear suitable for critical parts. Finally, small and large applied ramps demonstrate accurate strength prediction, and this novel observation in the numerical results also reveals chaotic behavior.

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abst. 1153
SANT'EFISIO
Friday
June 26
10h00

## Salinity-Induced Degradation of PMMA-Based Carbon Fiber Composite Structures

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Polymer matrix composites are widely used in the marine industry due to their excellent performance. However, increasing environmental concerns have driven the development of alternative matrices to conventional thermosetting systems, aiming to enable reuse and recycling without compromising application performance. In this context, Elium® 180 XO, a thermoplastic resin with a PMMA matrix developed by Arkema, has emerged as a promising solution. Its main advantage lies in its recyclability, while exhibiting mechanical and service properties comparable to those of thermosetting resins. In addition to maintaining favorable performance, this resin offers the potential to reduce waste, as most end-of-life boats are currently abandoned or sunk. Despite these advantages, prolonged exposure to saline environments leads to resin degradation due to salt absorption, accelerating deterioration of the polymer matrix and compromising the structural integrity of the composite. This work investigated the influence of salinity on the degradation of structural composite laminates based on a PMMA matrix reinforced with carbon fibers, manufactured by the liquid resin infusion technique for nautical applications. After infusion, the laminate was cured for 24 hours at room temperature and subsequently cut into two equal parts. As recommended by the manufacturer, one part was post-cured in an oven at 80 °C for 2 hours, while the other was left without post-curing. Both plates were then machined into test specimens for Short Beam Strength (SBS) testing and water absorption measurements. In parallel, non-reinforced polymer resin immersed in the saline solution was analyzed by Differential Scanning Calorimetry (DSC), Thermogravimetric Analysis (TGA), and Fourier Transform Infrared (FTIR) spectroscopy to evaluate changes in material properties. Over a period of six months, specimens immersed in water at room temperature were periodically characterized monthly to monitor property changes indicative of aging, in comparison with reference (non-immersed) samples. The results showed that, despite the saline exposure being conducted at room temperature, the composite laminates exhibited apparent deterioration, predominantly driven by polymer matrix degradation. This behavior was consistently observed across the different characterization techniques employed. Ultraviolet spectrophotometry revealed a reduction in visible-light transmittance exceeding 85% after the first three months of immersion, indicating progressive structural changes in the polymer over time. Furthermore, variations in the carbonyl and hydroxyl indices between the initial and exposed conditions evidenced matrix aging and/or hydrolysis after six months of saline exposure. From a mechanical perspective, although the post-cured (PC) composite initially exhibited an interlaminar strength approximately 12% higher than that of the room-temperature-cured (RT) composite, this difference decreased to 1.5% after four months of saline immersion. At this stage, interlaminar strength losses of 21% and 12% were observed for the PC and RT conditions, respectively. Additionally, viscoelastic properties such as storage modulus, loss modulus, and tan  reflected the polymer's behavior before and after high-salinity aging, yielding results consistent with the observed degradation of the composite material. These results suggest that, while recyclable PMMA-based composites represent a promising alternative for sustainable marine structures, their long-term performance under saline environments may limit their application without additional protective or design strategies.

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## Tension-shear damage evolution of plain-woven SiC/SiC composites: 4D in-situ X-ray CT characterisation

abst. 1184
**CIMA**
Thursday
June 25
12h10


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Owing to their superior high-temperature performance, ceramic matrix composites (CMCs) offer excellent potential for applications in the hot-end components of aerospace engines, nuclear energy systems, and hypersonic vehicles. Under hostile service environments, CMCs are inevitably subjected to off-axis loading, leading to complicated damage evolution and failure mechanisms. However, effective methods for accurately identifying and quantitatively evaluating such damage in CMCs under successive loading remain limited. In this study, an in-situ X-ray micro-computed tomography (-CT) tensile test was conducted on the ±45° plain-woven SiC/SiC composites, during which six successive damage states were captured by high-resolution -CT. An attention U-Net-based deep learning image segmentation approach was adopted, achieving precise damage identification. Successive deformation fields were obtained through the digital volume correlation (DVC) technique. Finally, the damage evolution and failure mechanisms were elucidated. The results show that the main damage mode is matrix cracking, with micro and elongated transverse cracks predominating within the fibre tows and the adjacent inter-tow matrix. At an early loading stage, a "transverse crack concentration region" formed, and its orientation rotated clockwise with increasing load, eventually aligning with the fracture path ( 45°). The evolution of the tensile strain field exhibited a similar phenomenon, with corresponding orientation rotation of strain concentration bands with increasing loading; while the shear strain field of the in-plane woven surface showed strain concentration bands adjacent to inter-tow voids, oriented at approximately -45° at every loading level. As failure was approached, extensive damage developed, with the crack volume fraction increasing by several times. The final fracture path exhibited a  45° orientation, characterised by severe kink-band, tow splitting, interface debonding, fibre fracture, and fibre pull-out, demonstrating the tension-shear coupled damage mechanisms.


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## Buckling and failure analysis of thermoplastic composite pipes under thermomechanical loading: optimal design

abst. 1186
**CIMA**
Thursday
June 25
12h30

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The increasing demand for lightweight, corrosion-resistant, and cost-effective pipeline systems in offshore oil and gas applications has accelerated the adoption of thermoplastic composite pipes (TCPs) as alternatives to traditional metallic and thermoset-based pipes. TCPs offer significant advantages, including high specific strength and stiffness, superior fatigue and corrosion resistance, spoolability, and reduced installation and lifecycle costs. However, their structural behaviour under realistic offshore service conditions remains insufficiently understood due to the anisotropic nature of composite laminates, the temperature sensitivity of thermoplastic materials, and the complex interaction between mechanical and thermal loads. In offshore environments, TCPs are subjected to combined internal pressure, external hydrostatic pressure, bending moments, axial loads, and steep thermal gradients arising from hot internal fluids and cold seawater, all of which can significantly influence failure mechanisms. This study develops a high-fidelity 3D finite element modelling framework to investigate the buckling and material failure behaviour of multilayered TCPs under combined thermomechanical loading. The model incorporates temperature-dependent elastic properties for the composite laminate and thermoplastic liners, through-thickness thermal gradients, and realistic boundary conditions representative of offshore installation and operational scenarios. The TCP configuration analysed consists of AS4/PEEK unidirectional carbon fibre-reinforced laminates bonded between inner and outer PEEK liners. Mechanical loads including bending, axial compression, internal pressure, and external pressure are applied individually and in combination to capture realistic service conditions. Structural instability and material damage are evaluated using established failure criteria, with the Hashin failure criterion employed for composite plies and the von Mises criterion for the isotropic thermoplastic liners. The numerical framework enables the identification of critical buckling loads, failure initiation loads, and dominant failure modes across a wide range of thermal and mechanical loading conditions. Model predictions are validated against available analytical solutions, experimental data, and previously published numerical results, demonstrating good agreement and predictive reliability. A key contribution of this work is the integrated assessment of buckling and material failure as interacting phenomena rather than isolated failure modes. The results reveal that temperature-dependent stiffness degradation significantly alters stress redistribution within the pipe, influencing the transition between global buckling, liner yielding, matrix cracking, fibre failure, and delamination. Increasing thermal gradients are shown to shift failure from elastic instability to material-dominated mechanisms, while variations in laminate winding angle and stacking sequence strongly affect buckling resistance and failure progression. Failure mode maps are developed to delineate regions in the load–temperature space where buckling or material failure governs structural collapse. The findings provide new insights into the coupled effects of laminate architecture, geometry, and temperature-dependent material behaviour on TCP performance. The proposed modelling approach offers practical guidance for optimising TCP design to ensure controlled and predictable failure under severe thermomechanical loading, thereby enhancing safety, reliability, and service life in offshore oil and gas applications.

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abst. 1198
**CIMA**
Thursday
June 25
12h50

## Durability testing of CFRP plates subjected to preload impact

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The composite skin of modern (semi-monocoque) aircraft structures operates primarily under shear conditions, and the equivalent of this type of stress on the skin can be found in hinged and sheared plates. At the same time, the strength and functional properties of composite laminates used in aircraft skin can change significantly as a result of dynamic loading of this type of layered material, even at low impact energies – BVID (Barely Visible Impact Damage) loads. The aim of the research was to determine the impact of a BVID-type impact on the fatigue life of plates made of CFRP material with quasi-isotropic properties. Plates loaded under uniform shear conditions failed due to loss of stability at a load of 33.5$\pm$1.2 kN. Prior to fatigue testing, the plates were preloaded dynamically on a drop

hammer. Damage to the plates caused by preliminary dynamic loading was assessed using computed tomography. The plates were struck at three different points: at the geometric center of the plate, 38 mm from the center of the plate in the direction of the force, and perpendicular to it. Durability tests were performed by loading the plates in single-sided positive cycles in the range of 2–27 kN (the maximum load value in the cycle was approximately 80% of the load destroying the plate) at a frequency of 2 Hz. Since the variable loads caused the plate to lose stability, changes in plate deformation were recorded using a DIC (Digital Image Correlation) system. During the tests, it was observed that the damage introduced resulted in a reduction in fatigue life compared to undamaged plates. The greatest decrease in durability was observed in plates that were initially impacted in the geometric center of the plate and at the same time in the place where the greatest deformations occurred, which suggests that even damage in composite plates that is invisible to the naked eye can be the seed of fatigue damage to the plate laminate.

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## Scattering of elastic waves by defects in quasicrystal coating structure [Invited lecture]

abst. 1220
**SANT'EFISIO**
Friday
June 26
12h30

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In key fields such as aerospace, transportation, and chemical engineering, stress concentration caused by cracks is the main threat to structural failure, and detection technology based on elastic waves is the core means of identifying and evaluating such damage. For quasicrystal materials with unique phonon-phason field coupling characteristics, the scattering behavior of elastic waves by internal cracks directly affects the propagation path and energy distribution of waves, which cannot be accurately described by traditional homogeneous material theory. This study established a new crack tip field model that considers microstructure effects and directly analyzes the singularity part in the integral kernel, effectively handling high-order singularities at the crack tip and improving computational efficiency and accuracy. By combining the complex analysis method, the problem of constructing complex Green functions in traditional methods has been solved, and the boundary value problem under multiple crack interactions or complex load conditions has been explored, significantly reducing computational complexity. The study further proposed a dimensionality reduction calculation method based on the coupling of complex variable functions and integral equations, constructed complex frequency domain analytical basis functions, explicitly embedded the crack tip singularity and phason terms in the Helmholtz equation, accurately described the longitudinal/transverse wave multi-mode scattering field, and provided high-precision theoretical tools for composite material damage detection and acoustic emission inversion.

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## Prediction of Buckling-Driven Delamination Growth in Composites Under Compressive Fatigue Loading

abst. 1229
**SANT'EFISIO**
Friday
June 26
12h50

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Delaminations pose a serious threat to the structural integrity of composite structures by locally reducing bending stiffness and creating conditions favourable for sublaminate buckling. The onset of such buckling can, in turn, progress delamination growth in the structure and ultimately result in a loss of load-carrying capacity. In the present study, nonlinear finite element (FE) analyses are conducted on composite laminates to investigate the evolution of buckling-induced delamination under strain-based fatigue loading. To this end, two laminate configurations are investigated: thick and thin laminates, each featuring a single through-width delamination located near the surface. Under compressive fatigue loading, thick laminates exhibit local buckling, whereas thin laminates display a mixed local-global buckling mode, both of which can promote the delamination growth. The primary objective of this study is to identify the conditions that lead to stable delamination growth which is characterised by a decreasing growth rate with increasing delamination length, as well as those that result in unstable growth. Delamination propagation is modelled using an established cohesive zone model from the literature, implemented through a user-defined material subroutine in the commercial finite element software ABAQUS. To establish the fatigue limits of the problem and to determine the strain levels for fatigue analysis, an efficient preselection approach has been presented. The study considers short initial delamination lengths of 16 mm and 17 mm for the thick and thin laminates, respectively. The results show that the delamination growth rate initially increases with increasing delamination length until a peak value is reached, beyond which the growth rate decreases as the delamination propagates further. The influence of geometric imperfections is investigated for the thick laminate, demonstrating that while imperfections initially affect the delamination growth rate, their influence gradually diminishes as the delamination propagates. For the thick laminate, it is further shown that a reduction of only 10.0% in the applied fatigue strain can lead to a substantial decrease in the delamination growth rate, owing to its pronounced effect on the buckling displacement. Moreover, the results indicate that delamination propagates at a significantly slower rate in thin laminates than in thick laminates. Finally, delamination growth is evaluated for a benchmark case from the literature, demonstrating that incorporating a mode-mixity-dependent adaptation of a model parameter improves the predictive capability.

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abst. 1244
**Repository**

## Experimental Study on Mixed-Mode I/II Delamination Behavior of 3D-Printed Hybrid CFRP Fabricated via Intra-Bead Multi-Fiber Hybridization

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Additive manufacturing (AM) techniques have become widely used in the fabrication of continuous fiber-reinforced polymers (CFRP). The 3D printing process of CFRP offers various benefits, such as the ability to create lightweight, high-strength, and geometrically complex components. Additionally, it enables shorter production timelines and the possibility of integrating multiple functionalities into a single part. However, the performance of 3D-printed CFRP is inherently limited by the properties of the single type of continuous fiber used. This constraint becomes particularly noticeable in scenarios that require optimized properties, which a single fiber material may not adequately provide. A key challenge in 3D-printed CFRPs lies in their weak interlaminar bonding, which can lead to delamination, a catastrophic failure mode strongly attributed to low interlaminar fracture toughness. This issue is further exacerbated by the layer-by-layer deposition inherent in AM, which restricts interlayer diffusion and compromises energy absorption at interfaces. To overcome these limitations, hybridization strategies combining fibers with complementary mechanical properties, such as carbon fibers (CFs) and Kevlar fibers (KFs), offer a promising solution. CFs are known for their high strength and stiffness but suffer from low fracture toughness, while KFs provide high fracture toughness and impact resistance at the cost of reduced stiffness. Leveraging these complementary properties through hybridization can potentially enhance the delamination resistance of CFRPs, especially under mixed-mode (I/II) loading conditions. The primary focus of this study is the application of a multi-fiber manufacturing technique using the FDM method to achieve a balance between the stiffness and toughness of 3D-printed CFRP. This multi-fiber approach leverages the capabilities of AM, which allow for the integration of different types of fibers within a single printed structure. The main idea involves the simultaneous deposition of two distinct fiber types, including CFs with low elongation and KFs with high elongation, both impregnated with PA6. Since a single nozzle is used throughout the printing process to deposit both fiber types together, this technique is called an "intra-bead" hybridization approach. The intra-bead hybridization approach operates at the microscale, with both fiber types co-deposited within a single hybridized bead. Here, the CKFs are

typically arranged side-by-side (e.g., CF/KF/CF/KF within a single layer), which promotes a more continuous and uniform distribution of mechanical properties across the entire printed structure. In this research, two types of unidirectional CFRP are manufactured: CF/PA6 composites as a benchmark and hybrid CKF/PA6 composites fabricated using the intra-bead hybridization method. A systematic investigation is carried out in three phases to assess the interfacial bonding performance of 3D-printed CFRP. In the first phase, the mixed-mode I/II interlaminar delamination behavior is examined, which is particularly relevant for practical applications where components are often subjected to combined loading. Mixed-mode bending (MMB) tests are conducted at different mixed-mode ratios (0.25, 0.5, 0.75), and a failure envelope is developed for each to provide a comprehensive characterization of delamination resistance across the full range of mixed-mode conditions. In the second phase, the focus is on identifying the fracture mechanisms contributing to enhanced mixed-mode fracture toughness, emphasizing the distinctive mechanisms resulting from the intra-bead hybridization approach. Finally, in the third phase, the interfacial bonding mechanisms of CKF/PA6 hybrid CFRP are compared with those of CF/PA6 non-hybrid CFRP, revealing differences in bonding behavior and offering valuable insights into how the proposed hybridization strategy influences the interfacial bonding. These findings offer valuable insights for the design of damage-tolerant, high-performance 3D-printed CFRP, particularly for applications that require a trade-off between stiffness and toughness, by demonstrating improved mixed-mode delamination resistance achieved through the proposed hybridization approach.

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## High-Efficiency and Low-Damage Machining of Ceramic Matrix Composites

abst. 1252
**CIMA**
Wednesday
June 24
10h40

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This study addresses the critical challenges of machining-induced damage and low processing efficiency associated with ceramic matrix composites (CMCs), stemming from their inherent high hardness and brittleness. A systematic investigation was conducted to develop an integrated machining methodology. Initially, the research focused on ultrasonic vibration-assisted grinding (UVAG). A quantitative characterization system for machining damage was established, defining clear criteria for various defect types. The correlations between damage extent, surface roughness, and key process parameters were subsequently elucidated. Based on this analysis, a parameter optimization methodology targeting minimal damage and low surface roughness was developed and successfully implemented for precision machining of CMCs at different densification stages. To overcome the limited material removal rate of UVAG, a novel hybrid machining strategy combining electric arc machining (EAM) and UVAG was proposed. The strategy employs EAM for high-efficiency, large-volume material removal in the roughing stage, followed by UVAG for high-precision, low-damage finishing. This synergistic approach effectively balances the requirements for high efficiency and superior surface integrity, resulting in a significant enhancement in the overall machining performance of CMC components.

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## A novel simulation framework for progressive failure analysis of composite laminates under compression after impact

abst. 1257
**SANT'EFISIO**
Friday
June 26
10h40

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This study investigates the compression-after-impact (CAI) strength of carbon fibre-reinforced epoxy composite laminates subjected to low-velocity (LVI) and medium-velocity (MVI) impacts. Impact experiments at varying energy levels were conducted to characterise the dynamic response and damage modes. A strain rate-dependent finite element (FE) model was developed by integrating the Puck failure criterion, continuum damage mechanics (CDM), and surface-based cohesive behaviour to simulate intra- and inter-laminar damage. The intralaminar model was implemented via a VUMAT subroutine in Abaqus/Explicit. A Python-based interface was developed to extract and transfer key damage variables, such as matrix cracking and permanent indentation, into the CAI model with corresponding boundary and loading conditions. This novel modelling approach avoids empirical damage equivalence and enables more accurate simulation of progressive intralaminar and delamination damage. Predicted

force-displacement curves, energy absorption, and delamination areas showed strong agreement with experimental results. Finally, the effects of varying impact energies on impact response, failure mechanisms, and CAI strength were systematically analysed, providing an efficient and validated numerical framework for assessing the damage tolerance of composite structures.

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abst. 1273
**CIMA**
Wednesday
June 24
10h20

## Experimental and Numerical Investigation of Fatigue Damage Behaviour in Short Fibre Reinforced Adhesive Materials

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The fatigue performance of adhesive joints is a critical factor governing the structural integrity of wind turbine blades, particularly in trailing-edge regions subjected to cyclic loading. In modern blade designs, short fibre reinforced polymer (SFRP) adhesives are increasingly employed due to their enhanced strength-to-weight ratio, suitability for complex geometries, and improved fatigue life. Despite their growing industrial relevance, the progressive fatigue damage behaviour of SFRP adhesives remains insufficiently understood, limiting the accuracy of existing lifetime prediction approaches. In this work, a coupled experimental–numerical framework is proposed to investigate and predict fatigue damage evolution in SFRP adhesive joints. A progressive fatigue damage model based on an energy-based approach, developed at the Institute for Structural Analysis (ISD) for continuous fibre-reinforced composites, is extended to short fibre-reinforced adhesives. The model captures material degradation through energy-dissipation-based stiffness and strength reduction, providing a consistent link between static and cyclic damage parameters. To account for the anisotropic nature of SFRP adhesives, three-dimensional Hashin failure criteria are employed, allowing clear differentiation between fibre-dominated and matrix-dominated damage mechanisms. Although the adhesive exhibits elasto-plastic behaviour under quasi-static loading, a linear elastic constitutive assumption is adopted for the fatigue analysis, which is justified by the focus on high-cycle fatigue at low stress levels and the need for computational efficiency. The numerical framework is supported by a comprehensive experimental campaign. SFRP adhesive plates were manufactured by injection moulding, and specimens were extracted in two principal orientations relative to the injection flow direction, indicating preferential fibre alignment and motivating the use of a transversely isotropic material description. Load-controlled fatigue tests were conducted at a stress ratio of $R = 0.1$ over a wide range of load levels. Full-field strain measurements were obtained using digital image correlation. In addition, open-hole tension–tension fatigue tests were performed to assess the model's predictive capability under stress concentration conditions. Microscopic fracture surface analyses were carried out to identify dominant damage mechanisms and to support the interpretation of the observed fatigue behaviour. The proposed model demonstrates good agreement with experimental fatigue lives and stiffness degradation trends for both material orientations, capturing the influence of fibre alignment and stress concentration effects on fatigue performance. The fracture surface analyses reveal fibre pull-out and matrix cracking as dominant damage mechanisms, with pronounced differences between quasi-static and fatigue fracture morphologies. The proposed framework provides an effective computational tool for fatigue life prediction and improved understanding of progressive damage in SFRP adhesive joints, contributing to the reliable design and assessment of wind turbine blade trailing-edge bondlines and structural adhesive joints.

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## Force-Heat Equivalence Energy Density Principle and its applications to the characterization of composite material properties under extreme conditions

abst. 1278
**SANT'EFISIO**
Friday
June 26
10h20

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With the rapid development of modern science and technology, the demand for expanding the service conditions of materials has become increasingly intense. The mechanical/physical properties of materials under diverse and wide-range extreme conditions have become a core issue of concern in various fields, and there is an urgent need to establish the ability to predict the performance of materials under such conditions. Focusing on the major needs of the country, aiming at the advanced materials and structures that have a wide application prospect in national strategic equipment, focusing on their mechanical behaviors, strength theory and characterization methods under diverse and wide-range extreme conditions, the author originally proposed a method that could quantitatively characterize the effect of temperature on the mechanical/physical properties of materials - the Force-Heat Equivalence Energy Density Principle (Li's principle of energy equivalence). Based on this principle, for the first time, established a series of theoretical quantitative characterization models for the mechanical/physical properties (fracture strength, yield strength, ultimate strength, fatigue strength, creep life, buckling strength, hardness, melting point, band gap width, electrical breakdown strength, and exciton energy, etc.) of various material systems, including inorganic non-metallic, metallic, polymeric, and composite materials, without any fitting parameters.

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## Failure mechanism and progressive damage modelling of stealth functional laminated composites for aircraft inlet structures under tensile loading

abst. 1282
**SANT'EFISIO**
Friday
June 26
09h00

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Next-generation aircraft inlets need a single solution that is lightweight, aerodynamically efficient, and radar stealthy. This study investigates a stealth functional laminated composite for inlet skins. We combined in situ tensile tests, scanning electron microscopy, and progressive damage finite element analysis. The laminate has two co-cured parts. A functional layer is placed near the outer aerodynamic surface to absorb and control electromagnetic waves. A load-bearing layer is placed on the inner side and is made of T800 carbon fibre-reinforced polymer. The two layers differ strongly in stiffness, strength, and thermal expansion. Together with an unsymmetric layup, this results in strong anisotropy and tension-bending coupling. During curing and service, the laminate can develop distortion and high interlaminar stresses. These effects may lead to interfacial debonding, interlaminar shear slip, and local spallation of the functional layer, which can reduce assembly accuracy and in-service reliability. To reveal the microscale damage evolution of the laminate under tension, we used in situ tensile testing together with scanning electron microscopy. Clear differences were observed on the two sides. On the load-bearing side, damage follows a brittle fracture sequence: microcracks initiate, grow, coalesce, and finally form a through-thickness fracture. Cracks mainly propagate perpendicular to the loading direction and drive stiffness degradation. On the functional side, the response is mixed plastic-brittle. At low to medium loads, local yielding first appears in stress concentration zones, while cracking remains limited and small. A sparse crack network forms only near the ultimate load and overlaps with the plastic zones. Because the two sides are damaged in different ways and at different rates, the interface experiences high shear and coupled deformation. Crack growth often coincides with interfacial debonding, forming an asymmetric coupled damage pattern. A layered finite element model was developed in ABAQUS to capture the material mismatch and the unsymmetric layup. Hashin criteria were adopted for fibre and matrix failure, and progressive damage was used to simulate stiffness degradation and stress redistribution. The model predicts the ultimate strength and the global load-displacement response well compared with the tests. The simulations indicate that matrix tensile damage initiates at the interface between the functional and load-bearing layers. Damage then spreads into adjacent plies and interacts with fibre and matrix damage in tension and compression, forming a

weakened zone near the interface. This zone agrees with the crack initiation and debonding regions observed in the in situ microscopy, confirming that the interlaminar interface is the key weak region controlling failure. The results provide design guidance on functional layer selection and thickness, layup symmetry, interface toughening, and distortion control for stealth composite inlet structures.

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abst. 1291
**SANT'EFISIO**
Friday
June 26
09h20

## Study of the compressive behaviour of an L shaped flax fiber reinforced PLA composite profile

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The rapid advancement of modern engineering technologies is opening new pathways for designing structures that combine mechanical performance with environmental responsibility. Increasingly, the focus is not only on the strength of a material but also on its origin, sustainability, and end of life options such as recycling or biodegradation. As public awareness grows, users and consumers are paying closer attention to the ecological footprint of the products they choose. This shift in expectations drives global research efforts toward materials that can deliver high durability while maintaining a significantly lower environmental impact than conventional solutions. In the field of fiber reinforced composites, natural fibers such as flax, hemp, sisal, and jute are emerging as viable alternatives to synthetic reinforcements like carbon or glass fibers. Flax fibers, in particular, offer substantial environmental advantages: producing one kilogram requires only 1.1 kWh of Energy , approximately 99% less than carbon fiber production 250 kWh. Additionally, CO emissions associated with flax fiber manufacturing are markedly lower (1.65 kg per kilogram of fiber) compared to carbon fiber (24 kg), representing a 93% reduction. Motivated by these benefits, the present study investigates the failure behavior of a simple structural component ( L-shaped angle) subjected to axial compression. Both numerical and experimental approaches were employed. Experimentally, five specimens made from a natural composite consisting of flax fibers embedded in a polylactic acid (PLA) matrix were tested. Compression tests were performed using a universal testing machine to determine the mechanical response of the laminates. A non-contact optical measurement system (Aramis) was used to track deformation, while an acoustic emission system captured sound signatures associated with fiber and matrix damage initiation. Numerical simulations were carried out using an idealized geometry corresponding to the real specimen. The finite element method implemented in Abaqus was used to determine the critical buckling load for the first mode. Damage initiation was assessed using maximum stress criteria as well as Tsai-Wu, Tsai-Hill, and Azzi-Tsai-Hill failure theories. The Hashin criterion was applied to identify the dominant failure mechanisms. Based on Hashin parameters, a stability analysis was performed, enabling the determination of equilibrium paths and the load level at which structural integrity is lost. Overall, the findings support the growing view that biocomposites can serve as viable, sustainable alternatives to traditional synthetic fiber materials. Continued development of such materials may significantly expand their applicability across engineering sectors while contributing to reduced environmental impact and promoting more sustainable design practices. Acknowledgements: The research was funded by the Lublin University of Technology program titled „Investing in Potential" (Grant No: 33/IP/2025/F).

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abst. 1296
**RIVA**
Friday
June 26
15h50

## Multidamage and Failure Evolutions of CFRP Composite Structures under Progressive Loading

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Carbon fiber reinforced polymer (CFRP) composite laminates are widely used in advanced industries such as aerospace and automotive engineering. The reliability assessment of composite laminate structures depends on understanding elastic-to-damage behavior, failure mechanisms, and their interactions under continuous loading. Continuous loading in the damage regime of mesoscale CFRP composites often leads to multiple failure modes, including matrix yielding and cracking, fiber–matrix debonding, multidirectional delamination, and fiber fracture or crushing. This study presents a combined computational–experimental approach to establish hybrid deformation mechanisms that activate multiple damage modes and failures in multidirectional (MD) CFRP composite laminates. In the computational framework, finite element (FE)–based damage models are employed, including a lamina continuum model coupled with an interlaminar model, to enable hybrid deformations that produce linear–nonlinear interlaminar and intralaminar stress development. Three-dimensional continuum elements are used to establish internal displacement and strain states through the laminate thickness, providing a three-dimensional representation of failure locations. The material response, characterized by a progressive elastic-to-failure process, is based on a continuum formulation incorporating classical lamination theory, damage initiation criteria, post-damage evolution, and an energy-based damage propagation model for the laminas, while cohesive failure criteria are defined for multidelamination. Experimentally, a case study focusing on the flexural behavior of a CFRP composite was conducted to induce multiple damage modes and subsequent failures, serving to demonstrate the validity and credibility of the computational approach. A CFRP composite beam with an antisymmetric ply sequence of [-45/45/-45/90/45/90/90/-45/90/45/-45/45] was subjected to four-point bending until complete failure. The model and simulation results were validated through strong correlation with experimental observations of (1) linear–nonlinear structural response and (2) the prediction of multiple fracture states. The results are discussed in terms of flexural stiffness degradation, stress distributions within equivalent orthotropic laminas, the sequence of damage events in individual laminas and interfaces, the evolution of damage variables, and critical energy components. The capability of the FE model is demonstrated by accurately capturing both linear and nonlinear structural responses, as well as predicting multiple fractured regions, including multidamage events in lamina No. 1 (matrix shear failure and fiber buckling), matrix cracking in lamina No. 9, and multidelamination at interfaces No. 8 and 9, consistent with experimental findings. Additionally, the FE predictions indicate that fiber damage propagation without fracture—an invisible failure mode at the mesoscale—in laminas No. 10, 11, and 12 (critical layers) is the primary contributor to load-bearing degradation, rather than the visibly fractured regions. In this context, challenges related to model limitations, prediction accuracy, and overall validity are discussed.

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## Thermodynamically Consistent Modeling of the Nonlinear Damage Behavior of Carbon Fiber Reinforced Thermoplastics

abst. 1358
**SANT'EFISIO**
Friday
June 26
09h40

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The increasing demand for lightweight structural components in the automotive and aerospace sectors has accelerated the adoption of Thermoplastic Fiber-Reinforced Composites (TPFRCs). Unlike most composites, TPFRCs offer superior recyclability, high specific strength, and rapid processing capabilities. However, the mechanical behavior of the semi-crystalline thermoplastic matrix is highly

complex, exhibiting pronounced nonlinearities driven by viscoelasticity, elasto- plasticity, and damage evolution, particularly under cyclic loading conditions. The primary objective of this study was to accurately predict the nonlinear damage behavior of the thermoplastic matrix, while accounting for finite strains and other inelastic phenomena, while maintaining thermodynamic consistency. The developed approach utilized a rheological framework consisting of a parallel arrangement of intermolecular and molecular network components to decouple viscoelastic and elastoplastic mechanisms [2]. To address the interaction between inelastic deformation and material degradation, a bipotential formulation was employed; this method introduced two distinct potentials in the intermediate configuration: one governing the viscoelastic-elastoplastic flow and the other controlling damage evolution. This separation was crucial for ensuring the thermodynamic consistency of the model, specifically when dealing with the non-associative flow rules often required for polymers. The model accounted for isotropic damage but explicitly incorporated Tension-Compression Asymmetry (TCA). This was essential for TPFRCs, where the matrix behavior differs significantly under tensile versus compressive loads, influencing the onset of failure mechanisms such as matrix cracking. To overcome the pathological mesh dependency inherent in local damage formulations, the framework integrated a gradient-enhanced regularization scheme (micromorphic approach). This introduced non-local field variables that regularized the damage localization zone, ensuring that energy dissipation remained objective and independent of the finite element mesh size. This feature is particularly critical for the subsequent steps of this project, where the matrix model will be employed within Representative Volume Elements (RVEs) for homogenization. The model was validated against experimental data obtained from uniaxial and cyclic tensile, compressive, and shear tests on pure matrix specimens. Preliminary results demonstrated the capability of the model to capture rate-dependent stiffness degradation and permanent deformation.

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abst. 1362
**CIMA**
Wednesday
June 24
13h10

## A variational foundation–bar composite model with tension–compression plasticity and fatigue-induced damage

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This contribution proposes a minimal yet physically interpretable model to capture fatigue-driven degradation arising from the interaction between plasticity and damage in composite-like structures. A compliant axial member is coupled to a rigid substrate through a distributed spring layer, representing an interphase/interface region (e.g., an adhesive layer, a matrix-rich zone, or a compliant foundation) mediating load transfer between constituents. Each spring is equipped with two tension–compression plastic accumulations and a scalar damage variable, whose activation thresholds are coupled to the plastic internal variables. Such constitutive coupling makes each cycle slightly irreversible and progressively more damaging, so that failure can develop under constant-amplitude cyclic loading without prescribing S–N laws a priori. The evolution problem is formulated in a variationally consistent energetic setting, leading to a hemi-variational inequality that guarantees thermodynamic admissibility and irreversibility of plasticity and damage at the local (spring) level, while compatibility along the axial member introduces nonlocal interaction and redistribution effects. Numerical examples demonstrate: (i) progressive degradation and narrowing of distributed hysteresis; (ii) growth of damage and dissipation with spatial localization along the interphase; and (iii) the emergence of Wöhler-type (S–N-like) curves at the structural scale. The model provides a reduced-order building block for analyzing fatigue degradation in bonded interfaces and composite assemblies, supporting parametric studies and guiding the design of safer load-transfer architectures.

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abst. 1369
**SANT'EFISIO**
Friday
June 26
11h30

## Debonding prediction in multilayer systems using a closed-form analytical model

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Bonded joints and sandwich structures are widely used in lightweight engineering and composite mechanics due to their high load-to-weight ratio and the possibility of damage-free joining. In this study, a three-layer system is investigated, serving as a simplified model for both bonded joints with thick adhesive layers and for sandwich structures with a thick core. It is common for such structures that the inner or adhesive layer is made of a more flexible material, and the outer layers are made of a stiffer material like a fiber reinforces polymer. Due to the geometry and the mismatch in material properties, stress concentrations arise at the material interfaces, reaching their maximum values at the free edges. These elevated interfacial stresses may initiate interlaminar cracks, which can subsequently propagate as delaminations and thereby compromise the structural integrity. Within the framework of finite fracture mechanics, crack initiation is predicted using a coupled stress and energy criterion. For this purpose, both the stress distribution in the considered structural configuration and the incremental energy release rate for the potential delamination cracks are evaluated. To approximate the required field quantities, a closed-form analytical model based on a higher-order displacement approach is developed. The validity and accuracy of the proposed model are assessed through comparison with finite element simulations.

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## Cost-effective phase-field fracture prediction in composite structures via a moving-mesh adaptation scheme

abst. 1371
**SANT'EFISIO**
Friday
June 26
13h10

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Both traditional and innovative composites have an intrinsically complex mechanical behavior, usually exhibiting damage-induced anisotropy strictly related to multiple interacting failure modes when subjected to general external loads. In this context, well-established phase-field fracture approaches have proven to be reliable numerical tools for accurately simulating multiple crack propagation inside matrix along nonprescribed paths and in the absence of initial defects. Nevertheless, a proper phase-field regularization often requires that the internal length scale be much smaller than the size of the fracture process zone, and in turn the finite element discretization be very fine at least in the cracking regions. This is true also for the recently developed length-scale insensitive phase-field damage models for cohesive fracture. It follows that adaptive mesh refinement is desirable for improving overall computational accuracy and efficiency at the same time. The aim of this work is to present an efficient mesh refinement strategy for the phase-field regularized cohesive zone model, relying on a moving mesh adaptation scheme within a finite element framework. The proposed approach is able to achieve excellent computational savings while preserving high accuracy in reproducing cracking processes in heterogeneous media along arbitrary trajectories. The key feature of the proposed strategy is a new criterion to dynamically refine the mesh in critical regions, where microscopic damage evolution is expected, without the need for expensive remeshing operations. The efficacy of the proposed methodology has been assessed through comparisons with other numerical techniques available in technical literature as well as with direct numerical simulations conducted by using uniformly fine meshes. The present results underscore the reliability of the proposed moving mesh adaptation scheme as a robust, cost-effective tool for simulating damage and failure phenomena in a wide range of composite materials and structures for engineering applications.

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## An AE damage identification method for woven composites by modal energy analysis

abst. 1375
**SANT'EFISIO**
Friday
June 26
11h50

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Recently, acoustic emission (AE) methods have been widely used for damage mechanism of woven composites, by combining digital image correlation (DIC), computed tomography (CT) etc. However, limitations cannot be ignored: 1) conventional AE feature-based methods may lose critical time-frequency information; 2) waveform-based approaches may lack clear physical linkage between frequency characteristics and damage modes. This talk will introduce our latest progress in AE damage identification method for woven composites by modal energy analysis. The damage mechanism of woven composites with the influence of structural variations are present by a combined analysis of AE, DIC, and microscopic observations.

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abst. 1384
**SANT'EFISIO**
Friday
June 26
12h10

## Parametric Assessment of a Fast Linear Method for Mixed-Mode Delamination Onset in Composite Structures

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Accurate prediction of delamination onset in composite laminates is crucial for the design of reliable structures. Traditional approaches, such as nonlinear simulations based on the Virtual Crack Closure Technique (VCCT) or Cohesive Zone Models (CZM), are computationally expensive and often impractical for early-stage design. To overcome these limitations, a linear methodology has been developed that efficiently predicts delamination initiation under both Mode I and mixed-mode loading conditions, providing a fast and reliable alternative to full nonlinear analyses. This work presents a dedicated parametric sensitivity analysis to evaluate the influence of delamination position on the predictive capability of the proposed fast linear method. A benchmark composite configuration with an embedded circular delamination is considered, systematically relocated both along the in-plane direction and through the laminate thickness, while keeping material properties, geometry, and boundary conditions constant. For each configuration, the onset load is estimated using linear static analyses combined with eigenvalue buckling simulations and a mixed-mode fracture criterion. All predictions are critically compared against nonlinear results obtained from the well-established SMart-Time XB approach, demonstrating the accuracy and robustness of the linear methodology across a wide range of delamination positions. The results show that variations in the damage position, despite modifying the local stress distribution and the relative contributions of Mode I and Mode II energy release rates, do not compromise the consistency of the predicted initiation loads. Within the previously identified applicability domain, the method maintains good agreement with nonlinear reference solutions, confirming its robustness against geometric perturbations of the defect. The study further supports the suitability of the proposed linear approach as a fast and reliable tool for preliminary composite design, where rapid parametric evaluations are essential.

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## Design and applications of composites

### Development and assessment of a lightweight type III COPV for high-pressure helium storage in flight systems

abst. 1045
**CIMA**
Friday
June 26
11h30

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This paper presents a comprehensive design and structural assessment methodology for a Type III composite overwrapped pressure vessel (COPV) developed for high-pressure helium storage in flight applications within the framework of the DLR ATHEAt project. The vessel, manufactured through filament winding, consists of an aluminum 5083-O liner and a carbon fiber–reinforced polymer (CFRP) T700SC/LY556 overwrap. The sizing process addresses the specific requirements for flight use—including weight optimization, flight hardware safety factors, and robustness under combined thermo-mechanical loading conditions. The sizing methodology is divided into two main steps: (i) automated optimization of the composite layup based on a linear axisymmetric static analysis to meet target burst and proof pressures, and (ii) detailed nonlinear finite element assessment accounting for liner plasticity and the interaction between the metallic and composite layers. Key parameters investigated include the geometric details of the liner and boss region, material properties over a temperature range, and the definition of safety margins for critical failure modes. The results demonstrate that the proposed approach yields a structurally efficient configuration that satisfies flight-relevant design constraints while maintaining adequate safety margins against liner yielding and fiber rupture. The findings support the ongoing efforts of the ATHEAt project to research new technologies for reusable space transportation systems and to develop lightweight, high-pressure composite storage solutions.

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### A ductile seismic design strategy for the beam / column joints of FRP pultruded profiles

abst. 1060
**CIMA**
Thursday
June 25
16h50

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Characterized by their lightness, simple connectivity and brittle behaviour, structures built with pultruded profiles are typically considered as "non-dissipative" structures. These considerations are received in the recent seismic codes by the absence of capacity design and the adoption of very low behaviour factors (or sometimes completely absent, with no specifications) if compared with the ones of ordinary material structures. This limited capability of stress redistribution significantly increases the vulnerability of pultrude profiles structures under beyond design seismic hazards and raises the demand for more resilient designs. Along these lines, the proposed approach focuses on the plasticization of the bolted connections of the profiles attempts to increase the ductility of the individual frames, and, at the same time, to preserve their easy-to-assemble nature. As for the Plastic Ovalization Strategy (POS) of industrial racking systems and for the Johansen Theory of European Yield Model (EYM) of the design of the wooden joints, the strategy of Pultruded Profiles Ductile Connections (P2roDuCo) is achieved by tasking the pin bearing failure mechanism of the bolt hole to absorb seismic deformations, while capacity design is employed to keep the rest of the structure in the elastic zone. Introducing a preliminary discussion on the transposed motives and basic principles of the strategy, one structure with pultruded profiles, designed twice by professional engineers, once using standard approaches and then by additionally employing the proposed dissipative model. Finally, the design solution is compared by conducting a preliminary seismic assessment for these structures, which employs a phenomenological macro-model comprising elastic elements and nonlinear springs to simulate the bearing failure mechanism.

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abst. 1065
**CIMA**
Friday
June 26
11h50

## Taking advantage of the continuity for a comprehensive timber-concrete composite structural system (Frame TCC)

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Timber-concrete composite systems are an efficient solution for engineering structures by taking advantage of the benefits that each material provides. Timber provides lightness, flexibility, workability and sustainability, while concrete provides continuity, rigidity and improvements in acoustic and fire performance, among other advantages. These systems have traditionally been used for the development of bending simply supported flooring elements where the concrete works on the upper face mainly in compression and the wood is placed on the lower face either in the form of ribs or in the form of a slab and works mainly in tension. Our team has developed a comprehensive structural system solution in which beams, slabs, and supports are all resolved using the same wood-concrete composite system. The system is based on a shear connection made with perforations made in the wooden pieces and filled by the freshly poured concrete, so that no additional ironworks or adhesives are needed to ensure the transmission of forces between both materials. The perforations are made in T-shaped pieces for beams and slabs and in box-shaped pieces for supports. These wooden pieces can be prefabricated and easily transported, and they serve as permanent formwork for pouring the concrete that fills the supports and creates a thin layer on the slabs. Concrete provides continuity in all elements, allowing for semi-rigid connections between beams and floors, and between beams, and support. The possibility of developing these connections greatly improves the behaviour in relation to the simply supported systems that are usually carried out. On the one hand, bending stiffness is improved and deflections are limited allowing to reduce the thickness of the floors or to increase span. On the other hand, stiffness against lateral actions and the overall stability of the buildings are increased. An extensive experimental campaign has been carried out to validate this solution. Firstly, tests have been carried out on the timber-concrete shear connection, testing the effectiveness of different shapes and arrangement of the perforations and different types wood-derived materials, plywood boards, and cross-laminated panels. Secondly, floor slabs with spans ranging from 6.0 to 8.4 meters and a span-to-depth ratio of 24 were tested. These floor slabs have a double-T cross-section, consisting of a lower wooden slab, an upper concrete slab, and a wooden rib with the perforations separating the two slabs. Insulation material can be placed between the ribs. This cross-section provides significant stiffness to the floor slabs, which, with these proportions, meet the deflection requirements for public buildings. Secondly, floor slabs with spans ranging from 6.0 to 8.4 meters and a span-to-depth ratio of 24 were tested. These floor slabs have a double-T cross-section, consisting of a lower wooden slab, an upper concrete slab, and a wooden rib with the perforations separating the two slabs. Insulation material can be placed between the ribs. This cross-section provides significant stiffness to the floor slabs, which, with these proportions, meet the deflection requirements for public buildings. The behaviour of supports subjected to centred compression has also been tested. It has been verified that the casing effect generated by the wooden box, which serves to allocate the connecting perforations and acts as permanent formwork, also significantly improves the load-bearing capacity and the supports when compared to the resistance of isolated only-concrete supports. Finally, beam-floor and beam-support joint tests have been carried out to assess the ability to develop semi-rigid connections. The experimental results obtained have confirmed the viability and good performance of the system.

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abst. 1086
**Repository**

## New Italian Guidelines for the Design, Execution and Inspection of Structural Strengthening Interventions Using Fiber-Reinforced Composites

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The second revision of the Guidelines for the Design, Execution and Inspection of Structural Strengthening Interventions Using Fiber-Reinforced Composites. Materials, Reinforced and Prestressed Concrete

Structures, masonry structures (CNR-DT 200 R2) represents a comprehensive revision of the previous R1 version (2013), aimed at aligning Italian guidelines for polymer matrix composites (FRP) with the latest international scientific literature and national regulatory frameworks. Unlike standard design codes, the CNR Technical Documents maintain an informative and explanatory approach to ensure practitioners understand the underlying mechanical and technological principles of composite reinforcement. Main primary novelties were introduced in R2. Material Qualification and Scope in Chapter 2 are aligned to the significant technological progress in fibers and resins over the last decade. The document acknowledges new materials emerging on the market while maintaining its formal scope focused on aramid, carbon, and glass fibers, steel wires/strands, and thermosetting resins. A detailed overview of material qualification is provided, strictly aligning with current Italian law and the procedures required for CE marking. Design Fundamentals and Safety Factors in Chapter 3 involve recalibration of partial safety factors for FRP materials and environmental conversion factors. These updates are based on extensive experimental programs that quantified uncertainties in material properties and align with modern approaches for reliability. Structural Reinforcement in Chapters 4 and 5 were improved with the inclusion of Near Surface Mounted (NSM) systems. In previous versions, only Externally Bonded Reinforcement (EBR) was addressed. Meanwhile the bond coefficients for both reinforced concrete (RC) and masonry have been recalibrated based on recent test data. R2 now provides formal design rules for reinforcements inserted into grooves in the substrate, significantly expanding the practitioners' more precise tools for both standard and seismic retrofitting of RC. Anchorage Systems and Special Detailing were inserted for the first time, new criteria for evaluating the diagonal tension capacity of beam-column joints and provisions for predicting crack width opening under Serviceability Limit States. Theoretical Models and Monitoring have been completely revised to detail the mechanical formulations for debonding from the substrate for both EBR and NSM systems. Finally, updates of the protocols for the control and monitoring of structural interventions, incorporate a decade of field experience and evolution.

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## Development of multi-layered carbon fibre reinforced PPS/PES composites for high toughness and high thermal conductivity

abst. 1100
**CIMA**
Friday
June 26
12h50

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Applications of carbon fibre reinforced plastic composites, such as nuclear power plant heat exchangers and battery cases of electric vehicles, call for enhanced thermal conductivity as well as high strength and corrosion resistance. This study systematically investigated the effect of fibre type, fibre content and hot pressing temperature on the thermal and mechanical properties of carbon fibre-reinforced thermoplastic composites. A biomimetic layered structure was developed by adding carbon fibre prepreg to the short carbon fibre reinforced PPS-PES composite. Results showed that the pitch-based short carbon fibre reinforced composites exhibited superior thermal conductivity compared to the PAN-based composites. The thermal conductivity of the pitch-based composite reached 1.46 W/m.K in the thickness direction. The introduction of the intermediate prepreg layers to form a multi-layered structure enhances the toughness of the material compared to the conventional sandwich structure, transforming the failure mode from brittle fracture to progressive failure, thereby improving the safety and durability of the material. The numerical simulation validates the model assumption. These findings provide a novel approach to the design optimisation of hybrid short and long carbon fibre composites for enhanced thermal conductivity while maintaining good mechanical properties.

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## Probabilistic assessment of composite-repaired pipelines with interacting dent-corrosion defects using an interpretable hybrid machine learning framework

abst. 1127
**CIMA**
Friday
June 26
12h30

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Interacting dent-corrosion defects pose a substantial risk to pipeline integrity and process safety as their geometric indentation and wall-loss contribute to stress concentration not accounted for in single-defect assessment models. The performance of composite repair systems applied to pipes containing these combined defect scenarios is not well understood, hindering the assurance of a safe, reliability-based decision framework. In this study, a novel hybrid machine learning-based predictive model was proposed to estimate the failure-pressure capacity and reliability of composite-repaired pipelines with combined dent-corrosion defects. Expressions consistent with the underlying physics were learned using Symbolic Regression (SR), and a high-performance ensemble learner, namely CatBoost, was included to model nonlinear residuals. The resulting hybrid SR-CatBoost framework achieved almost perfect accuracy ($R2=0.998$) and outperformed pure symbolic and ensemble models. By integrating the hybrid model into the Monte Carlo Simulation, the probability of failure was determined, and the most impactful variables were identified. The SHAP analyses illustrated that the pipe diameter-to-thickness ratio, strength ratios, operating internal pressure, and defect severity were the main drivers of reliability change; however, the composite sleeve features played secondary roles. The results show that uncertainty in geometry and operating pressure affects the reliability of repaired pipes, underscoring the importance of using conservative design factors for combined defects.

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abst. 1210
**CIMA**
Thursday
June 25
17h10

## Structural design and interface optimization of intelligent heterogeneous composite materials

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Metal-SiCf/SiC multilayer cladding is considered to be a promising accident-tolerant fuel cladding because it overcomes the gas-tightness limitation of SiCf/SiC cladding. However, the mechanisms by which structural changes affect their thermomechanical properties are unclear, and the excessive interface stress remains a major obstacle to their application. In this study, a parametric modeling approach was employed to rapidly construct different heterogeneous cladding structures with 2D braided SiCf/SiC composites, incorporating five types of metal liners (W, Mo, Re, Ta, Nb) at three different thickness levels. Their thermo-mechanical properties were systematically analyzed using finite element simulation at different temperature. The results show that among the five metal liner systems, the Re- and W- lined systems exhibit superior overall performance in the non-irradiated state, with their thermomechanical properties consistently improving as liner thickness increases. In contrast, the Mo-, Ta-, and Nb-lined systems display inconsistent trends. To effectively alleviate this issue, we designed a porous SiC interlayer carrying monitoring and sensing elements, which reduced the interfacial stress by about 30%.

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abst. 1415
**CIMA**
Friday
June 26
12h10

## Construction of rapidly gelatinising nanocomposite hydrogel films by spraying

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In situ hydrogels are an emerging class of hydrogels with unique advantages, though their overall performance still requires further enhancement. We adopted a dual-precursor solution strategy to rapidly crosslink and obtain in situ formable hydrogel films. The hydrogel precursor solution can uniformly spread over various material surfaces without forming droplets, ultimately resulting in a sprayable hydrogel with adjustable thickness and broad applicability. This presents a highly promising novel wound dressing, offering a new therapeutic approach for wound treatment. The precursor solution exists in liquid form, facilitating the easy loading of additional functional components. By incorporating magnetic nanoparticles into the polymer network, a responsive hydrogel film can be formed, characterized

by simple preparation, convenient operation, unique magnetic responsiveness, and favorable mechanical properties. As soft intelligent materials, hydrogel actuators hold extensive development potential; however, such actuators are rarely fabricated using in situ formation strategies. This study overcomes the limitations of current sprayable hydrogels and expands their versatility in biomedical applications.

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# Dynamics of composite structures

abst. 1049
**CIMA**
Wednesday
June 24
15h10

## Effects of Temperature on the Dynamic Fracture Behavior of Rigid Insulation Tile Materials

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This study employs a modified high-temperature split Hopkinson pressure bar (SHPB) setup to perform three-point bending (3-p-b) tests on rigid insulation tile (RIT) materials, with the aim of evaluating their fracture toughness across an extensive temperature range from 78 K to 1423 K. By accounting for temperature-dependent fiber spacing and inertial effects, we extend the boundary effect model (BEM) to dynamic loading conditions under high temperatures. The experimental results demonstrate a pronounced temperature dependence of the fracture toughness of RIT materials at various loading rates. Specifically, as the temperature decreases from 293 K to 78 K, the fracture toughness increases. Between 973 K and 1173 K, viscous flow and micro-crack self-healing contribute to a marked rise in fracture toughness. Around 1473 K, however, fiber compaction and softening lead to a significant reduction in toughness. Furthermore, the fracture toughness shows clear sensitivity to the loading rate, as reflected by distinct crack propagation patterns and fiber fracture mechanisms under different rates. These findings provide valuable insight into the thermomechanical behavior of RIT materials under extreme temperature and dynamic loading conditions.

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abst. 1067
**CIMA**
Wednesday
June 24
15h30

## A finite element model for the free vibration analysis of laminated beam-type structures

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In this paper, an improved finite element beam model for the free vibration analysis of laminated composite beam-type structures with thin-walled cross-sections is presented. The cross-sections are modeled as thin, symmetric and balanced angle-ply laminates. Based on the Hamiltonian principle and the kinetic energy of a thin-walled beam element, a consistent mass matrix is formulated and the associated eigenvalue problem is established. Hooke's law and a nonlinear displacement field of the thin-walled cross-section are incorporated to account for restrained warping and large rotation effects. The formulation employs the same shape functions as those used in the definition of stiffness matrix: linear interpolation functions for axial displacement, cubic Hermitian interpolation functions for transverse deflections and twist rotation and quadratic Hermitian interpolation functions for slopes and warping. The accuracy of the proposed model is evaluated through several numerical examples. The results show very good agreement with those reported in the literature, as well as with numerical results obtained using an NX Nastran shell-element model. These comparisons confirm the capability of the proposed approach to accurately predict the natural frequencies of thin-walled composite beam and frame structures.

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abst. 1074
**CIMA**
Wednesday
June 24
15h50

## Passive suppression of aeroelastic instability on composite panel in supersonic flow

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Aeroelastic panel flutter is a typical self-excited and self-sustained oscillation that can be potentially destructive to structural skin components in the supersonic regime, often leading to fatigue and failure. Recently, aeronautical structures have been redesigned to achieve more lightweight designs, which make

them prone to aeroelastic effects and more susceptible to fatigue from sustained oscillations. With this in mind, passive control devices are beneficial for dissipating energy and acting as safety mechanisms while not relying on external actuation sources. In this context, Nonlinear Energy Sinks (NES) are promising devices, exhibiting an inherently nonlinear coupling that enables passive vibration control under various excitation conditions, including supersonic panel flutter. Whereas NESs have been applied for panel flutter control, distributed NES configurations can enhance passive control performance by not relying on careful optimization of device positioning and tuning. This work proposes a conceptual study of multiple NES distributed on a composite panel subject to supersonic flow. The traditional cubic NES will be employed as a conceptual nonlinear dissipator, while a periodic array will be considered as a distribution strategy. Concerning the structural model, the originally two-dimensional simply-supported composite plate problem will be reduced to one dimension by considering an infinitely large width. Structural nonlinear behavior will be accounted for using the von Karman strain relation, which introduces stretching effects. The resulting equations of motion will then be discretized and numerically solved. The numeric characterization aims to understand the impact of NES distribution and its benefits compared to a single optimally positioned NES.

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## Tensile mechanical behavior of 2D-SiCf/SiC composites under coupled high-temperature and high-strain-rate loading

abst. 1128
**CIMA**
Wednesday
June 24
16h10

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The tensile mechanical behavior of two-dimensional plain-woven silicon carbide fiber-reinforced silicon carbide (2D-SiCf/SiC) composites was investigated over a wide temperature range (from room temperature to ultra-high temperature of 1600 °C) and a broad strain-rate range (from quasi-static 10-5 s-1 to dynamic 102 s-1). The experimental results demonstrate that both strain rate and temperature exert significant influences on the tensile response of 2D-SiCf/SiC composites, including stress–strain behavior, damage accumulation processes, fracture modes, and fiber pull-out length. Moreover, a certain degree of coupling between temperature and strain rate is observed in the tensile response mechanisms. The failure mechanisms were analyzed through in-situ and post-test microstructural observations, and the damage evolution process was elucidated using strain fields obtained by digital image correlation (DIC). In addition, the rate- and temperature-dependent behaviors of the constituent phases (fibers, matrix, and interface) were theoretically analyzed. A micromechanics-based constitutive model was employed to predict the stress–strain curves of the 2D-SiCf/SiC composites, thereby revealing the deformation mechanisms under coupled high-temperature and high-strain-rate conditions.

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## Dynamic Modelling and Vibration Characteristics Analysis of Composite Sandwich Cylindrical Shells

abst. 1216
**Repository**

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To fulfill the stringent requirements for weight savings and mechanical capabilities in aerospace and other critical engineering components, the deep integration of advanced composites into lightweight sandwich cylindrical shell structures emerges as a promising strategy. This study develops novel sandwich cylindrical shells featuring two three-dimensional four-directional braided composite skins and a pyramidal truss honeycomb core, and a theoretical dynamic model of the target structure under both free vibration and forced vibration conditions are proposed, which may serve as prediction and evaluation tools. The virtual spring technique is incorporated into the developed model to extend elastic

constraints and enable flexible switching between arbitrary boundary conditions. In the framework of the theoretical formulations constructed, explicit expressions for the effective mechanical properties of spatially knitted composite skins and cellular cores are derived. Afterwards, the first-order shear deformation shell theory and Jacobi-Ritz approach are utilized to deduce energy expressions, and the mode shapes, inherent frequencies, response amplitude, and decay signature are obtained by adopting the eigenparameter solutions and Newmark-Beta techniques. Compliant model parameters with low running costs and guaranteed calculation precision are given in convergence analyses, which pave the path for efficient data output and numerical calibration. After undertaking the model validation work, the impact laws of key variables on the dynamic indicators are released, with some contributions being made conducive to upgrading the vibration resistance capabilities.

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abst. 1251
**CIMA**
Wednesday
June 24
16h30

## Nonlinear Response of Composite Joint Structures under Thermo-Acoustic Loads

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To address the challenge of predicting the response of composite joint structures in aircraft operating under high-temperature and intense acoustic environments, a study was conducted on joint structure modeling and mechanical behavior based on parametric analysis methods. First, for a Chemical Vapor Infiltration (CVI) hybrid joint structure, a multi-degree-of-freedom Hybrid-Bonded/Bolted(HBB) model was used. The mechanical behavior of an adhesively bonded CVI–screw joint plate containing an interlayer was investigated under thermo-acoustic loading. Furthermore, a multi-degree-of-freedom Iwan joint model considering nonlinear stiffness and damping was developed for composite joint structures, enabling efficient dynamic response prediction of complex joint structures with group fasteners under thermo-acoustic loading. This research provides a method for predicting the response of composite joint structures in complex environments.

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abst. 1305
**CIMA**
Wednesday
June 24
16h50

## Parametric finite element investigation on the dynamic response of delaminated composite laminates

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Delamination is among the most critical and challenging damage mechanisms in laminated composite structures, especially in wind turbine rotor blade components and aircraft structural parts, as it significantly degrades stiffness and alters dynamic behavior while often remaining undetectable at the surface. This work presents a comprehensive numerical investigation of the vibration response of delaminated carbon-fiber-reinforced polymer (CFRP) laminates, with particular emphasis on the effect of delamination parameters on mode sensitivity and their implications for vibration-based structural health monitoring. A fully parametric finite-element framework has been developed to model predefined through-width delaminations of varying length and through-thickness location, while also considering the possibility of embedded delaminations. Delamination interfaces are represented using linear elastic cohesive zone models coupled with post-separation contact formulations to capture stiffness degradation, interface opening, and re-contact effects. Delamination growth is not modeled at this stage of the

study, and geometric parameters such as delamination length and width are systematically varied across all simulations. Linear modal analyses are conducted to establish baseline frequency shifts, complemented by investigations into the influence of geometric imperfections and in-plane axial preload. The results indicate that increasing delamination length generally leads to monotonic reductions in natural frequencies, with the magnitude of the reduction strongly dependent on mode number and delamination depth. Higher-order modes exhibit the largest fractional frequency drops, while the fundamental bending mode is most sensitive to mid-plane delaminations. Near-surface delaminations primarily affect higher modes due to localized curvature and interlaminar shear effects. Delamination width influences modal localization and mode ordering, whereas axial preload modifies baseline frequencies and can amplify stiffness loss for larger delaminations. In contrast, geometric imperfection amplitudes are observed to have only a minor effect on normalized frequencies. Based on the results obtained from the finite-element framework, an efficient energy-based semi-analytical model is also proposed for initial studies; however, further refinements are required to fully capture the observed behavior. Overall, the findings demonstrate that vibration-based modal indicators, when interpreted with consideration of mode number, delamination depth and width, and operational preload, provide a robust and physically meaningful basis for delamination detection and characterization in composite laminates. The study also provides insights to support future investigations into fatigue-induced delamination buckling and associated effects arising from prolonged nonlinear dynamic loading conditions.

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## Performance Assessment of Composite Sandwich Structures for Enhanced Passenger Passive Safety in Aircraft Seats through Numerical Simulations

abst. 1383
**CIMA**
Wednesday
June 24
17h10

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Sandwich structures with lattice-based cores, embedded within composite structural components and optimized for additive manufacturing, provide an effective solution for impact energy dissipation and passive safety improvement. By combining low weight and compact geometry with high energy absorption capability, these systems can be tailored to fit within existing composite assemblies and positioned in critical zones close to passengers. In the aerospace sector, such integrated composite sandwich structures may be incorporated into fuselage frames, interior panels, and seat architectures to enhance crashworthiness and mitigate risks during crash landings. This study focuses on the design and effectiveness evaluation of composite sandwich structures with lattice-based cores aimed at enhancing occupant safety in aircraft seating systems. Recognizing the critical importance of mitigating injury risks during impact events, the research positions these lattice-core sandwich systems as a key innovation, capable of significantly improving energy absorption and dissipation. The work is driven by the need for advanced protective solutions that can be effectively integrated into the confined and dynamic environment of aircraft cabins, where conventional safety measures may be insufficient. Several configurations of composite sandwich structures have been systematically investigated by varying both the lattice-based core microarchitecture and the choice of materials compatible with additive manufacturing (AM) processes. These variations aim to optimize the structural response and energy absorption capabilities of the sandwich system when integrated into aircraft seating assemblies. To this end, a Finite Element (FE) model of the aircraft seat, incorporating the composite sandwich structures in their different core configurations, was developed in LS-DYNA to simulate dynamic sled tests under controlled impact scenarios. An FE-based anthropomorphic test device (ATD) was included in the simulations to replicate forward-impact conditions against the front seat, enabling a detailed assessment of the energy dissipation performance of each sandwich configuration. Key metrics, such as the Head Injury Criterion (HIC), were employed to quantitatively evaluate passenger safety and the effectiveness of the composite sandwich structures in reducing injury risks. The study also explores the influence of core density, lattice topology, and face-sheet material properties on the overall impact response, providing insights into how different design choices affect energy absorption. The overarching objective of this work is to

identify the optimal composite sandwich structure configuration capable of maximizing passive safety for occupants. By combining advanced lattice-core designs with lightweight composite materials, these integrated structures not only offer superior energy dissipation but also can be tailored for strategic placement within seat systems and cabin components. This research highlights the potential of composite sandwich structures to serve as a transformative approach for improving crashworthiness in the confined and dynamic environment of business jet cabins, where conventional safety solutions may be limited.

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abst. 1398
**CIMA**
Wednesday
June 24
17h30

## Experimental Investigation of Thermally Dependent Nonlinear Dynamics in a Bimetallic Beam

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This study presents a comprehensive experimental investigation of the temperature-dependent nonlinear dynamics of a bi-metallic beam composed of aluminum alloy and copper layers joined by explosive welding. The focus is placed on the coupled influence of thermal loading, material heterogeneity, geometric nonlinearity, and damping evolution on structural stability and vibration characteristics. While thermal buckling and vibration of beams have been extensively addressed through analytical and numerical approaches, experimental studies capable of capturing the combined effects of thermal stresses, large deflections, nonlinear stiffness, and temperature-dependent dissipation—particularly across the buckling transition—remain limited. To fill this gap, an extensive experimental campaign was carried out using impact hammer testing, random excitation, and stepped-sine base excitation. The beam was mounted on an electrodynamic shaking table and tested inside a controlled climate chamber, enabling precise regulation of the environmental temperature over the range 5°C–70°C. This setup allowed the identification of modal parameters and nonlinear frequency–response curves under large-amplitude vibrations and varying thermal conditions. The experimental results reveal a pronounced and non-monotonic evolution of the fundamental natural frequency with temperature. As the temperature increases toward the critical buckling threshold (approximately 30°C), the fundamental frequency progressively decreases, exhibiting a total reduction of nearly 32% due to thermally induced compressive stresses and stiffness softening. Beyond the critical temperature, in the post-buckling regime, the frequency partially recovers as geometric stiffening effects become dominant. This transition clearly highlights the interplay between thermal stress softening and post-buckling structural reconfiguration. The damping ratio shows an opposite trend, increasing significantly as the beam approaches instability and reaching a maximum value of approximately 3.5% around 35°C. This behavior suggests enhanced energy dissipation mechanisms near the buckling condition, potentially associated with micro-slip at the material interface and nonlinear strain distribution. For comparison purposes, a uniform aluminum beam was also tested under identical thermal conditions to isolate the effects of material coupling and differential thermal expansion. The comparison confirms that the complex dynamic behavior observed in the bi-metallic configuration is primarily governed by the mismatch in thermal expansion coefficients and the resulting internal stress redistribution. At the buckling threshold, nonlinear frequency–response curves exhibit a clear softening-to-hardening transition, indicating a change in the effective nonlinear stiffness as the structure evolves from pre-buckled to post-buckled configurations. This transition is consistently observed across different excitation levels and represents a key experimental evidence of temperature-driven nonlinear stiffness modulation. Overall, the results provide new experimental insights into the thermal dependence of nonlinear vibrations in layered metallic structures. The findings contribute to a deeper understanding of stability-driven dynamic phenomena and offer valuable guidelines for the design, reliability assessment, and performance optimization of thermally loaded multi-material components commonly employed in aerospace, mechanical, and energy systems. The authors acknowledge the support by NATO grant SPS program, project G6176 "Composite Metamaterials for Aerospace Structures – CoMetA".

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## Experimental Study of Thermally Induced Nonlinear Vibrations in a Bio-Inspired Metamaterial Beam

abst. 1400
**CIMA**
Wednesday
June 24
17h50

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This study presents a comprehensive experimental investigation of the temperature-dependent nonlinear dynamics of a bio-inspired metamaterial beam featuring an architected internal layout designed to emulate natural compliant–stiff hierarchical systems. The focus is placed on the coupled influence of thermal loading, architectural heterogeneity, geometric nonlinearity, and temperature-driven dissipation on structural stability and vibration characteristics. While thermally induced buckling and nonlinear vibration of beams have been widely explored through analytical and numerical methods, experimental studies able to describe the combined effects of thermal stresses, large deflections, amplitude-dependent stiffness, and evolving damping—especially across thermally triggered stability transitions in architected metamaterials—remain limited. To address this gap, an extensive experimental campaign was conducted using impact hammer testing, broadband random excitation, and stepped-sine base excitation. The specimen was mounted on an electrodynamic shaker and tested inside a controlled climate chamber, enabling precise regulation of the ambient temperature over the range 5°C–70°C. This setup allowed robust identification of modal parameters and nonlinear frequency–response curves under large-amplitude oscillations and varying thermal conditions. The experimental results reveal a pronounced and non-monotonic evolution of the fundamental natural frequency with temperature, governed by the competition between thermally induced stress states and architecture-enabled reconfiguration mechanisms. As temperature increases toward a critical instability threshold, the fundamental frequency progressively decreases, exhibiting a total reduction of nearly 30% due to effective stiffness softening driven by thermally activated compliance in the micro-architecture (e.g., strut bending, cell-wall rotation, or programmed ligament deformation) and compressive pre-stress buildup. Beyond the critical temperature, in the post-instability regime, the frequency partially recovers as the metamaterial transitions into a reconfigured load path where geometric stiffening and engagement of secondary structural members become dominant. This transition highlights the interplay between thermal softening at the unit-cell level and post-buckling structural rearrangement at the macroscale, a hallmark of bio-inspired architected systems. The damping ratio exhibits an opposite trend, increasing markedly as the structure approaches instability and reaching a maximum value of approximately 3.5% around 35°C. This behavior indicates enhanced energy dissipation near the transition, plausibly linked to frictional micro-interactions, local contact events between architectural features, viscoelastic contributions (if polymeric or hybrid constituents are present), and spatially non-uniform strain localization intrinsic to bio-inspired layouts. For comparison, a geometrically equivalent uniform beam (without internal architecture) was tested under identical thermal conditions to isolate the effects of metamaterial architecture from baseline material behavior. The comparison confirms that the complex dynamic response in the bio-inspired metamaterial configuration is primarily governed by temperature-mediated architectural mechanisms—including internal stress redistribution, constraint activation, and unit-cell deformation mode switching—rather than by homogeneous material softening alone. Near the critical temperature, nonlinear frequency–response curves show a clear softening-to-hardening transition, indicating a change in the effective nonlinear stiffness as the system evolves from a pre-instability regime dominated by compliant architectural modes to a post-instability regime where geometric constraints and engaged members introduce a hardening backbone. This transition is consistently observed across excitation levels and provides key experimental evidence of temperature-driven nonlinear stiffness modulation enabled by bio-inspired metamaterial design. Overall, the results offer new experimental insights into the thermal dependence of nonlinear vibrations in architected bio-inspired structures. The findings advance the understanding of stability-driven dynamic phenomena in metamaterials and provide practical guidance for the design, reliability assessment, and performance optimization of thermally exposed, vibration-sensitive components in aerospace, mechanical, and energy applications. The authors acknowledge the support by NATO grant SPS program, project G6176 "Composite Metamaterials for Aerospace Structures – CoMetA".

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## Experimental Methods

abst. 1027
**TIGELLIO**
Thursday
June 25
15h10

### Mechanical Performance Assessment of Sustainable Composites for Electric Two-Wheeler Chassis Applications

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The accelerating shift toward electric mobility has intensified the need for sustainable engineering materials capable of combining high mechanical performance with a reduced environmental footprint. Lightweight composite structures are essential in electric vehicle design, as they lower overall mass, extend driving range, and enhance energy efficiency. Within this context, natural-fiber-reinforced composites are emerging as compelling alternatives to traditional synthetic reinforcements such as carbon or glass fibers. Their renewability, reduced embodied energy, and interesting specific properties position them as promising candidates for next-generation vehicle components. This study evaluates the mechanical performance of environmentally conscious biaxial non-crimp fabric composites intended for integration into the chassis of two-wheeled electric vehicles. Three fiber systems, carbon, linen, and glass, were combined with appropriate resin matrices to manufacture structural laminates. A comprehensive mechanical characterization program was carried out following ISO standards, assessing tensile, compressive, shear, and flexural responses. Key parameters analyzed include tensile strength, elastic modulus, Poisson's ratio, strain at failure, and overall stiffness behavior. Results show that carbon-fiber composites, manufactured with a synthetic epoxy resin, deliver the highest structural performance, reaching a tensile strength of 1126 MPa and exhibiting superior stiffness. Linen-reinforced laminates, although presenting a lower tensile strength of 102 MPa, demonstrated the largest strain at rupture, revealing a notably ductile behavior advantageous for impact-tolerant components. Glass-fiber composites displayed 351 MPa tensile strength, a cost-strength compromise economic solution, maintaining moderate elasticity and acceptable failure strain, confirming their relevance in cost-sensitive designs. The work forms part of a broader initiative aimed at developing a next-generation smart electric scooter with an emphasis on eco-efficient materials and innovative structural concepts. Beyond durability and lightweighting, the project prioritizes aesthetic value and the integration of low-impact or recycled constituents. The mechanical data gathered in this study will support advanced numerical simulations and optimization procedures for the vehicle frame, enabling a design that balances sustainability, safety, and visual appeal. Funding: This work was developed in the scope of the Project AM2R – Agenda Mobilizadora para a inovação empresarial do setor das Duas Rodas" [C644866475-00000012 – project n. 15], financed by PRR – Recovery and Resilience Plan under the Next Generation EU from the European Union, and has laboratory support of the Centre for Mechanical Technology and Automation (TEMA).

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abst. 1053
**TIGELLIO**
Thursday
June 25
15h30

### Linen composites in the development of a new lightweight bike – mechanical testing

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The growing demand for sustainable and lightweight bicycles has intensified interest in natural fibre–reinforced composites as alternatives to conventional metallic and synthetic composite materials. Among these, linen (flax) fibre composites offer a compelling balance between low density, renewable sourcing, and favourable mechanical compliance. This study investigates the mechanical behaviour of biaxial non-crimp fabric (NCF) linen composites intended for the structural and semi-structural components of a new lightweight bicycle frame. Vacuum-infused $\pm 45^\circ$ and [0°,90°] linen NCF laminates were manufactured using a partially bio-based epoxy system and post-cured under industrially relevant conditions. Mechanical characterization was conducted following international standards, including tensile

(ISO 527-4), flexural (ISO 14125), compressive (ISO 14126), and in-plane shear (ISO 14129) testing. Full-field strain measurements were obtained using 3D Digital Image Correlation to capture strain mechanisms and failure modes. The results demonstrate that linen composites exhibit moderate strength and stiffness but good deformation capability. Tensile strengths around 100 MPa and compressive strengths near 75 MPa were measured, accompanied by low elastic moduli ( 6 GPa in tension and compression). In contrast to their limited load-bearing capacity, linen laminates sustained significantly higher failure strains, reaching approximately 2% in tension, over 4.5% in compression, and shear strains exceeding 5%. Flexural tests further revealed large deflections at failure, highlighting strong energy-absorption potential. These characteristics make linen composites attractive for bicycle applications where vibration damping, impact tolerance, and rider comfort are critical, such as rear stays, forks, or integrated energy-absorbing zones. While not intended to replace high-stiffness materials in primary load paths, linen NCF composites provide a sustainable solution for non-critical structural components, supporting weight reduction and reduced environmental impact in next-generation lightweight bicycle design.
Funding: This work was developed in the scope of the Project AM2R – Agenda Mobilizadora para a inovação empresarial do setor das Duas Rodas" [C644866475-00000012 – project n. 15], financed by PRR – Recovery and Resilience Plan under the Next Generation EU from the European Union, and has laboratory support of the Centre for Mechanical Technology and Automation (TEMA).

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## Corrosion effect on axial compressive behaviour of additively and conventionally manufactured CFRP tubes

abst. 1058
**TIGELLIO**
Thursday
June 25
15h50

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This study examines the effect of seawater exposure on the crashworthiness of conventionally manufactured and additively manufactured (AM) carbon fiber-reinforced polymer (CFRP) composite tubes under quasi-static compression. CFRP composites are widely used in marine structures due to their high strength-to-weight ratio and inherent corrosion resistance; however, prolonged exposure to harsh marine environments can alter their mechanical response. To assess these effects, quasi-static crushing tests were conducted on composite tubes after one month of immersion in natural seawater. The specimens were fabricated using both conventional hand lay-up and additive manufacturing (3D printing) techniques, enabling a direct comparison between the production methods. Analysis of the compression behavior revealed a pronounced reduction in maximum crushing force following seawater exposure, particularly in AM specimens. In contrast, hand lay-up composites demonstrated greater retention of structural integrity. The findings provide valuable insight into the mechanical behavior of CFRP composites in marine environments and offer guidance in the introduction of AM composite-based maritime structures.

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## Mechanical Characterization, Analysis, and Modeling of FRP under Quasi-static and Fatigue Loading Conditions

abst. 1192
**TIGELLIO**
Thursday
June 25
16h10

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The contribution presents a methodology for fatigue lifetime prediction of Glass Fiber Reinforced Polymer (GFRP) composite laminates in multiple stacking configurations. Besides mechanical characterization under quasi-static loading, the investigations include examination under cyclic fatigue tension-tension loading which are of vital importance for the desired applications for future use in e.g. automotive. The optical investigations presented include the use of a machine vision camera for image analysis and image processing. The aim is an automated feature extraction of GFRP using optical non-destructive damage detection based on computer vision for pattern recognition, instead tedious by-eye measurement. The experimental and data-driven analytical investigations and - Advanced data reduction are accompanied by analytical modeling. Based on the quasi-static behavior approaches for

predictions of the performance of FRP under cyclic loading are presented. Lifetime prediction of GFRP under fatigue loading is carried out using the results from the optical investigations under quasi-static loading. A quantification of stiffness degradation via a deduction of three different types of modulus is provided for fatigue loading.

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abst. 1197
**TIGELLIO**
Thursday
June 25
16h30

## An innovative methodology for the gigacycle fatigue characterization of composite materials under biaxial loads

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The mechanical characterization under multiaxial loading conditions, typically encountered in real-world applications, requires dedicated methodologies and setups. In the literature, tubular specimens are usually employed for combining axial and torsional loads, while the material response under biaxial in-plane loads is assessed through cruciform specimens. In the case of composite materials, the biaxial fatigue characterization is of particular interest. However, this is severely limited to tension-tension tests, as compressive loads likely induce the inelastic buckling response. Moreover, the fatigue characterization is still limited to the High Cycle Fatigue (HCF) regime. In this work, we propose an innovative methodology for the gigacycle fatigue characterization of composite materials under biaxial loads. To accelerate the fatigue test and investigate the Very High Cycle Fatigue (VHCF) response, an ultrasonic testing setup is adopted. In this setup, all the components resonate at 20 kHz according to the longitudinal mode. A piezoelectric transducer converts the electric signal provided by a generator into a mechanical vibration, which is then amplified by a booster and a horn. For the specimen design, a cruciform geometry is selected to enable in-plane biaxial excitation at resonance. A quasi-isotropic GFRP laminate manufactured from unidirectional prepreg is here adopted, whose material properties are initially identified through the Impulse Excitation Technique (IET). An optimization process based on Finite Element (FE) modal analyses is here proposed for the specimen design which aims at maximizing the in-plane stress amplitude and at ensuring frequency isolation of the target mode. The first advantage of the technique is that, during the test, the specimen vibrates at 20 kHz, thus allowing the investigation of the VHCF response in reasonable testing duration. Secondly, by vibrating according to its biaxial longitudinal mode, the methodology allows to perform fully reversed fatigue test without the occurrence of buckling. Finally, the ratio between the axial stresses along the two perpendicular directions of the specimen arms can be tuned by modifying the specimen geometry. As such, a unique setup can be used to investigate different loading conditions. Optimal specimens are identified for different stress ratios and validated by comparing the displacement fields measured in the ultrasonic test through a high-speed camera and computed in the FE analysis. The agreement between the experimental and numerical results confirmed the effectiveness of the design strategy and of the proposed ultrasonic methodology for biaxial fatigue tests of composites.

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abst. 1270
**TIGELLIO**
Thursday
June 25
16h50

## Experimental and Machine Learning Prediction of Springback in Brass Alloy Sheet Metal V-Bending

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In this study, springback is investigated in v-bending for yellow brass material (UNS C27000 brass). The investigation of the springback will consider three parameters. The selected parameters to be varying will be the thickness of sheet metal (1.5, 3 and 5mm), the die opening (22 and 35mm), and the punch

holding time (0 5 and 10 seconds) and all the other parameters will remain constant like the die angle and punch angle (85°). A full factorial multilevel DOE method is used to conduct the experimental test. Experimental investigation results are compared with machine learning prediction methods. ANN and SVM methods are used to predict the springback. The analysis of the result done with ANOVA showed interesting facts. The Pareto chart reveals that in comparison with the two other parameters, the sheet thickness has the highest significant effect on the springback and the die opening has the lowest significant effect. In overall the metal behaved approximately like the other metals because the springback decreased when the die opening increased and also when the holding time increased, and also when the sheet thickness increased. However, the brass material went in contradiction with the previous researches on the 3mm sheet thickness.

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## Thermal Conductivity Enhancement of Cu Nanoparticle Coatings by Intense Pulsed Light Sintering Evaluated Using a TPS Stacking Method

abst. 1405
**TIGELLIO**
Thursday
June 25
17h10

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Due to the continuous miniaturization and increasing power density of power modules and portable electronic devices, efficient thermal management has become a critical factor for ensuring device reliability. In particular, thermal conductive coatings applied to components such as chips and modules play an important role in spreading and dissipating generated heat. When a coating layer is fabricated using nanoparticle (NP) ink, close interconnection between NPs forms continuous heat flow paths within the coating. Metal NPs exhibit rapid and efficient heat transfer through free-electron conduction and electron–phonon coupling. Therefore, accurate evaluation of the thermal conductivity of NP-based coating layers is essential for effective thermal management design. However, coating layers composed of NPs generally possess mechanical weakness and cannot be easily fabricated as freestanding films. As a result, the measured thermal conductivity is significantly affected by the substrate thermal interference. To overcome this limitation, this study employed a transient plane source (TPS) method with a stacking configuration to minimize the influence of the substrate and evaluate the effective thermal conductivity of the coating layer. For the experiment, Cu NP paste was screen-printed onto a glass substrate to form a coating layer with a thickness of a few micrometers. The coating layer was then subjected to intense pulsed light (IPL) irradiation with an energy density ranging from 7.42 to 34.38 J $cm^2$. To measure thermal conductivity using the TPS method, a four-layer stacked structure composed of alternating glass substrates and Cu NP coating layers was prepared. The experimental results showed that the thermal conductivity of the coating layer increased by up to 93.5% compared with the non-irradiated coating. This improvement is attributed to the photothermal effect during IPL irradiation, where absorbed light energy is converted into heat, leading to the volatilization of organic binders and enhanced interparticle necking between Cu NPs, which forms continuous conductive pathways. Based on the experimental correlation between IPL energy density and thermal conductivity, the proposed approach provides a basis for estimating coating thermal conductivity under different annealing conditions. This provides a practical guideline for designing coating layers that meet various heat dissipation performance requirements in electronic devices.

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## FRP reinforced structures

abst. 1009
**SANT'EFISIO**
Thursday
June 25
16h10

### Revolutionising offshore wind: FRP-Reinforced concrete foundations for floating turbines

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Offshore floating wind turbines (FOWTs) are emerging as a key technology for harnessing deep-sea wind resources, yet their conventional steel foundations suffer from severe corrosion, fatigue, and high maintenance costs. Recent advances in fiber-reinforced polymer (FRP) reinforced ultra-high-performance concrete (UHPC) – termed FRU composites – offer a durable and sustainable alternative. FRU composites combine the ultra-high compressive strength and durability of UHPC with the tensile capacity and corrosion resistance of FRP reinforcement, eliminating the need for steel in aggressive marine environments. This paper presents development and comparative studies of FRU for marine construction, as well as hydrostatic and hydrodynamic performance of FRU versus steel foundations for 10 MW floating wind turbines. Results demonstrate that FRU is excellent in mechanical properties and durability under marine environemnt, and the foundations exhibit lower centers of gravity, improved resistance to overturning, and reduced surge and pitch responses under coupled wind-wave-current conditions. These improvements not only enhance structural stability and energy efficiency but also significantly reduce lifecycle costs. The paper also discusses durability assessments, design methodologies, and pathways for industrial adoption of FRU-based floating foundations towards carbon reduction, highlighting their potential to revolutionize offshore renewable energy infrastructure.

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abst. 1106
**Repository**

### Machine-learning–guided interpretable development of explicit bond strength equations for FRP–UHPC systems across different design codes

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Accurate prediction of bond strength between fibre-reinforced polymer (FRP) bars and ultra-high-performance concrete (UHPC) is critical for the design reliability and durability of high-performance composite structures. Existing design provisions in major standards, such as the American Concrete Institute (ACI) 440.1R-15 and the Canadian Standards Association (CSA) S806, employ distinct equation formats, including additive and multiplicative formulations, yet both rely largely on simplified empirical assumptions that struggle to represent the nonlinear and threshold-dependent bond behaviour observed in FRP–UHPC systems. This study proposes a unified machine learning (ML)-guided framework for developing interpretable and code-compatible explicit bond strength equations applicable to different design code structures. A comprehensive database comprising 290 pullout test results of glass fibre-reinforced polymer (GFRP) bars embedded in UHPC is established, covering key geometric and material parameters, including cover-to-diameter ratio, bonded-length-to-diameter ratio, rib-height-to-diameter ratio, and concrete compressive strength. Random Forest and XGBoost models are trained to capture complex nonlinear interactions, and SHapley Additive exPlanations (SHAP) are employed to decompose ML predictions into parameter-wise contributions with clear physical meaning. For additive code formats such as ACI 440.1R, SHAP contributions are directly fitted using physically interpretable nonlinear functions, including saturation, exponential-decay, and extreme-type relationships, and integrated into an ACI-style additive equation. For multiplicative code formats such as CSA S806, a logarithmic mapping strategy is introduced to transform multiplicative modification factors into an additive explanatory space, enabling SHAP-based interpretation and subsequent reconstruction of explicit factor expressions through exponential mapping. The resulting ML-guided equations significantly outperform their original code counterparts, achieving $R^2$ values up to 0.84 for the ACI-type formulation and 0.86 for the CSA-type formulation, while preserving transparency and explicit calculability. Parametric analyses further demonstrate the ability of the proposed equations to capture nonlinear confinement effects, load-transfer mechanisms, and mechanical interlock behaviour that are overlooked by conventional linear or empirical models. Overall, this study establishes a general and extensible ML-guided paradigm for embedding

explainable artificial intelligence into diverse code-format design equations, providing a robust pathway toward intelligent, interpretable, and standardised bond strength formulations for FRP–UHPC and other next-generation composite systems.

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## Out-of-plane bending behaviour of CLT panels reinforced with GFRP bars in tension zone

abst. 1146
**SANT'EFISIO**
Thursday
June 25
16h30

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Cross laminated timber (CLT) is relatively new engineering timber composite product made by gluing orthogonally oriented layers of solid timber boards (laminations), thus forming large-scale panels. CLT panels are usually fabricated with an odd number of layers (typically three, five or seven layers) indicating dominant bearing direction. Having both in- and out-of-plane resistance, CLT panels can be used either as wall, floor, roof or stairs elements. They present an efficient and sustainable alternative solution to more traditional construction materials for single- and multi-storey buildings. Integration of various materials with timber is frequently used to enhance mechanical performance and reliability of timber structures. Advanced composite materials, such as fibre reinforced polymers (FRP), can be used as reinforcement for these purposes, as they have many important advantages (low weight, high mechanical properties, easy installation, high durability). Previous studies have proven good compatibility and complementarity of characteristics between FRP and both solid timber and glulam. This research aims to assess the feasibility of employing glass fibre reinforced polymer (GFRP) bars as reinforcement for cross laminated timber (CLT) panels. Experimental research included bending tests of unreinforced (control) CLT panels and CLT panels reinforced with GFRP bars in tension zone. A total of 15 panels were tested – five unreinforced CLT panels (Series A), five CLT panels reinforced with three GFRP bars (Series B) and five CLT panels reinforced with six GFRP bars (Series C) in tension zone. All CLT panels were made of softwood (spruce) classified in the strength class C24 according to EN 338. CLT panels had a length of 440 cm, width of 50 cm and thickness of 15 cm. Panels consisted of five 3 cm thick layers. GFRP bars with a nominal diameter of 12 mm were placed along the near-surface grooves that were cut into panels along their entire length. In that way, reinforcement was hidden and protected by the surrounding wood. Epoxy adhesive was used to bond GFRP bars. Reinforcement was symmetrically distributed in the outer longitudinal layer in tension zone using a relatively small amount of composite material with reinforcement percentage of 0.45% for Series B and 0.90% for Series C. All specimens were tested in out-of-plane bending until failure as simply supported beams with a span of 420 cm symmetrically loaded with two concentrated forces at a distance of 90 cm, in accordance with EN 16351. The bending tests were performed in the main bearing direction of CLT panels. The bending behaviour of reinforced CLT panels was compared with unreinforced CLT panels regarding failure modes, load-deflection relationship, load-carrying capacity and bending stiffness. Unreinforced panels showed linear-elastic behaviour until the brittle tensile failure in bottom layers. GFRP reinforcement had a big influence on bending performance and global behaviour of CLT panels. Behaviour of reinforced panels was linear-elastic until the appearance of local damages caused by wooden knots or finger joints in the outer longitudinal layer in tension zone. Activation of GFRP bars caused nonlinear load-deflection behaviour for both reinforced series that ended with tensile failure of timber. Although reinforcement cannot prevent initial opening of cracks, it can limit their further propagation. Improvement in load-carrying capacity and bending stiffness of reinforced over unreinforced panels was evident. Compared to unreinforced panels, ultimate load was increased by approximately 10% for Series B and 27% for Series C. Increase in bending stiffness was around 7% and 12% for Series B and C, respectively, compared to Series A. Sign of plastification in timber in the compression zone was observed in panels with higher reinforcement percentage (Series C). Proposed reinforcement technique is quite easy to implement, achieving excellent bond quality between CLT and GFRP bars using epoxy adhesive. Reinforcing panels in the tension zone allows efficient use of nonlinear compressive characteristics of timber and introduces nonlinearity into the global behaviour of panels which enables less brittle failure compared to the unreinforced panels. Reinforcement significantly improves load carrying capacity, stiffness and ductility

of CLT panels. Varying percentage and arrangement of reinforcement can optimise performance of CLT panels.

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abst. 1165
SANT'EFISIO
Thursday
June 25
16h50

## The influence of orientation and reinforcement basis weight on the strength and performance properties of CFRP laminates and their joints

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Carbon fibre reinforced polymer composites are key structural materials in modern aviation due to their favorable strength-to-weight ratio, high stiffness and resistance to corrosion and fatigue. CFRP applications include both primary structural elements of airframes and secondary components, where mechanical properties, durability, and the ability to integrate with other materials are also significant. One of the important design issues remains the joining of composite elements. Despite the dynamic development of bonding techniques, mechanical joints, in particular screw joints, are still widely used in aerospace structures due to their disassembly, technical condition control, and predictability of failure mechanisms. The mechanical properties of CFRP laminates are characterised by strong anisotropy, due to the orientation of the fibres and the reinforcement architecture. The layer arrangement determines the distribution of stiffness and load-bearing capacity in different load directions and influences the mechanisms of damage initiation and propagation. The basis weight of the fabrics determines the volume fraction of the fibres, the thickness of the layers and the ability of the laminate to transfer static and dynamic loads, which is particularly important in the area of holes and mechanical joints. The aim of the research is to assess the influence of fibre orientation and the basis weight of reinforcing fabrics on the strength and performance properties of CFRP laminates and their bolted joints. Laminates with different layer arrangements (including [0/90], [±30] and [±45]) and weights ranging from 90 to 160 g/m². The results of the research show that quasi-isotropic materials are more suitable due to the significant deterioration of the mechanical properties of orthotropic composites outside the direction of the reinforcement fibres. The results indicate that the use of reinforcement with a higher weight leads to a significant increase in the Young's modulus and tensile strength of the laminate, and the scale of this effect is strongly dependent on the architecture of the layer arrangement. The load-bearing capacity of bolted joints in the case of composites reinforced with higher-weight fabric was twice as high, with a significant influence of fibre orientation on the dominant failure mechanism and fatigue life of the joints.

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abst. 1215
SANT'EFISIO
Thursday
June 25
17h10

## Long-term durability of GFRP rebars in the alkaline environment under sustained loading using machine learning and empirical modelling

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The use fiber-reinforced polymer (FRP) bars to reinforce concrete offers an effective way to eliminate steel-corrosion problems owing to the material's inherent corrosion resistance. While the alkaline durability of glass-FRP (GFRP) reinforcement has been widely investigated, most studies have overlooked the simultaneous effect of sustained loading. This research exam-ines the synergistic effects of sustained loading and alkaline degradation on the mechanical re-sponse of GFRP rebars. Two GFRP rebars (Epoxy/vinyl ester-based) were considered: bare bars and concrete-embedded bars, immersed in an alkaline medium. A total of 308 tensile-tested specimens were averaged to obtain 107 datasets. Eleven input parameters were used to evaluate the degradation process. To forecast long-term performance, an XGBoost machine learning model was developed to predict residual tensile strength, enabling the calculation of an envi-ronmental reduction factor (CE). SHAP analysis of the model corroborated

experimental find-ings, identifying a two-stage degradation process: an initial rapid loss of strength, followed by a more gradual decline. The study further established that sustained loading only becomes detri-mental when it exceeds 20% of the rebar's ultimate strength. Finally, a predictive mathematical model was formulated by integrating SHAP values with multiple linear regression, and a comparative analysis of different environmental reduction factor approaches is provided.

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## A Unified Fracture Mechanics Framework for the Life Cycle Performance of RC Elements with Prestressed FRP

abst. 1297
**SANT'EFISIO**
Thursday
June 25
15h10

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The structural performance of reinforced concrete (RC) members strengthened with fibre reinforced polymers (FRP) is primarily governed by the stress transfer mechanisms at the composite-to-concrete interface. While the application of prestressed CFRP laminates effectively enhances serviceability by delaying crack initiation, it necessitates a rigorous accounting for bond stiffness degradation and anchorage zone stability. Current design approaches often rely on isolated models for bond and flexure, which may fail to capture the complex interaction between interface slip and macro-cracking. This work presents a unified analytical framework based on fracture mechanics to evaluate the life cycle performance of RC elements strengthened with prestressed FRP. The methodology integrates the non-linear behaviour of the bond-slip interface with the flexural response of the normal section. A key feature of the proposed framework is its versatility; it employs universal bond representations that remain valid for both externally bonded (EB) and near-surface mounted (NSM) reinforcement layouts. The framework enables a continuous assessment of the structural state through four distinct stages: (i) evaluation of bond strength and the non-linear reduction of interface stiffness; (ii) crack development and spacing analysis in the normal section under prestressing effects; (iii) the complete moment-curvature and moment-deflection response up to ultimate limit state; and (iv) the mechanical analysis of anchorage-related debonding. By coupling the fracture mechanics of the concrete substrate with the constitutive laws of the FRP-concrete joint, the model provides a consistent prediction of crack widths and deflections. The validity of the framework is demonstrated through comparison with experimental data, showing high correlation across varying prestressing levels and strengthening configurations. The results provide a mechanics-based foundation for the selection of optimal strengthening strategies and support the implementation of advanced anchoring systems. This unified approach facilitates the transition from empirical design to a more robust, performance-based evaluation of FRP reinforced structures.

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## Research progress on behavior of tubular joints strengthened with CFRP sheets and engineering application

abst. 1365
**SANT'EFISIO**
Thursday
June 25
15h30

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Welded truss joints made of circular hollow section (CHS) sometimes require reinforcement due to certain reasons which causes insufficient load-bearing capacity. Compared to a traditional method of

welding steel plates, the reinforcement method using carbon fiber reinforced polymer (CFRP) sheets has significant advantages. This paper presents the current research progress on behavior of tubular joints strengthened with CFRP sheets and engineering application. First, the method and procedure of strengthening CHS joints with CFRP sheets are demonstrated. Second, the behavior of CFRP-strengthened CHS K-joints is described, including static tests, failure modes, ultimate loading capacity, ductility, parametric study by means of finite element analysis and design formulas of loading capacity. Third, the investigation on engineering application in CFRP-strengthened CHS joints of a sports stadium is presented, dealing with the tests such as behavior of CHS K'T and K'TT joints strengthened with CFRP sheets, shear strength of adhesives at different temperatures, influence of coatings on bonding strength of adhesives and bonding strength of fire coatings-CFRP. Finally, the ongoing research topics about durability of CHS joints strengthened with CFRP sheets are outlined, including fatigue behavior under cyclic loading and adhesive property subjected to atmospheric corrosion.

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abst. 1379
**SANT'EFISIO**
Thursday
June 25
15h50

## Parametric design, FEA and progressive damage modelling for composite pressure vessels

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Projected growth in the use of gaseous hydrogen in automotive and aerospace applications is driving new developments in fuel storage solutions. Composite pressure vessels offer an exceptional strength-to-weight ratio; however, despite the significant number of previous studies, widely used modelling and analysis methods still exhibit notable limitations due to complexities arising from the filament winding process. In the present study, a novel modelling approach is outlined that provides multiple advantages in terms of accurate geometrical description of filament-wound composite cylinders for finite element analysis, such as consideration of winding band undulations and realistic thickness buildup. The filament-wound geometry algorithm is developed using a computational design framework to generate data for use in the finite element code Ansys. Based on design inputs — mandrel shape, winding angles, bandwidth, and thickness of the towpreg — the algorithm constructs the full 3D winding geometry, including the width of winding bands. Subsequently, the winding angle gradient can be calculated in zones with changing mandrel curvature. By analyzing groups of individual winding passes, winding band crossover zones can be identified. These zones correspond to triangular regions with alternating winding directions ($\pm$) in the FE model. The overlap and stacking of winding bands are analyzed over the surface of the pressure vessel to calculate realistic thickness variations along the section. This approach yields improved results compared to traditional methods and agrees well with thickness predictions reported in recent studies. High-accuracy data on fiber orientation and thickness are then mapped onto a finite element mesh. The model employs an orthotropic composite formulation based on classical laminate theory, accompanied by Hashin and Puck failure criteria, a post-failure material property degradation model, and a bilinear elastoplastic model for the aluminum boss and/or liner. The approach has been validated against several previous studies, demonstrating good predictions of stiffness, stress distribution, damage progression, and ultimate burst pressure. The stress distribution reveals a notable effect of winding band undulation that has not been observed in previous studies. In several cases, the predicted damage location and characteristics correspond well with experimental observations from multiple studies. Therefore, detailed representation of damage initiation and evolution is obtained, enabling identification of the mechanisms leading to pressure vessel failure. A data processing procedure has also been proposed to identify damage based on strain data, replicating actual measurements obtained using electromechanical strain sensors. Strain normalization with respect to pressure is performed by obtaining pressure–strain (flexibility) coefficients. Using these coefficients, strain can be predicted based solely on internal pressure and compared with the simulated strain from the FE model. The strain and differential strain (with respect to pressure) are then correlated with a damage variable. Damage initiation is associated with divergence between predicted and simulated strain curves and can be effectively used as a damage indicator, particularly because it is applicable to both short and long load cycles. This approach shows strong potential for further development in damage localization and higher-level analysis within a structural health monitoring framework.

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## Functionally graded and porous materials and structures

### Mechanism of Mechanical Properties of Continuous Fiber Composites Enhanced by Gel-Polymer (PVA-PP) Biphasic Discrete Interface for Functionally Integrated Structures

abst. 1099
**RIVA**
Thursday
June 25
15h10

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This study addresses biphasic semi-solid electrolytes for continuous fiber-reinforced energy storage applications, focusing specifically on the strength-toughness relationship in continuous carbon fiber-reinforced biphasic gel-polymer (PVA/PP) composites. By investigating interfacial mechanical behavior within the biphasic system, a shear-lag theoretical model incorporating discrete biphasic interfacial architecture was established. The model analyzes a regular representative volume element (RVE) comprising continuous carbon fibers embedded in a biphasic gel-polymer matrix, wherein the interfacial layer is characterized as discrete alternating units of elastoplastic resin and ideal elastoplastic hydrogel phases; analytical solutions for stress and displacement were derived. Utilizing the model's effective stress-strain relationship, systematic analysis evaluated composite properties including load-transfer efficiency, ultimate strength, and fracture toughness. Results demonstrate that under fiber-direction tension, the designed discrete biphasic interface maintains high stress-transfer efficiency while significantly enhancing material toughness, thereby achieving an optimum strength-toughness balance. Nevertheless, this toughening effect gradually diminishes as fiber fracture (length reduction) progresses during tensile deformation. Experimental results further validated the model's accuracy. This model elucidates the interfacial reinforcement mechanism of biphasic systems in continuous fiber composites, providing a theoretical basis for designing structural-functional integrated composites with concurrent high strength and high toughness.

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### Effects of Functionally Graded Nitrided Layer on the Structural Performance of TC6 Titanium Alloy

abst. 1123
**RIVA**
Thursday
June 25
15h30

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Ion nitriding of titanium alloys can form a high-hardness functionally graded nitriding layer on the surface of the alloys, significantly enhancing wear resistance and fatigue life. However, after nitriding, the mismatch in material properties between the nitrided layer and the substrate induces residual stresses during the high-temperature nitriding process, leading to varying degrees of deformation in the component and thereby influencing its high-precision applications. This study first establishes a finite element simulation model for the titanium alloy in nitriding process. Both experiments and the JMatPro software are used to determine the temperature-dependent thermophysical parameters of the titanium alloy within the temperature range of 600-900°C. On the Abaqus platform, a sequential thermal-mechanical decoupling strategy was employed to solve the transient temperature field and perform mechanical simulations. The material properties of each layer of the titanium alloy during

the nitriding process are defined, and spatially distributed heat flux is applied to describe the non-uniformity of glow discharge heating. Based on the simulation results, the residual stresses induced by the functionally graded nitrided layer and their effects on the deformation of the titanium alloy component are analyzed. Finally, the influence of process parameters such as nitriding temperature and heating/cooling rates on temperature uniformity and residual stress distribution is examined, and process optimization measures are proposed. The present study is expected to be meaningful for optimizing the titanium alloy nitriding process.

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abst. 1199
**RIVA**
Friday
June 26
14h50

## Multimaterial hybrid structures based on cellular materials for engineering applications

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Multimaterial hybrid structures based on cellular materials represent a promising class of advanced engineering systems, combining lightweight design with enhanced mechanical and functional performance. This study presents novel hybrid structural concepts integrating architected cellular materials, including cellular metals, cellular ceramics and metal foams, within multimaterial configurations, enabling enhanced mechanical performance through controlled architecture and material synergy. The proposed multimaterial hybrid structures are manufactured by combining conventional processing techniques with additive manufacturing techniques, enabling precise control of cellular geometry, relative density and material distribution. Structural and mechanical characterisation is carried out using scanning electron microscopy equipped with an energy dispersive X ray spectroscopy system, X ray micro computed tomography and quasi static uniaxial compression tests. Micro computed tomography is employed to assess interfacial bonding quality between different cellular materials, internal structural integrity and manufacturing induced features, supporting the optimisation of the fabrication process. Mechanical testing under quasi static uniaxial compression focuses on stiffness, load bearing capacity, energy absorption, specific energy absorption, and deformation and failure mechanisms. The results demonstrate that the integration of architected cellular materials into hybrid configurations leads to improved stiffness to weight ratios and more stable failure responses when compared to non hybrid components. Good interfacial bonding and effective mechanical interaction promote efficient load transfer and stable, near axisymmetric deformation, resulting in a mechanical response superior to that of the individual cellular constituents under compressive loading. In metal ceramic hybrid structures, the ductile cellular metal stabilises the brittle cellular ceramic phase, leading to a ductile global response and significantly enhanced mechanical performance. These findings highlight the potential of multimaterial hybrid structures based on cellular materials for advanced engineering applications where lightweight design and structural performance are critical.

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abst. 1334
**RIVA**
Thursday
June 25
15h50

## Design and Mechanical Performance Study of Lightweight Rod-Based Metamaterials

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The pursuit of advanced lightweight materials that integrate high specific strength with adaptable functionality is pivotal for next-generation engineering applications, particularly in domains demanding concurrent load-bearing capacity, energy dissipation, and impact resistance. However, a significant challenge lies in overcoming the performance constraints inherent in conventional metamaterials with static topologies, which often struggle to achieve synergistic multifunctionality under diverse loading conditions. To bridge this gap, this study introduces a design paradigm focusing on dual-tunable, strut-based architected materials. We propose and fabricate two distinct families of lightweight cellular metamaterials from AlSi10Mg, wherein the critical design freedom is the independent tuning of strut diameters within the unit cell. Our investigation comprehensively evaluates the static compressive properties and dynamic impact response of these metamaterials. The results reveal that strategic diameter optimization enables a wide, effective tuning range of the effective elastic modulus while maintaining a low relative density, demonstrating exceptional design flexibility. Under quasi-static loading, the two architectures exhibit fundamentally different deformation modes—one characterized by tensile-dominated mechanics and the other by bending-dominated behavior—directly attributable to their distinct topological configurations. This topological distinction further governs their dynamic performance. Under impact loading, both types exhibit pronounced geometrically dependent deformation, including buckling and fracture, but with markedly different energy absorption mechanisms and rate sensitivities. Tuning the strut diameter parameter is shown to be a highly effective strategy for multifunctional performance enhancement, leading to substantial simultaneous improvements in both specific energy absorption under dynamic conditions and total energy absorption capacity under static loading. This work successfully demonstrates that through topology-aware, parameter-driven design, it is possible to break the traditional trade-offs imposed by fixed architecture and density. We achieve a synergistic optimization of stiffness, strength, and energy absorption within a lightweight framework. The study provides fundamental insights into the structure-property relationships governing the static and dynamic behavior of strut-based metamaterials and establishes a robust design methodology for creating tunable, high-performance lightweight materials for demanding multifunctional applications.

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## Influence of a Piezomagnetic Coating on SH Waves in a Pre-Stressed and Electrically Biased Piezoelectric Semiconductor Half-Space with Functional Grading

abst. 1354
**RIVA**
Friday
June 26
14h30

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This study presents an analytical investigation of SH-wave dispersion in a functionally graded n-type piezoelectric semiconductor (PSC) half-space with and without a piezomagnetic coating layer. The PSC substrate is subjected to initial stress and a uniform static biasing electric field applied along the direction of propagation. The three-dimensional governing equations of piezoelectric semiconductors are employed to derive the dispersion relation under appropriate boundary and interfacial conditions. The effects of functional grading, initial carrier density, piezomagnetic constant, initial stress, bias electric field, and coating thickness on wave velocity and attenuation are systematically examined. The analytical results are further validated using numerical simulations performed in COMSOL Multiphysics. The study demonstrates that SH-wave characteristics can be effectively tuned through electromechanical coupling and pre-stress effects, providing useful insights for the design of smart acoustic and sensing devices.

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## Size-Dependent Free Vibration of FG-GPL Lattice Nanostructures: A Nonlocal Strain Gradient Finite Element Approach

abst. 1408
**RIVA**
Thursday
June 25
16h10

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This study develops a new finite element model (FEM) to investigate the free vibration of functionally graded (FG) lattice nanostructures reinforced with graphene nanoplatelets (GPLs), incorporating size-dependent effects through nonlocal strain gradient elasticity theory. The theoretical framework is established based on Euler–Bernoulli beam kinematics, assuming that the effective material properties including elastic modulus and mass density vary continuously along the thickness direction according to a power-law distribution. To accurately capture nanoscale phenomena, the constitutive relations are enhanced by integrating the nonlocal strain gradient effects, enabling the model to represent coupled axial–bending responses influenced by the microstructure. The FEM formulation is derived from variational principles, beginning with the total potential energy of the system. The stiffness matrix is constructed from the strain energy expression, which explicitly includes contributions from nonlocal stress fields and strain gradients. Simultaneously, the mass matrix is formulated from kinetic energy considerations, accounting for both translational and rotary inertia effects. To satisfy the continuity requirements of the displacement field, higher-order Hermite interpolation functions are employed, introducing additional degrees of freedom that allow precise representation of axial and bending deformations and their interactions. The resulting multi-degree-of-freedom frame element is then transformed into global coordinates for the analysis of complex FG nanoframe structures. Extensive numerical validation demonstrates excellent agreement with existing analytical solutions across various boundary conditions, confirming the accuracy of the proposed approach. A parametric investigation systematically examines the influence of key factors such as nonlocal parameters, geometric parameters and material distribution profiles on the natural frequencies of all FG lattice nanostructure configurations and boundary conditions. The results underscore the efficiency and precision of the developed method, establishing it as a valuable tool for nanoscale structural analysis and the design of nanoelectromechanical systems (NEMS).

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## Health monitoring and inspection techniques for composite structures

### Effect of Matrix Length and Tensile Load on Acoustic Emission Signal Frequency in CFRP Using Pencil Lead Break

abst. 1069
**TIGELLIO**
Friday
June 26
11h30

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Thanks to their exceptional specific strength -to-weight ratio, and corrosion resistance: Carbon Fiber reinforced polymer (CFRP) composites have become essential in high-performance structural applications across oil and gas, aerospace, automotive, and civil infrastructure sectors. However, monitoring defects in these materials remains challenging due to their complex, heterogeneous structure. Acoustic emission (AE) testing has become a popular non-destructive testing (NDT) technique for detecting defects in composites, with many researchers, using AE frequency-based methods to identify damage modes in CFRP composites. The typical method categorizes damage types by assigning frequency ranges: low frequencies (50–200 kHz) for matrix cracking, intermediate frequencies for fiber-matrix debonding and delamination, and high frequencies (>300–400 kHz) for fiber breakage. However, this fixed-band classification has significant limitations, as frequency content is largely affected by wave propagation effects including wave dispersion, frequency-dependent attenuation, and acoustoelastic phenomena, rather than solely originating from source mechanisms. This study investigates the effect of matrix distribution and tensile loading on the frequency characteristics of acoustic emission signals in CFRP composites using controlled pencil lead break (PLB) excitation as a standardized broadband source. Four CFRP specimens of varying matrix lengths (0 mm, 40 mm, 70 mm, and 150 mm), were fabricated and subjected to sequential tensile loading (0-400N). The PLB generated AE signals were acquired with the piezoelectric sensor attached to the specimen under tensile load. The acquired signals were analysed, using Fast Fourier Transform (FFT) analysis, frequency band energy decomposition and continuous wavelet transform (CWT) techniques, in MATLAB proprietary and AGU Vallen software respectively. The results demonstrate that matrix length significantly influences the observed AE frequency spectra, through progressive frequency-dependent attenuation mechanisms. The specimen with 150mm matrix length exhibited the lowest wavelet transform (WT) coefficient, with the peak frequency shifts observed at 400kHz, compared to specimens without matrix, which maintained highest WT coefficient relative to other specimens across all loads. The 70mm matrix specimen exhibited the highest WT coefficient at 200kHz frequency across the respective tensile loads. The frequency shifts occurred independently of source mechanisms, being solely attributable to viscoelastic damping in resin-rich regions and elastic scattering, which further attenuates short wavelength components. The applied tensile stress also modified the WT coefficient, causing varying frequency shifts under 0N-400N loading, due to acoustoelastic effects and stress-dependent interfacial stiffness modulation, which in turn alter the wave velocity and interfacial characteristics. These findings reveal that the same damage mechanism can generate varied frequency signatures based on composite architecture and loading state, making fixed frequency bands for damage classification inaccurate. The study emphasizes the necessity for propagation-corrected interpretation methods in acoustic emission-based structural health monitoring of composite structures.

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### Composite structure deformation shape reconstruction method based on physics informed data driven iFEM with ANN concept

abst. 1277
**TIGELLIO**
Friday
June 26
11h50

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The ability to accurately determine the deformed shape of a structure under various loading conditions is crucial for assessing performance, ensuring safety, and guiding maintenance or adaptation. Structure deformation shape reconstruction, or shape sensing, is a prominent method of structural health monitoring to enable real-time assessment of structural deformation, stress distribution and health conditions. Classical inverse finite element method (iFEM) is in fact the first data-driven method for shape reconstruction directly based on sensor measured discrete strain data. The iFEM method was developed well before the recent fast-growing data-driven machine learning (ML) methods such as artificial neural networks (ANN) and physics informed neural networks (PINN). However, lack of input data or data scarcity, in particular for engineering application with restriction of number of sensors and failed sensors during in-service operations, had been and still is the main obstacle for all data driven method including classical iFEM and modern ANN and PINN methods. Consequently, an innovative structure deformation shape reconstruction method based on physics informed data driven multiple layer iFEM with ANN concept (PIDD-ML-iFEM) is proposed in this study. The current widely used classical iFEM method first carry out data augmentation with interpolation of measured strain data to create additional strain data and then run iFEM once to produce the shape reconstruction. The pre-interpolation of data requires pre-knowledge or pre-assumption of the deformation shape which is unknown and to be determined by the iFEM. Consequently, this is not really the data driven iFEM should be and also results in larger errors is the measured data cannot support the pre-knowledge or pre-assumption. The proposed PIDD-ML-iFEM does not rely on the data augmentation with interpolation of measured strain data. Instead, the small number of measured strain data is directly used to run the first layer of iFEM to produce first physics informed approximation shape reconstruction. Then the first layer of physics informed shape reconstruction is used for data augmentation based on data transfer learning widely used in modern machine learning methods without pre-knowledge or pre-assumption. A transformation function, similar as the activation function in ANN, is developed based on the physics informed approximation shape reconstruction obtained from first layer of iFEM. With increased input data from the proposed physics PIDD data augmentation technique, second iFEM running is carried out to improve the approximation shape reconstruction. Just like ANN with number of hidden layers, multiple layer iFEM (ML-iFEM) running can be carry out to gradually achieve the final high accuracy shape reconstruction. A number of examples have been provided to validate the proposed PIDD-ML-iFEM method and the results demonstrated the innovative and effectiveness of the proposed method.

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abst. 1359
**TIGELLIO**
Friday
June 26
12h10

## Quantitative cracking patterns analysis as a monitoring tool for cement-based composites exposed to elevated temperatures

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Thermal exposure induces multi-scale cracking in cementitious composites, reducing stiffness and durability. Reliable health monitoring therefore requires robust, repeatable descriptors of surface damage that can be extracted from inspection data with minimal operator bias. A machine-learning-assisted image analysis procedure to quantify thermally induced cracking patterns was proposed. The case study concerned cement paste modified with mesoporous silica MCM-41. The aim was to assess the suitability of an inspection/monitoring technique for cement-based composite structures operating at elevated temperatures. Four cement paste series were investigated: CP-0 (reference) and pastes containing 0.5, 1.0 and 2.0% MCM-41 by mass of cement (CP-MCM-0.5, CP-MCM-1, CP-MCM-2). Specimens were thermally loaded at 100, 300, 500 and 700 °C. After exposure, the cracked surfaces were scanned at very high optical resolution (1200 dpi) using an optical scanner. Such an approach provides a low-cost, field-ready acquisition route. Crack maps were obtained using a custom segmentation procedure based on Trainable Weka Segmentation (ImageJ/Fiji), enabling supervised classification and conversion to binary crack networks. Quantitative descriptors were then calculated: total crack area (TCA), crack density (CD), mean crack width (CW), fractal dimension of the cracking pattern (FDB), lacunarity (LAC) and selected multifractal indicators (D(Q) amplitudes and summed f() for Q>0). For each series/temperature combination, three replicates were analysed. The reference paste exhibited a pronounced temperature-driven escalation of damage, with mean TCA increasing from 4 $cm^2/m^2$ at 100 °C to 52 $cm^2/m^2$ at 300 °C and 134 $cm^2/m^2$ at 500 °C. CD rose from 12 1/m to 104 1/m and 216 1/m, respectively, accompanied by an increase in CW (from 55 m to 80 m) and FDB (from

0.73 to 1.48). Incorporation of MCM-41 mitigated cracking primarily in the 300–500 °C range. The most favourable performance was observed for CP-MCM-1, where TCA was reduced by 51% at 300 °C and 74% at 500 °C relative to CP-0, while CD decreased by 38% and 71%, respectively. CW was also lower in the 500–700 °C range (13–16% reduction). At intermediate temperatures, the modified pastes generally showed lower FDB (less geometrically complex crack networks) together with higher LAC, indicating a more clustered/heterogeneous spatial distribution of cracks. Multifractal outputs suggested a shift towards "smooth/ordered" scaling with increasing temperature, and multifractal scaling was indicated mainly at 500–700 °C, consistent with a change in the governing cracking regime. From a monitoring perspective, the proposed descriptors are scale-compatible and can be tracked over time, i.e. pre- and post-exposure, or after successive thermal cycles, to assess the degradation route. The combination of area-based (TCA), intensity-based (CD), morphology-based (CW) and complexity-based (FDB/LAC/multifractal) metrics reduces the risk of misclassification that may arise when a single indicator is used. The developed procedure yields reproducible segmentation, supporting consistent processing across campaigns. The workflow is readily extendable to higher-resolution imagery and can be integrated with complementary NDT signals (e.g. UPV or acoustic emission) as a feature-level fusion approach for composite condition assessment. The results demonstrate that the combination of segmentation based on machine learning and fractal/multifractal descriptors provides sensitive, objective damage data for thermal degradation. The research was financed by the National Science Centre, Poland, under the SONATA 17 programme. Research project no. 2021/43/D/ST8/01128 entitled "Investigation of crack development processes in a cement matrix modified with a reactive and non-reactive secondary additive under thermal loading conditions".

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## SHM of Composites AI approach using Diffuse waves

abst. 1360
**TIGELLIO**
Friday
June 26
12h30

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Wave propagation in composites is a complex phenomenon. The velocity of ultrasound depends on the stiffness and density of material. The directional properties of the composites cause the wave to propagate at different velocities in different directions. Diffuse waves are long duration waves and over this duration reach the receiver using different paths and different velocities. In the process, they encounter various stiffnesses and anomalies of composites and are an ensemble sum of the state of composites. This paper is concerned with the study of these diffuse waves on graphite/Epoxy composites. Since the waves are indeterminate in nature, the long duration signal before a damage and the signal after damage is compared. This comparison is performed both in magnitude and frequency domain. We first start with undamaged composites and study diffuse wave propagation, then we add defects in the form of we study the effect of low energy impact damage on the diffuse waves. Results show that the diffuse field is sensitive to presence and size of defects in composites and quantitative measurements are possible. Thus, the diffuse waves can be used as structural health monitoring method (SHM) for composites. The technique becomes amenable to AI as no human interaction is required.

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## AQUADA Technology for Smart Structural Health Monitoring of Large Composite Structures under Cyclic Loading

abst. 1368
**TIGELLIO**
Friday
June 26
12h50

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This study presents the research and development of AQUADA technology developed by Technical University of Denmark. The AQUADA technology is used for detecting and assessing the subsurface damage of large composite structures, such as wind turbine blades, subjected to cyclic loads. Laboratory development at both components and full-scale structural levels, field tests, and demonstrations are conducted to collect high-quality data, which enables the development of a large AI model based on computer vision and thermographic imaging. The achievements, remaining challenges and further development will be presented.

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abst. 1412
**TIGELLIO**
Friday
June 26
13h10

# Structural health monitoring of the all-FRP composite bridge using the DFOS system

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Since the early 1980s, fibre-reinforced polymer (FRP) composites have been used in various bridge applications. In Poland, the construction of bridge structures with load-bearing elements such as girders and decks made from FRP composites began in 2015. Rzeszów University of Technology led the first two research and development projects; one of the earliest results was an all-FRP composite road bridge built in 2016 in Rzeszów. Similar to early bridges in the USA and Western Europe, this Polish all-FRP composite bridge was fitted with a modern structural health monitoring (SHM) system to enable long-term monitoring of its health and performance during service. Over nearly a decade of use, the bridge's strain, stiffness, and dynamic properties have been assessed three times through static and dynamic load tests. The paper compares these assessments and provides insights into the long-term performance of Poland's first all-FRP composite bridge. The first all-FRP composite road bridge spans an urban road over a small local stream and is 10.7 metres long. This single-span bridge features a 7.7-metre-wide deck, accommodating a 2-metre-wide roadway on each side, along with two pavements measuring 0.75 metres and 1.1 metres in width, respectively. The superstructure of this bridge consists of four FRP composite girders, which support a 0.13-metre-thick sandwich deck slab made of FRP. The deck slab is bonded to the top flanges of the girders using epoxy adhesive. The FRP girders feature a U-shaped cross-section with slightly inclined webs. The top and bottom flanges are constructed from solid GFRP composites, while the webs are designed as sandwich panels comprising a PVC foam core sandwiched between two GFRP face-sheet laminates. The sandwich deck panels incorporate two 12 mm-thick GFRP laminate face sheets and a 105 mm-thick PUR foam core reinforced with internal vertical GFRP ribs. The entire composite superstructure was produced using VARTM infusion technology, employing epoxy resin as the matrix for all composite parts. To monitor the bridge's behaviour during service, three load tests were conducted between 2016 and 2025. Identical load schemes were used in each test to enable comparison of the FRP structure's performance over time. Each of the three tests included both static and dynamic load scenarios. The distributed fibre optic sensing (DFOS) technology was chosen as the primary structural health monitoring (SHM) system for the bridge. An optical reflectometer based on linear Rayleigh scattering was used to measure strain. Single-mode telecom-grade optical fibres were employed, with virtual measurement sections spaced 10 mm apart along the fibres to ensure accurate strain measurement. The measured strain distributions can also be utilised to assess displacements, which are defined as changes in the shape of the laminates relative to their original form before loading. The fibre-optic sensors were installed in the workshop immediately after the FRP girders and deck panels were manufactured. A total of 10 sensors, each approximately $9.60 \pm 0.10$ m in length, were bonded inside two bridge girders. This setup allows strain measurement at approximately 10,000 virtual discrete points along the girder. Only one deck panel was fitted with fibre optic sensors. Based on monitoring data, the first all-FRP composite bridge in Poland has demonstrated satisfactory structural integrity and durability over a 10-year service period. The monitoring data show minimal changes in strength, stiffness, and dynamic performance over the long term. Periodic field load testing has confirmed that this all-FRP composite bridge has maintained reliable performance throughout the monitoring period and can be regarded as a dependable structure. The DFOS strain measurement system has proven to be an efficient and cost-effective method for monitoring FRP bridges. It enables assessment of changes in the bridge's load-carrying capacity, stiffness, and dynamic characteristics while in service. Future research should focus on further long-term observation of the bridge's performance under service loads. In subsequent measurement phases, the effects of temperature and creep on the behaviour of the all-FRP composite structure will be evaluated. This research was co-financed by the Minister of Science and Higher Education within the following RD project: "Regional Centre of Excellence in Engineering for Quality of Life and Technology Development" within the framework of the "Regional Excellence Initiative" Programme; grant number RID/SP/0032/2024/01.

## Impact problems

### Impact damage and residual bending performance of sustainable sandwich beams at low temperatures

abst. 1070
**SANT'EFISIO**
Wednesday
June 24
12h10

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Sandwich structures are widely used in the transportation and energy sectors due to their high stiffness-to-weight ratio and suitability for lightweight structural components such as panels, beams, and protective elements. During their service life, these structures may be exposed to impact loads arising from accidental events, including tool drops during maintenance operations or debris and animal strikes. Depending on the impact energy, such events can result in a broad range of damage scenarios, from barely visible internal damage to localized indentation or complete perforation of the structure. The high susceptibility of composite materials to impact loading makes damage resistance a critical design consideration for sandwich structures. In addition to mechanical loading, environmental conditions strongly influence the damage response of sandwich structures, with temperature playing a particularly significant role. Variations in temperature modify the stiffness and strength of both the skins and core materials, while mismatches in the coefficients of thermal expansion generate additional internal stresses. In sandwich configurations, these effects are further intensified by the interaction between face-sheet bending, core shear deformation, and localized indentation phenomena. Sandwich structures can be manufactured using a wide range of skin and core material combinations, resulting in markedly different mechanical responses and damage characteristics. Growing concerns regarding the environmental impact of industrial processes have motivated the development of eco-friendly alternatives to conventional composite systems. Bio-based fibres and natural core materials offer clear environmental advantages, including renewable sourcing and improved end of life management, while maintaining mechanical properties suitable for structural applications. However, the combined influence of impact loading and sub-zero temperatures on the damage mechanisms and damage tolerance of sustainable sandwich structures remains insufficiently studied. In this study, sandwich beams manufactured with flax fibre laminate skins combined with an agglomerated cork core are experimentally investigated. Flax fibres have emerged as a viable alternative to synthetic reinforcements due to their low density, favourable specific mechanical properties, enabling structural performance comparable to glass fibre in selected applications. The core material considered is a lightweight cellular solid that plays a fundamental role in sandwich structures by providing shear stiffness and stabilising the face sheets under transverse loading. Agglomerated cork, derived from renewable bark granules, represents a promising sustainable core solution, offering reduced environmental impact, improved end of life management. An experimental study was conducted on these sustainable sandwich beams, and their response was benchmarked against a conventional reference configuration consisting of woven glass/epoxy skins and a PVC foam core. Low-velocity impact tests were carried out over a range of impact energies (30–130 J) to generate different damage scenarios, from barely visible damage to severe failure modes approaching perforation. These experimental tests were conducted at two different temperatures, 23 °C and 40 °C. The impact response was characterized using global parameters such as peak contact force, absorbed energy, and effective bending stiffness, complemented by an analysis of damage initiation and evolution. In addition, the residual structural performance was evaluated through bending-after-impact (BAI) tests conducted at the same temperatures , allowing the damage tolerance of sustainable sandwich structures under combined thermal and mechanical loading conditions to be assessed.

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### Ignition Mechanism and Criterion for High-Viscosity Aluminized Explosive Slurry under Drop-weight Impact

abst. 1119
**SANT'EFISIO**
Wednesday
June 24
13h10

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High-viscosity aluminized explosive slurry poses increasing safety concerns in explosive production. Therefore, understanding ignition mechanisms is critical for this type of manufacturing slurry. This slurry features high viscosity with solid particle dispersion. Consequently, these characteristics lead to distinct performance under external impact or friction compared to traditional explosives. To address this complexity, we established an ignition criterion based on plastic work and frictional heat between internal particles. We assume the microstructure consists of a three-dimensional regular packing of explosive and aluminum grains, along with a fluid binder. The ignition criterion developed in this study is based on calculating macroscopic pressure and plastic shear rate within grains of the aluminized explosive slurry during drop-weight impact tests. Then, the positive pressure translates to a contact force at the grain scale, resulting in friction between the particles. This study provides new theoretical insights into ignition mechanisms in high-viscosity aluminized explosive slurry and offers guidance for enhancing safety in explosive production processes.

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abst. 1180
**SANT'EFISIO**
Wednesday
June 24
12h50

## Predictive Analysis of Low-Velocity Impact Damage in CFRTP Corner Regions Through Advanced Fiber-Aligned Modeling Framework

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Low-velocity impact (LVI) damage in corner regions of thermoplastic composite structures presents significant challenges for accurate damage prediction due to complex stress states, fiber orientation transitions, and coupled damage mechanisms. This study developed a high-fidelity fiber-aligned parametric modeling framework for precise simulation of LVI damage evolution in T700/PPS thermoplastic composite corner regions with [(0, 90)/(±45)]4s layup configuration. The proposed methodology integrated three key advanced modeling techniques: (1) fiber-aligned mesh generation that aligned element edges with local fiber orientations to accurately capture fiber-direction crack propagation, (2) zero-thickness cohesive elements inserted between plies to simulate delamination initiation and growth, and (3) a user-defined material subroutine (VUMAT) incorporating plastic flow factors to represent the thermoplastic matrix behavior under impact loading. This comprehensive approach enabled realistic representation of intralaminar matrix cracking, fiber breakage, and interlaminar delamination in a fully coupled manner. The modeling framework was systematically validated through LVI and compression after impact (CAI) tests on flat laminate specimens, demonstrating excellent agreement in damage morphology, force-displacement response, and residual strength predictions. The validated high-fidelity model was subsequently applied to corner region structures, where geometric curvature introduced additional complexities in damage initiation and propagation patterns. Experimental characterization using C-scan ultrasonic inspection and computed tomography (CT) imaging revealed three-dimensional damage distributions that were accurately reproduced by the numerical predictions. Quantitative comparison showed that the fiber-aligned parametric model successfully captured characteristic damage features including matrix crack orientation, delamination shape, and through-thickness damage progression, with superior accuracy compared to conventional modeling approaches. The predicted damage footprints exhibited strong correlation with C-scan results (error $< 8\%$), while CT images confirmed the model's capability to predict complex damage interactions in the corner region. This research established a robust computational framework for impact damage assessment in thermoplastic composite corner regions, providing essential tools for damage-tolerant design of advanced composite structures in aerospace and automotive applications.

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abst. 1225
**Repository**

## Impact Performance of Glass-Polypropylene Laminates: Effect of Metal Mesh Reinforcement on Energy Absorption

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Hybrid composite laminates that combine thermoplastic matrices with metallic reinforcements have gained increasing attention for structural applications requiring enhanced impact resistance and damage tolerance. In this study, the low-velocity impact performance of polypropylene-based glass fiber laminates reinforced with stainless steel metal mesh layers is systematically investigated. Hybrid glass-polypropylene laminates incorporating three different plain-weave 304 stainless steel meshes with varying wire diameters were manufactured using a hot-press consolidation process. The laminates were produced through a two-step fabrication procedure. First, the stainless-steel mesh was embedded within polypropylene layers to form a reinforced core. This core was then sandwiched between glass fiber-reinforced polypropylene skins to create the final hybrid laminate architecture. All specimens were fabricated under identical processing conditions to ensure consistent consolidation quality, interfacial bonding, and repeatability of the experimental results. Low-velocity impact tests were performed at impact energy levels of 20 J, 50 J, and 70 J to assess the influence of mesh size on the impact response and energy absorption capability of the laminates. Key impact parameters, including peak force, absorbed energy, specific energy absorption, mean crushing force, and crushing force efficiency, were extracted from the force–displacement curves obtained during testing. The results indicate that, among the tested configurations, laminates reinforced with smaller mesh sizes consistently exhibited higher specific energy absorption across all impact energy levels. This enhanced performance is attributed to the denser metallic network provided by the finer meshes, which improves load distribution, delays damage initiation and progression, and effectively restricts crack propagation. Additionally, the metal mesh acts as an internal stiffening element, limiting the extent of the damaged zone under impact loading. Overall, these findings demonstrate the effectiveness of stainless-steel mesh reinforcement in improving the crashworthiness and impact resistance of thermoplastic composite laminates and provide valuable guidelines for the design of lightweight, impact-resistant hybrid composite structures.

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## A comparative study of the impact performance of aluminium laminates with different surface modifications

abst. 1264
**SANT'EFISIO**
Wednesday
June 24
12h30

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Impact resistance is one of the most important issues related to the reliability of structures made with fibre metal laminates, which are used in the manufacture of fuselages and many other applications. Low-velocity impact in fibre metal laminates can cause failure modes such as buckling, delamination initiation and propagation, and matrix and fibre cracking. Impact loads can cause susceptibility in fibre metal laminates due to the weak interface performance between metal and composite. Metal surface treatment is a key factor in achieving adequate adhesion at the metal–composite interface in FMLs, enabling high joint strength and resistance to interlayer cracking and environmental effects. It also plays a crucial role in effective stress transfer between the metal and composite layers. All of the methods more or less change the metal's structure and morphology, which affects adhesion at the metal–composite interface. The main objective of the evaluation of the assessment of FMLs was to conduct a deep analysis of the damage growth range, size and mechanisms during load from the application of various methods of metal surface treatment. Aluminium-Carbon Fibre Polymer Epoxy Laminates were manufactured using autoclave technology with aluminium alloy sheets modified using mechanical, chemical, electrochemical surface treatment methods. The effectiveness of chromic acid anodizing, sulphuric acid anodizing, etching, sandblasting and transition layers in improving adhesion at the metal-composite interface in fibre metal laminates was compared. Low-velocity impact tests were conducted using impact energies ranging from 2.5 J to 10 J. Failure of laminates subjected to low-velocity impact was analyzed using non-destructive testing with the Through Transmission Phased Array ultrasonic testing method and C-scan imaging. An analysis of the failure at the metal-composite interface was also carried out, indicating the failure mechanisms.

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# Joints

abst. 1037
SANT'EFISIO
Tuesday
June 23
16h50

## Experimental and Numerical Analysis of Single-Lap Adhesive Joints: A CZM Approach for Correlating ASTM D1002 Test Results

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Composite materials are increasingly adopted in sectors such as aerospace, automotive, marine, and energy due to their high strength-to-weight ratio, stiffness, and design flexibility. However, the manufacture of large or geometrically complex components often requires joining multiple parts, making the mechanical performance of the joint a critical factor in overall structural reliability. Adhesive bonding has emerged as an attractive lightweight alternative to mechanical fastening because it provides a more uniform stress distribution, avoids stress concentrations due to drilled holes, and offers potential improvements in fatigue behaviour. Nevertheless, adhesive joints remain challenging to design, as failure mechanisms depend on complex interactions between material properties, joint geometry, and loading conditions. Standardized experimental testing is essential for characterising these behaviours. The ASTM D1002 single-lap shear test is widely used to evaluate the shear strength of structural adhesives under tensile loading, though the presence of peel stresses complicates the interpretation of results. To complement experimental observations, finite element modelling has become a fundamental tool for analysing stress states and predicting failure. Among available numerical techniques, Cohesive Zone Models (CZM) enable a physically consistent simulation of crack initiation and propagation in adhesive layers through traction–separation laws and fracture energy criteria. This study investigates hybrid aluminium–composite adhesive joints through a combined experimental and numerical approach. Single-lap shear tests following ASTM D1002 were performed to assess load-bearing capacity, failure mechanisms, and variability. In parallel, CZM-based finite element models were developed with the objective of reproducing the experimental load–displacement curves and fracture patterns. The comparison between experiments and simulations allows us to evaluate model accuracy, identify discrepancies, and refine the numerical strategy. The outcomes provide a validated framework for analysing bonded joints and support the development of robust design methodologies for high-performance composite structures.

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abst. 1173
SANT'EFISIO
Tuesday
June 23
17h30

## Laser welding of dissimilar thermoplastic composite structures

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There is an increasing demand for lightweight thermoplastic composite structures in the automotive and aerospace industries. In addition, these have also intensified the search for efficient and sustainable joining technologies, in alternative to conventional adhesive bonding methods. These often rely on solutions with relevant levels of toxicity and require lengthy curing times, which can hinder productivity and compliance with environmental regulations. Laser welding has been previously utilised to join commodity and engineering thermoplastics. The success of this joining process relies significantly on the thermoplastics' compatibility and the process parameters that influence the contact between materials to weld or the heat input. This study investigates the feasibility of using laser welding as a solvent-free and rapid manufacturing process to join dissimilar thermoplastics with dissimilar morphologies, a topic that has not been addressed in the literature. Joining these without adhesives poses a challenge due to the multiple dissimilarities. Laser welding experiments were conducted with systematic variations of parameters, aiming to optimise joint strength while preserving the structural integrity of both materials: polypropylene and polyethylene foam. The joints' strength was determined by conducting shear lap tests. Several non-destructive tests, including scanning electron microscopy and X-ray microtomography analysis, were also performed to assess the interfacial joining and thermal damage, while correlating these with the mechanical performance. Preliminary findings demonstrate that adequate joining between dissimilar thermoplastic composite structures is achievable

under carefully controlled processing conditions. Process optimisation proved essential to enhancing joint strength while minimising foam collapse and degradation. These results highlight the potential of laser welding as a clean and efficient joining method for morphologically dissimilar thermoplastic composite structures. Acknowledgements: This work was funded by National Funds by FCT – Fundação para a Ciência e a Tecnologia, I.P., in the scope of the project 2023.14833.PEX with the following DOI https://doi.org/10.54499/2023.14833.PEX. This work was supported by national funds from FCT - Fundação para a Ciência e a Tecnologia, I.P., for the project UID 00481/2025 - Centre for Mechanical Technology and Automation, https://doi.org/10.54499/UID/00481/2025

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## Study of the end joint of a composite material tube

abst. 1214
**Repository**

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To reduce the weight of structural components, one of the fundamental approaches is the use of materials that exhibit better mechanical performance compared to conventional steel materials (higher ultimate and yield strength, higher Young's modulus) combined with lower density. Composite materials represent a very important solution in this context, as their mechanical performance can be significantly higher than that of traditional steel materials. One of the main tasks is joining components made of composite materials (such as sandwich structures, filament-wound components, and similar configurations) to the rest of the structure, in order to avoid generating critical zones that could compromise the overall structural strength. In many cases reported in the literature, the joint between composite components and other structural elements is identified as the most critical zone, due to high local stresses and elevated stress intensity factors. In this research, the innovative joint between a cylindrical composite tube and a plate (assumed to be made of an aluminium alloy) was studied numerically. The analysis was carried out by considering several variables, such as the adhesive properties and its thickness, as well as the joint geometry, varying the length and size of both the inner and outer elements. After comparison with joint configurations reported in the literature, a new solution was developed and implemented. The final design (obtained after several iterations) shows a significantly lower stress intensity factor at the end of the joint zone compared to a conventionally designed joint.

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## Experimental testing and numerical modelling of hybrid joints for wooden structures

abst. 1258
**SANT'EFISIO**
Tuesday
June 23
16h30

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The performance of wooden structures is significantly impacted by their structural connections. Depending on the design strategy, the internal stresses and overall structural deformations can be amplified or reduced. Typically, mechanical connections in timber structures are classified as either plastic hinges or semi-rigid connections. Incorporating adhesive into a hybrid joint can substantially boost stiffness in contrast to conventional joints. This improvement can successfully make the joint rigid, significantly decreasing stresses and deformations in the structure. This research involves conducting experiments and using computer simulations to analyse hybrid adhesive-mechanical joints in shear layout. For the experimental phase, the MTS 809 strength-testing machine and Digital Image Correlation (DIC) were utilised. Next, Simulia ABAQUS software was incorporated into the numerical simulations. The numerical simulation outcomes were juxtaposed with those derived from experimental tests, followed by an in-depth discussion.

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abst. 1263
SANT'EFISIO
Tuesday
June 23
16h10

## The influence of micro-arc oxidation surface treatments on the enhancement of interfacial integrity in composite structures

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Fibre Metal Laminates (FMLs) are an interesting group of materials characterized by low density, high static and fatigue strength, and resistance to impact and corrosion. The prevalent failure mechanism in FML laminates is delamination at the metal–composite interface, resulting directly from inefficient metal surface modification. Therefore, one of the most important scientific problems in FMLs remains achieving appropriate adhesion at the metal–composite interface through metal surface treatment. This determines the ability to obtain a combination of high strength and a quality joint with increased resistance to interlayer cracking and environmental conditions. The adhesion properties of FML laminates can be designed by using various metal surface treatment methods. Appropriate surface roughness, modified surface topography, increased surface free energy and polar component, and controlled pore size and density can be obtained by selecting the suitable surface treatment technology and process parameters. Such an advantageous oxygen layer structure can be obtained by applying the micro-arc oxidation (MAO) process, which allows the voltage-current ratios, intensity, process time, acid concentration and bath temperature to be controlled. Furthermore, sol-gel coatings can promote high adhesion at the metal–composite interface. This is due to the possibility of chemical reactions and the action of chemical adhesion mechanisms. The objective of the study was to analyze the effect of aluminium 2024-T3 surface treatment on fibre metal laminates in order to achieve high adhesion at the metal–composite interface. This was examined in relation to the various parameters of the micro-arc oxidation process. The study examined the impact of various MAO process parameters (including voltage, current, time) on surface free energy, topography, and morphology in relation to potential adhesion in fibre metal laminates. Scanning electron microscopy was used to examine the morphology, and the surface free energy and its components were determined using the Owens–Wendt method. Surface characterization revealed that the oxide layer thickness, porosity, topography, roughness and morphology depend significantly on the applied MAO conditions. A mechanical test demonstrated differences in interfacial bonding and failure mechanisms depending on the applied process parameters, as opposed to the classic methods of aluminium surface treatment. The results emphasize the potential of bespoke MAO surface modification strategies to improve aluminium-composite interface adhesion and enhance the strength of fibre metal laminates. These findings provide valuable information for designing advanced metal–composite systems for structural applications.

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abst. 1271
SANT'EFISIO
Tuesday
June 23
15h50

## Fracture Behavior and Failure Criteria of CFRP/Al Adhesive Joints Induced by Moisture Absorption

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Humidity environments can lead to degradation of adhesive bond strength, compromising structural safety. In this study, the moisture sorption behavior of the adhesive was characterized through accelerated moisture absorption tests on adhesive bulk specimens. Subsequently, double cantilever beam (DCB) tests and end-notched flexure (ENF) tests were performed on adhesive layers both before and after moisture absorption to determine their Mode-I and Mode-II fracture properties. A cohesive zone

model incorporating moisture-induced degradation was developed. Furthermore, a corresponding VUMAT subroutine was implemented in the ABAQUS platform to simulate the shear-tensile behavior of CFRP/Al adhesive joints after moisture absorption. Experimental results show that the saturated moisture absorption of the adhesive bulk specimens was 3.22%. After 10 and 30 days of moisture exposure, the failure loads of the joints under shear-tensile tests decreased by 19.37% and 31.09%, respectively. Moreover, significant reductions were observed in both the critical fracture energy release rates and maximum interfacial stresses for Mode-I and Mode-II in the moisture-conditioned adhesive layers. Numerical simulations indicated that the relative errors between the experimental and simulated ultimate loads for joints after 10-day and 30-day moisture absorption were only 1.74% and 3.92%, respectively. The simulated load-displacement curves showed excellent agreement with the experimental results.

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## Enhanced Interfacial Adhesion in Al/PU and Al/epoxy joints via Eco-Friendly Potassium Chloride Anodizing

abst. 1281
**SANT'EFISIO**
Tuesday
June 23
17h10

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Laminated composites are widely utilized in aerospace and automative industries due to their outstanding mechanical performance: high strength-to-weight ratio and fatigue and impact resistance [1, 2]. However, the interfacial strength between metallic and polymeric layers continues to pose a constraint on their broader application [3]. Conventional metallic surface treatment enhances interfacial strength [4, 5]. However, their substantial costs and the use of hazardous chemicals pose economic and environmental concerns. In this regard, an innovative aluminum (Al 2024-T3) electrochemical surface treatment with potassium chloride (KCl) electrolyte is developed in this study and applied to both soft – polyurethane (PU), and rigid – epoxy, adhesives. A full factorial experimental design was employed to evaluate the effects of electrolyte concentration (0.05, 0.1, and 0.2M) and anodizing time (5, 10, and 20min) at a constant voltage of 12V. Al surface morphology and the lap shear and peel strength of Al-PU and Al-epoxy joints were investigated. Scanning electron microscopy and atomic force microscopy images showed the formation of a porous surface structure, promoting adhesive penetration and mechanical interlocking. Significant improvements in both lap shear and peel strength were achieved: lap shear strength increased by 3.0-fold for Al-PU joints (0.05M, 5min), while a 7.6-fold increase was obtained for Al-epoxy joints (0.1M, 20min). Fracture analysis confirms enhanced interlocking at Al-PU and Al-epoxy interfaces and transition from adhesive to cohesive failure mode. The results position novel KCl-anodizing process as a promising, environmentally benign, and scalable Al surface treatment method which improves metal-adhesive interfaces for soft and rigid adhesives.

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abst. 1057
CIMA
Tuesday
June 23
14h30

## Layer-Wise Theories for the Analysis of Laminated Glass Structures in a Peridynamic Framework

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Laminated glass components, such as automotive windscreens, architectural glazing, and photovoltaic modules, are routinely subjected to diverse mechanical actions including wind pressure, snow loads, hail impact, and gust-induced loading. Structural analysis of laminated glass is traditionally performed using layer-wise theories, in which each layer is modeled by beam, plate, or shell theories, coupled through compatibility conditions or interlayer force transfer relations. This presentation introduces an extension of classical layer-wise approaches by incorporating peridynamic (PD) nonlocality, enabling a unified and consistent treatment of both intact and damaged laminated glass configurations. Beginning with a single-layer formulation, a first-order shear deformation theory is developed within a peridynamic framework. The approach is then extended to multilayered laminates, resulting in governing equations of motion that allow both cross-sectional responses and interlayer force and moment interactions to exhibit long-range, nonlocal behavior. Local kinematic compatibility between adjacent layers is enforced, which naturally gives rise to nonlocal interaction forces in the peridynamic sense. Numerical examples demonstrate that, for smooth laminated glass beams, the proposed PD layer-wise theory produces results in close agreement with published solutions obtained from classical layer-wise beam formulations. For beams containing pre-existing cracks, the analysis reveals that the crack opening displacement increases with the peridynamic horizon size, highlighting the intrinsic nonlocal character of the PD crack model. In cases where one glass layer is fractured, the maximum interlayer shear force is found to scale inversely with the horizon size, indicating a direct influence of nonlocality on interlayer load transfer mechanisms. The proposed formulation offers a computationally efficient alternative to fully three-dimensional peridynamic models while retaining the ability to capture key physical effects, such as interlaminar load transfer and finite interfacial shear stresses near cracks, regions where classical plane-stress-based approaches often predict singular behavior. Although minor discrepancies arise due to the neglect of transverse normal deformation in compliant interlayers, the overall predictive capability of the model remains robust, making it well suited for practical analysis of laminated glass structures.

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abst. 1221
CIMA
Wednesday
June 24
14h30

## Modeling composite structures with Reissner Mixed Variational Theorem

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Advanced modeling strategies for composite structures are considered with special attention to the mixed approach that was first completely stated by Reissner in 1984, and therefore often referred to as Reissner Mixed Variational Theorem (RMVT). This variational formulation has the displacements and the transverse stresses as independent field variables, i.e., only those field variables that are required to fulfil the interlaminar continuity across a heterogeneous stack of perfectly bonded plies. For this reason, RMVT can be seen as the "natural variational framework" for constructing structural models for composite structures. The presentation addresses displacement- and stress-driven variants of RMVT and comparisons with the analogous Hellinger-Reissner (HR) principles. Two-dimensional plate/shell models are formulated within the so-called "axiomatic" dimensional reduction procedure, in which trial distributions are introduced for the field variables across the composite stack, and subsequently the dependency on the thickness coordinate is eliminated by carrying out the integrations. The general variable-kinematics approach is here adopted, that was first introduced by Carrera with his Unified Formulation. When dealing with mixed formulations, particular attention must be given to a proper choice of the introduced approximations in order to obtain well-posed problems and avoid non-physical responses. Results are presented for laminated and sandwich structures, obtained by means of semi-analytical as well as numerical solution methods.

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## Biobased Composites for Load Bearing Applications: Key Performance Targets, Challenges and Future Opportunities

abst. 1222
**CIMA**
Thursday
June 25
11h30

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Biobased composites have gained considerable attention from industry and academicians in various applications due to their key attributes including high specific-strength-to weight ratios, sustainability and better environmental performance compared to their conventional glass and carbon fibre reinforced composites counterparts. This keynote talk will focus on some of the work performed on natural plant fibre reinforced sustainable lightweight biobased composites for load-bearing engineering applications including marine, automotive, renewable energy and building and construction sectors. Key performance targets (mechanical, thermal, long-term durability and exposure to extreme environmental conditions) relating to key application areas, challenges and ways to achieve them will be presented and discussed. Additionally, microstructures and physicochemical characterisations using advanced characterisations techniques such as micro-CT, SEM and advanced imaging will be presented. The keynote talk will focus on three key aspects: First, the talk will introduce the importance of sustainable natural plant fibre reinforced biobased composites in tackling the current environmental issues caused by use of fossil-based materials in advanced engineering applications. The keynote talk will then concentrate on structure property relationships, influence of exposure to various harsh environmental conditions on the key mechanical, thermal and long-term properties by analysing some results obtained from various experimental works from ongoing and recently completed research projects. Some fabrication techniques and their influence on the various properties will also be discussed. Finally, the potential use of these lightweight sustainable biobased composites in load bearing applications (non-structural, semi-structural and structural) relating to key application areas, major challenges will be further highlighted and discussed by analysing some experimental results and by presenting ways to enhance the key properties by reviewing some current and previously published works. Keywords: Biobased composites; Mechanical property; Morphological characterisation; Long-term durability; X-ray micro-CT; Sustainability; Processing parameters.

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## Composites in structural engineering and architecture

abst. 1224
**CIMA**
Tuesday
June 23
10h40

*Keller, Thomas (thomas.keller@epfl.ch), Swiss Federal Institute of Technology Lausanne, EPFL, Switzerland*

The lecture is about the lessons learnt from a 30 years' journey of the author as a pioneer, scientist, designer, and lecturer in the field of fibre-polymer composites, applied to structural engineering and architecture. The lecture starts with the appearance of first composite bridges and buildings in the 1990s and then focuses on vehicular bridges, adhesive connections, function integration in building construction, durability and sustainability, and ends with conclusions about opportunities for composites and research needs.

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## Alternative methods to qualify adhesively-bonded repair composites in damage pipelines

abst. 1236
**CIMA**
Wednesday
June 24
11h30

*Reis, J.M.L. (jreis@id.uff.br), Universidade Federal Flumiensne, Brazil*

Composite repair systems for metallic pipelines presenting a through-wall defect must be qualified in accordance with either ISO 24817 or ASME PCC-2 standards. This qualification method requires a number of hydrostatic tests to obtain the failure pressure, which demands time and high costs. In the oil and gas industry, the failure pressure estimation is often performed using a linear fracture mechanics analysis described in both ISO and ASME standards. These standards require the determination of a constant fracture energy, also called the energy release rate. In the case of monotonically increasing

loading histories, in the framework of linear fracture mechanics, brutal interfacial debonding occurs when the fracture energy reaches a critical value. This study is an attempt to show that simpler tests, such as, shaft-loaded, pressurized blister test or DCB joints can be employed as an alternative to hydrostatic tests in the qualification of repair systems. Results show a reasonable similarity between the critical energy values found using such alternatives with the ones obtained with the standard required hydrostatic tests.

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abst. 1239
**CIMA**
Thursday
June 25
14h30

## Atomistic Simulation of Toughness Increase due to Crack-Tip Shielding by Embedded Nanoparticles in Carbon Nanocomposites

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It is now well documented in the literature that the inclusion of nanoparticles, such as graphene nanoplatelets (GNP), in matrix materials, such as epoxy, can result in significantly improved fracture toughness in mode I and mixed-mode. One of the mechanisms postulated to increase the effective crack initiation fracture toughness is the crack tip shielding effect due to nanoparticles in the fracture process zone. This effect is deemed to arise due to debonding of nanoparticles from the matrix material in the process zone, which in turn reduces the stress state at the tip of the primary crack via shielding. Thus, debonding of nanoparticles act to redistribute stress in the crack tip region, thereby lowering the near tip stress intensity factor, depending on their orientation relative to the crack. Therefore, higher far-field loads can be achieved before the critical stress intensity is reached at the crack tip. In this paper the novel K-field approach is used in conjunction with molecular dynamics (MD) to model fracture in an amorphous carbon matrix material, with embedded GNPs. Amorphous carbon matrix is deliberately selected to facilitate the computational efficiency of the solution process, because the fracture process zone size for amorphous carbon is relatively small from a MD simulation viewpoint. Moreover, amorphous carbon is gaining popularity as a precursor for high temperature carbon-carbon composites. The effect of GNPs on the shielding of the crack tip, with different orientations (vertical, horizontal, and 45 degrees to the crack plane) and location relative to the crack-tip is thoroughly investigated using detailed virial stress plots, the atomistic J-integral, and compared with linear elastic fracture mechanics (LEFM) predictions. Significant crack-tip shielding by GNPs is predicted from MD simulations, both at crack initiation and also during crack propagation.

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abst. 1313
**CIMA**
Thursday
June 25
09h00

## GFRP Rebars in Concrete Construction: Carbon-Footprint Reduction and End-of-Life Reuse/Recycling Pathways

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Most pultruded composite bars used as internal reinforcement in concrete elements and structures are GFRP rebars (Glass Fiber Reinforced Polymer). The primary driver is economic: when expressed as cost per unit of allowable tensile capacity, GFRP bars are typically around one quarter of the equivalent carbon-FRP option, even after accounting for the lower elastic modulus of GFRP, which may require a larger bar area to control serviceability (crack width and reinforcement strain). In normal-strength concrete, tensile cracking occurs at very small strains (on the order of 150 micro strain) depending on the concrete tensile strength and modulus), making stiffness a governing parameter at SLS. Because of the relatively low modulus of GFRP and the limited ductility of concrete, demolition/deconstruction of GFRP-reinforced concrete tends to impose lower peak stresses on the continuous reinforcement. As a result, pultruded bars may have a higher probability of being recovered intact and potentially reused (after appropriate inspection and qualification), rather than being downgraded to waste. Beyond end-of-life considerations, replacing steel reinforcement with GFRP can reduce the whole-life carbon footprint,

primarily by eliminating corrosion-driven deterioration and the associated repair/strengthening cycles. Steel-reinforced concrete durability is often governed by carbonation- or chloride-induced depassivation and corrosion; once alkalinity is reduced and corrosion initiates, repairability and remaining service life can be severely compromised. Corrosion-free reinforcement is therefore particularly attractive for structures in aggressive environments (marine/offshore, saline soils), where it can unlock longer design working life and enable structurally optimized concrete components intended for prolonged exposure to seawater (e.g., coastal protection systems). The talk will quantify these aspects from the literature and will also outline ENEA's ongoing RD actions aimed at improving the performance, durability, and sustainability of pultruded GFRP rebars, with specific attention to circularity and end-of-life pathways.

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## AI-driven damage evaluation and characterization methods for woven composites and structures

abst. 1381
**CIMA**
Wednesday
June 24
09h00

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Woven composites have significant applications in industrial fields, but their complex macro-meso-micro multiscale structural characteristics and spatially interlaced mesoscopic woven architecture lead to multiple bottlenecks in the multiscale damage evaluation and characterization: (1) Damage evolution is a highly localized problem, but there is a lack of computational methods for composite RVE meeting the demand for "fast and accurate" solutions; (2) There is a lack of concurrent multiscale damage models that address the need to overcome the "curse of dimensionality"; (3) The fundamental mechanical parameters of woven composites are difficult to measure comprehensively, the multiscale damage mechanisms are challenging to characterize accurately, achieving dual-validation including strength and life predictions is difficult. To address these issues, the investigation removes the constraints of static partitioning schemes and piecewise uniform assumptions on cluster-based reduced-order models. The Damage-related Adaptive Self-Consistent Clustering Analysis method and the Self-consistent Clustering Analysis framework with field refinement capability are proposed. They provide effective strategies for achieving "fast and accurate" computations of composite damage evolution. A meso-micro concurrent multiscale model SCA-DNN based on the damage evolution genome database is proposed. It achieves a multiscale computational dimensionality reduction of seven orders of magnitude compared to the $FE^2$ method. The multiscale damage characterization and strength prediction techniques based on AI+acoustic emission for composites are established. An attention mechanism-improved U-NET model is proposed to achieve precise crack identification in CT images and quantitative analysis of multi-mode crack evolution.

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## Inverse Differential Quadrature Method for analysing sustainable high performance composite structures

abst. 1397
**CIMA**
Tuesday
June 23
11h30

*Weaver, Paul M. (paul.weaver@ul.ie), University of Limerick, Ireland*

Sustainability and high-performance are not mutually exclusive. Using the least amount of a material in a structure that is required to move (i.e. transport systems) is arguably the most environmentally favourable choice available. Efficient analysis and design tools are required to minimise mass of structures. State-of-the-art finite element analysis codes are wonderfully versatile and increasingly reliably effective tools for analysing structures. However, their inherent adaptability comes at a cost of computational efficiency. New structures with highly varying material properties, where performance driven by nonlinear behaviour is challenging for commercial codes. Indeed rigorous analysis is not necessarily guaranteed and optimisation can be prohibitively computationally expensive. This bottleneck suggests the development of computationally structural analysis methods that fit the problem at hand. Here, we introduce the emerging inverse differential quadrature method that combines strong form solution methods with some elements of weak form to offer significant computational efficiencies compared to state-of-the-art. Example structures. will be drawn from beams, plates and shells as well as multiphysics problems.

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## Micro- and nano-mechanics

abst. 1001
**Repository**

### Micromechanical Modeling of Hysteretic Responses in Hybrid Magnetostrictive-Polymer Composites

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This study investigates the nonlinear and hysteretic responses of hybrid magnetostrictive-polymer composites. Magnetostrictive constituents exhibit hysteresis due to irreversible magnetic domain alignment and internal energy loss under applied magnetic fields, while polymer matrices often display pronounced time-dependent (viscoelastic) behavior under mechanical or environmental loading. To capture these coupled effects, a two-scale micromechanical framework is developed to analyze the combined influence of magnetostrictive hysteresis and polymer viscoelasticity on the overall hysteretic response of the composite. Model predictions are first validated against experimental data from the literature. Parametric studies are then conducted to examine the effects of boundary conditions, fiber volume fractions, prestress levels, loading rates, and environmental temperatures. In particular, the role of magnetostrictive hysteresis intensity (strong vs. weak) on the viscoelastic hybrid response is analyzed. The results provide valuable insight into the design of multifunctional composite structures and support their development for advanced engineering applications.

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abst. 1133
**CIMA**
Friday
June 26
09h00

### What kind of surface elasticity do we need? A view from the lattice dynamics perspective.

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The theory of surface elasticity originated from earlier works by Young, Laplace, Poisson and Gibbs. In the 1970s, Gurtin and Murdoch proposed a rational model [1-3], which was generalised by Steigman and Ogden in the 1990s [4, 5]. These models have been used to model various size effects observed at the nanoscale, as well as some macroscopic phenomena. Surface elasticity is based on the introduction of constitutive equations at a free surface or interface. These include surface deformation energy and surface kinetic energy density. It has been demonstrated that the presence of surface/interfacial stresses significantly impacts the effective properties of materials at small scales, particularly when the ratio of particles near the surface to particles in the bulk is relatively high [6]. Furthermore, surface energetics can result in the appearance of specific types of surface waves, sometimes referred to as Murdoch waves [7]. The continuum-type model of surface elasticity is closely related to lattice dynamics. Indeed, the appearance of surface tension or stresses can be explained by considering the crystalline structure of the material and the difference in bond properties near the free surface and in the bulk (see, for example, [8]). In particular, a scaling law connecting lattice dynamics with surface elasticity was proposed in [9]. It was also demonstrated in [10] that discrete systems, such as a square lattice, can exhibit more intricate dispersion properties than the continuum models of Gurtin and Murdoch or Steigman and Ogden. Surface elasticity can also describe thin coatings or interfaces. As demonstrated in [11], microstructured interfaces cannot be described by these models and require more complex models of surface elasticity. The aim of this lecture is to discuss the correspondence between lattice dynamics and surface elasticity, focusing on the relatively simple case of small anti-plane motions. Using the approach outlined in references [9, 10], we will discuss the dispersion relations of a few discrete structures. These include an elastic half space with a surface layer of different particles and some models of interfaces between two elastic half spaces. These interfaces differ in structure. We then use the obtained dispersion relations to discuss possible continuum models of surface elasticity that exhibit similar behaviour. References: 1. Gurtin, M.E. and Ian Murdoch, A., 1975. A continuum theory of elastic material surfaces. Archive for rational mechanics and analysis, 57(4). 2. Gurtin, M.E. and Murdoch, A.I., 1978. Surface stress in solids. International journal of Solids and Structures, 14(6). 3. Gurtin, M.E., Weissmüller, J. and Larche, F., 1998. A general theory of curved deformable interfaces in solids at equilibrium. Philosophical Magazine A, 78(5). 4. Steigmann, D.J. and Ogden, R., 1997. Plane deformations of elastic solids with intrinsic boundary elasticity. Proceedings of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences, 453(1959). 5. Steigmann, D.J. and Ogden, R., 1999. Elastic surface—substrate interactions. Proceedings of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences, 455(1982). 6. Duan, H.L., Wang, J. and Karihaloo, B.L., 2009. Theory of elasticity at the nanoscale. Advances in applied mechanics, 42. 7. Rousseau, M. and Maugin, G.A., 2012. Quasi-particle aspects of Murdoch surface acoustic waves. The Quarterly Journal of Mechanics  Applied Mathematics, 65(2). 8. Murdoch, A.I., 2005. Some fundamental aspects of surface modelling. Journal of Elasticity, 80(1). 9. Eremeyev, V.A. and Sharma, B.L., 2019. Anti-plane surface waves in media with surface structure: Discrete vs. continuum model. International Journal of Engineering Science, 143. 10. Eremeyev, V.A., 2025. Anti-plane interfacial waves in a square lattice. Networks  Heterogeneous Media, 20(1). 11. Eremeyev, V.A., Rosi, G. and Naili, S., 2024. On effective surface elastic moduli for microstructured strongly anisotropic coatings. International Journal of Engineering Science, 204.

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## Effect of Hydroxyapatite Particle Size on the Mechanical Properties of PMMA-Based Composite Bone Cement

abst. 1295
**CIMA**
Friday
June 26
09h20

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Poly(methyl methacrylate) (PMMA) bone cements are widely used in orthopaedic fixation; however, their limited mechanical strength and bioactivity restrict broader clinical applications. Reinforcement with hydroxyapatite (HA) can enhance both mechanical performance and biological integration, yet the effect of HA particle size on these improvements remains insufficiently understood. This study systematically evaluates how nanoscale and microscale HA particles influence the mechanical behaviour of PMMA-based composite bone cements. Three HA particle size ranges (60 nm, 200 nm, and 2.5 m) were incorporated into commercial PMMA cement at a constant volume fraction. Compressive strength, Young's modulus, and surface hardness were determined under controlled conditions following ISO specifications for acrylic bone cements. The composites were further analysed using scanning electron microscopy to assess filler dispersion and interfacial bonding. Experimental results reveal pronounced particle size dependence. These findings demonstrate that HA particle size critically governs the mechanical response of PMMA/HA composites, offering design guidelines for preparing bone cement formulations toward optimized performance.

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## Dispersion and localization of anti-plane waves in layered lattice composites

abst. 1434
**CIMA**
Friday
June 26
10h00

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We examine the propagation of anti-plane shear waves localized along a multi-layered interface within lattice structures. The system is composed of two semi-infinite media—either homogeneous or characterized by distinct mechanical properties—separated by a three-layer interface region, whose stiffness may differ from that of the adjacent bulk domains. A discrete lattice framework is adopted, where masses are interconnected through elastic bonds with region-dependent properties. Within this setting, a lattice-dynamics formulation is employed to analytically derive the dispersion relations governing wave propagation along the interface. Particular attention is devoted to the influence of mechanical contrast between the bulk media and the interfacial layers, assessing how variations in stiffness affect wave localization and dispersion characteristics. The results provide insight into the role of structured interfaces in guiding and confining wave motion in discrete systems, with potential implications for the design of engineered materials with tailored dynamic properties.

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abst. 1436
**CIMA**
Friday
June 26
09h40

## Multistability in beam-lattice structures

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In recent years, beam-lattice metamaterials have attracted increasing attention due to their ability to replicate the behavior of classical crystalline lattices while exhibiting advantageous properties such as low density, high deformability, and enhanced energy absorption. Within this class of materials, mechanical instabilities—analogous to Euler buckling—play a key role in governing their macroscopic response. For instance, in elastomeric open-cell foams, such instabilities give rise to characteristic plateau regions in the force–displacement response at the microscale, resembling plastic-like behavior. This contribution focuses on the analysis of multistable structures, defined as systems capable of admitting multiple equilibrium configurations under the same external load. These systems often exhibit complex nonlinear phenomena, including snap-through and snap-back responses. As a representative case, a periodic truss structure composed of unit cells inspired by the von Mises truss is investigated. Equilibrium equations are derived and the corresponding equilibrium paths are explored. Despite the apparent simplicity of the structural scheme, the resulting mechanical response proves to be highly intricate, with equilibrium paths characterized by multiple branches and loops. Parametric analyses are performed to highlight the influence of key geometric and mechanical parameters on system behavior. Finally, the study addresses advanced modeling strategies based on effective continuum descriptions incorporating material instabilities, providing a framework for bridging discrete lattice behavior and macroscopic response.

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## Drop-In Reinforcement: A Simple Method for integrating VACNTs into Epoxy Adhesive Films

abst. 1387
**TIGELLIO**
Friday
June 26
15h30

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Lightweight structures in aerospace and automotive are reliant on high-performance adhesive films for composite joining. However, shear strength and delamination at the bond line often remain limiting factors in joint design. Vertically Aligned Carbon Nanotubes (VACNTs) are promising reinforcements due to their high aspect ratio, tensile strength, and alignment perpendicular to the substrate. Despite this potential, it remains challenging to transfer the delicate VACNT architecture from the growth substrate into a thin adhesive film without damaging the forest. In this study, we 1) present a novel transfer method using a flip chip bonder for the precise integration of VACNTs into a commercial epoxy film and 2) evaluate the resulting effect on single lap shear performance. VACNT forests were synthesized via chemical vapor deposition (CVD). To enable a clean and effective removal from the silicon growth substrate, we performed an in-situ water etch at the end of the growth to weaken the interface between the catalyst and the CNT forest. Carbon fiber epoxy composite adherends were prepared, and a layer of FM300 epoxy film adhesive was applied to the bond area. Using a flip chip bonder, the VACNT forest was brought into contact with the uncured adhesive film at a slightly elevated temperature (below the cure onset) to promote tackiness and wetting, ensuring the forest was embedded without damaging its vertical alignment. The assembly was then cured according to manufacturer's specifications. Single lap shear (SLS) testing was conducted according to ASTM D1002 to quantify the adhesion strength, with neat adhesive films serving as reference. Mechanical testing revealed that the integration of the VACNT forest resulted in a measurable increase in joint single lap shear strength compared to the neat FM300 baseline. This enhancement confirms that the VACNTs were successfully transferred and remained engaged at the adherend-adhesive interface. The improvement is attributed to the VACNTs promoting enhanced load transfer and microcrack bridging. The process is designed as a simple post-application step: the VACNTs are applied directly to the uncured adhesive film immediately prior to bonding, rather than being incorporated during film manufacturing. This allows the reinforcement strategy to be applied to any adhesive film without modifying the existing production process. This study validates a method for the successful integration of VACNT forests into epoxy adhesive films using a flip chip bonding technique. The process preserves the structural integrity of the VACNTs and does not compromise the film's baseline performance. The positive gain in lap shear strength confirms that VACNTs contribute to the reinforcement of structural bonds. These findings open the door for further optimization, such as tuning VACNT density, height, and surface functionalization, to maximize the reinforcement potential for structural adhesives.

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## Multi-scale analysis of composites

abst. 1041
**TIGELLIO**
Tuesday
June 23
17h10

### Torsional dynamic response of swcnt-reinforced nanocomposites with interfacial stress concentrations

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Polymer nanocomposites reinforced with Carbon nanotubes are increasingly use in advanced composite structures, particularly in the aerospace, green energy, and automotive engineering applications. Therefore, a comprehensive investigation of their dynamic behaviour is vital for the development of novel material designs and cost-efficient manufacturing processes. Due to higher risk of buckling and fracture in the nanotubes and the interface regions in nanocomposites under torsional loadings, the torsional mode of vibration becomes critical. Moreover, torsional vibration is very common and critical in machine components such as power generation and transmission systems and spinning shaft-disc systems. Hence, understanding the torsional dynamic response and behaviour of Carbon-Nanotube-reinforced nanocomposites is important. In practical fabrication, interfacial defects, especially nanotube–polymer debonding, are inherent and unavoidable. Therefore, characterizing the influence of such defects on the material stiffness and the resulting changes in the dynamic behaviour of nanocomposites is essential. However, dynamic experimental characterization is very expensive, prone to inconsistency, and frequently infeasible. As an alternative, the multiscale computational material modelling developed based on multiscale finite elements and multiscale mechanics, provides a robust, accurate, and cost-efficient approach for assessing the dynamic behaviour. In the present study, a multiscale finite element model based on the Representative Volume Element (RVE) approach of a nanocomposite material with Single-Walled Carbon Nanotube (SWCNT) as reinforcement phase is developed in ABAQUS environment. The RVE model consists of SWCNT, interfacial region, and polymer matrix. The SWCNT is modelled as a thin shell characterized by using a spatial nano-frame atomic structure and the Morse potential law. The interface between SWCNT and polymer matrix is represented using Van Der Waals bonding based on the Lennard-Jones potential. The stiffness distributions within the RVE and the modal response of the RVE are determined for torsional vibrations. The dynamic material properties including torsional natural frequencies, torsional mode shapes and torsional critical damping coefficients of the RVE are determined. The simulation results are verified using existing studies. The effects of interfacial debonding at different locations and in various patterns on the stiffness distributions within RVE and consequently on the dynamic response of RVE in torsional vibration modes are characterized. Based on these, aspects of material design and manufacturing considerations are systematically established.

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abst. 1068
**TIGELLIO**
Tuesday
June 23
12h50

### Analysis of the effect of fibre-prestressing on residual stresses in CFRP/steel hybrid components using a micromechanics-based finite element simulation with a dehomogenization method

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Residual stresses in directly joined hybrid structures made of steel and carbon-fibre-reinforced epoxy (CFRP) significantly affect the interface and overall joint strength, and therefore must be considered when evaluating the structural integrity of lightweight components. The application of fibre-prestressing (FP) to the CFRP component allows control and reduction of these residual stresses. In this study, fibre-prestressing was applied to the CFRP layer at defined prestressing levels of 20 MPa and 60 MPa using a dedicated clamping and press-forming system, and hybrid laminates were manufactured by stacking unidirectional, pre-impregnated semi-finished products (prepregs). Following the direct hybrid

manufacturing process, the pre-impregnated CFRP layers were placed onto the pre-formed steel substrate and cured under controlled temperature and pressure conditions. The resulting residual stresses and their distribution in the thickness direction were analysed experimentally and numerically and compared between the without fibre-prestressing (w/oFP) and with fibre-prestressing (w/FP) conditions. For the strength evaluation of the metal-fibre laminates, quasi-static mechanical tests were conducted, including the single-lap shear and interlaminar shear strength (ILSS) methods, in order to analyse the influence of fibre-prestressing on the load-bearing behaviour and failure mechanisms of the hybrid joints. In the subsequent part of the study, a material model was developed using a numerical homogenization technique based on representative unit cells to calculate effective cure-dependent thermo-mechanical properties for numerical analysis. The heterogeneous microstructure was modelled with a thermo-chemo-viscoelastic constitutive model for the epoxy matrix, and the material model was implemented as a user material (UMAT) in Abaqus/Standard. The homogenized material was applied in the curing and simultaneous hybridization simulation of a flat steel–CFRP hybrid, in which the CFRP was modelled as a transversally isotropic unidirectional laminate. After passing through the hardening process, the resulting residual stresses in thickness direction were analysed for the CFRP and steel components and then validated using the incremental hole drilling method. Based on this modelling framework, a dehomogenization method was utilized that allows the deformation state to be measured at selected points in the macrostructure and applied to selected microstructures by subjecting the representative unit cell to the specified temperature-time curing profile followed by loading with the macroscopic strain tensor. The results demonstrate that fibre-prestressing reduces residual thermal stresses and laminate deflection, leading to improved structural performance. This confirms fibre-prestressing as an effective approach to tailor residual stress states and enhance dimensional stability in intrinsically manufactured fibre-metal hybrids. The simulation results were validated using the incremental hole drilling method, showing good agreement between predicted and experimentally measured residual stresses. Last but not least, the presented dehomogenization method closes the multi-scale analysis by enabling the feedback from the macroscopic level to the microscopic level, allowing the effect of the macroscopic residual stress state to be evaluated within the representative unit cell.

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## Multi-Scale Investigation of Matrix Failure in Fiber-Reinforced Composites: A Parametric Study of Constituent and Interface Properties

abst. 1079
**TIGELLIO**
Tuesday
June 23
12h30

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Multiscale analysis of fiber-reinforced composites has been widely conducted to investigate failure mechanisms induced by mesoscopic stress fields. Meanwhile, extensive efforts have been devoted to developing resin matrices with higher strength and interface toughening strategies that provide improved bonding performance. However, the compatibility between the properties of composite constituents under different loading conditions and fiber volume fractions, as well as the boundaries governing transitions between failure modes, has not been sufficiently studied. Based on a representative volume element construction method proposed by the author, this study investigates the failure behavior of composites over a wide range of fiber volume fractions (from 40% to 75%). The influences of variations in matrix, fiber, and interface properties on failure modes and failure loads are examined. In addition, different application scenarios are considered, including mechanical loading and thermo-mechanical loading conditions. The results indicated that the matching relationships between matrix

and interface properties depend on the type of fiber used. The thermal expansion coefficient, modulus, and strength of the resin matrix all affect the mesoscopic stress field and the resulting failure behavior. The properties of the fiber, matrix, and service conditions impose specific requirements on interface performance. When the interface properties are below a critical threshold, mesoscopic failure tends to occur through combined matrix and interface failure modes. When the interface properties exceed this critical value, further interface toughening provides little benefit in improving the overall performance of the composite. This study explicitly identifies the performance requirements for matrix modification and interface toughening aimed at enhancing the overall mechanical performance of fiber-reinforced composites, and provides useful guidance for future research.

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abst. 1089
**TIGELLIO**
Tuesday
June 23
15h10

## Macrohomogeneity in Micropolar Continua for Composite Materials

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Multiscale homogenization is a well-established technique, widely developed in computational schemes, which allows to evaluate the effective response of heterogeneous composite media both in linear and non-linear material behavior ranges [1]. Within this framework, a generalized Hill-type macrohomogeneity condition is proposed for the multiscale modeling of heterogeneous micropolar continua [2-4]. The formulation relies on an explicit separation of symmetric and skew-symmetric components of strain and stress, allowing a rigorous description of their energetic coupling with curvature and couple stress measures. Within a unified tensorial framework, consistent Dirichlet and Neumann boundary conditions are directly derived from power equivalence, ensuring scale-consistent energy balance. The approach is validated through Finite Element Analysis on both homogeneous and heterogeneous media, demonstrating the energetic consistency of the formulation [5]. The proposed framework provides a robust basis for advanced multiscale modeling of complex microstructured composite materials. Keywords: Micropolar continua, Generalized macrohomogeneity condition, Skew-symmetric strain and stress, Dirichlet and Neumann boundary conditions. Acknowledgements: This work is supported by MIUR, project: National Center on HPC, Big Data and Quantum Computing (ICSC), PNRR - CN1- Spoke6 (CUP: B83C22002940006), Sapienza Ateneo Progetti Grandi (CUP: B83C24007070005), and PROGETTO MUSICS - FISA-2023-00099 (CUP: B83C25000810001). References: [1] Trovalusci, P. Molecular approaches for multifield continua: origins and current developments. In Multiscale modeling of complex materials: phenomenological, theoretical and computational aspects, 211–278, Springer, 2014. [2] Hill, R. Elastic properties of reinforced solids: some theoretical principles. Journal of the Mechanics and Physics of Solids, 11(5):357–372, 1963. [3] Liu, Q. Hill's lemma for the average-field theory of Cosserat continuum. Acta Mechanica, 224, 851–866, 2013. [4] Trovalusci, P., Ostoja-Starzewski, M., De Bellis, M.L., Murrali, A. Scale-dependent homogenization of random composites as micropolar continua. European Journal of Mechanics-A/Solids, 49:396–407, 2015. [5] Trovalusci, P., De Bellis, M.L., Ongaro, G. On a macrohomogeneity condition for micropolar continua: the role of skew-symmetric strain and stress. To be submitted, 2026.

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abst. 1104
**TIGELLIO**
Tuesday
June 23
13h10

## Multiscale analysis of the interphase in ceramic matrix composites

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Interphase layer plays a crucial role on the pseudoplasticity behavior and failure mechanism of fiber reinforced ceramic matrix composites (FRCMCs). Experiments have demonstrated that increasing the interphase thickness can cause non-monotonic changes in both matrix cracking stress and ultimate strength. However, the underlying mechanism has not been revealed. Therefore, we conducted an multisacle analysis on the effect of the interphase layer on the damage and failure of FRCMCs. We

found that the interphase layer works mainly through relieving residual thermal stress (RTS), adjusting interfacial friction, altering interfacial shear stress, and influencing debonding toughness. To quantitatively evaluate these factors, we firstly conducted theoretical analysis for the damage evolution of FRCMCs at the mesoscale. The Coulomb friction law was adopted to describe the interfacial friction in the debonded region, and the influence of the Poisson effect, RTS, and interface roughness on the interfacial friction were further considered as thoroughly as possible. Thereby, a comprehensive mechanical model for the tensile behavior of FRCMCs, involving the matrix cracking stress, ultimate strength as well as stress-strain relationship was derived. Based on this model, three cracking modes, i.e., perfectly bonded, debonding with and without interfacial separation were identified and the mechanism of non-monotonic influence of interphase thickness was thoroughly revealed as the transition of the cracking modes. Moreover, a set of parameters describing the interfacial property of FRCMCs was proposed, including the Coulomb friction coefficient, debonding toughness, axial and radial residual stress. To further reveal the effect of interphase layer on FRCMCs, we then investigated the effect of microtexture of Pyrolytic Carbon (PyC) interphase layer on the interface performance through a series of molecular dynamics (MD) simulations at the nanoscale. MD results indicate that the orientation angle (OA) plays a dominant role on the interfacial behavior at the nanoscale. As the gradual increase of OA, interfacial shear deformation behavior transforms from localized penetrating sliding into large-scale uniform plasticity, attributed to the trade-off between domain dispersity and pore-like defects of PyC. The interphase layer of high texture (OA<50o) has a lower debonding toughness, making it easier to deflect matrix cracks and avoid brittle failure, while the interphase layer of low texture (OA>80o) leads to a higher interfacial friction, which helps to enhance the toughening effect of fibers on FRCMCs. These results provide theoretical guidance for the optimization of interphase layer of FRCMCs.

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## Predictive Multiscale Modelling and Simulation of Lightweight Honeycomb Sandwich Structures

abst. 1152
**Repository**

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Sandwich structures with honeycomb cores are widely used in lightweight engineering due to their exceptional stiffness-to-weight ratio, thermal stability, and damage tolerance. However, their design and optimization remain challenging because the structural response is governed by coupled phenomena acting across multiple length scales, from material microstructure to global structural behaviour. The objective of this study is to develop and demonstrate a multiscale simulation framework for sandwich honeycomb structures that enables weight-efficient design while ensuring structural integrity, thermal stability, and manufacturing feasibility under combined thermo-mechanical loading. The proposed approach integrates micro-, meso-, and macro-level modelling. At the micro-scale, effective properties of composite face sheets and adhesive joints are derived considering anisotropy, curing effects, and residual stresses. At the meso-scale, detailed honeycomb core models account for cell geometry, height, orientation, and material orthotropy. These homogenized properties are then transferred to macro-scale finite element models of full sandwich panels and representative components. The framework is validated through comparison with experimental data and full-scale tests reported in prior developments. The multiscale simulations reveal that local meso-scale parameters of the honeycomb core and face-sheet layup have a decisive influence on global stiffness, stress distribution, and failure margins. Optimization of honeycomb geometry and adhesive application strategy enables significant mass reduction while maintaining or improving load-bearing capacity. The proposed approach demonstrates weight savings of up to 20% compared to baseline designs, with good agreement between numerical predictions and experimental observations. The presented multiscale simulation framework provides an effective and physically consistent tool for the design and optimization of sandwich honeycomb structures. By enabling systematic transitions between length scales, the proposed approach enhances predictive accuracy

and supports the design and optimization of lightweight, reliable sandwich components for advanced lightweight engineering applications.

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abst. 1250
**TIGELLIO**
Tuesday
June 23
12h10

## A hybrid data-driven and symbolic regression approach for elastoplastic behaviors of composite materials

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To address the limitations in interpretability and physical consistency of machine learning (ML) models applied to solve elastoplasticity problems, this study proposes a hybrid ML framework that integrates symbolic regression (SR) with a data-driven approach. This integration ensures that the proposed model is not only highly accurate but also interpretable and consistent with the fundamental principles of elastoplasticity theory, while significantly reducing computational costs. Specifically, a representative volume element (RVE) incorporating microstructural information is employed to generate principal strain-stress data through finite element method (FEM). The internal variable that characterizes the plastic behavior of composite materials is then extracted from the strain-stress data. A yield surface function is formulated through SR based on the principal stress-strain data and internal variable. The resulting yield function and principal strain-stress data are incorporated into a data-driven computation framework to predict the elastoplastic responses of composite materials. The effectiveness of the proposed method is validated through comparisons with the direct numerical simulation in two case studies, demonstrating its superior computational efficiency and predictive accuracy.

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abst. 1316
**TIGELLIO**
Tuesday
June 23
15h30

## A novel multi-scale model for shear deformation of thick composite beams

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In thick beams, shear effects are often non-negligible. For composite beams, multiscale methods can significantly improve computational efficiency. However, the transfer of shear strain remains a challenge at both macro and micro scales. This study is based on the Timoshenko beam theory, incorporating the principles of microscale structure balance, energy equivalence, and stress averaging, and proposes a multiscale model for thick beams that accurately captures shear effects. In the axial direction of the beam, it is assumed that strain averaging is valid, leading to the derivation of periodic boundary conditions for axial displacement. Since shear strain averaging does not hold, non-periodic boundary conditions are applied for out-of-plane displacement. By approximating the normal stress under bending deformation as the normal stress under shear deformation, and utilizing the equilibrium equations to derive shear stress, the model is further developed. Additionally, the study uses the material's neutral axis instead of the geometric neutral axis to avoid introducing fictitious axial forces at the boundaries. Reference solutions from detailed models in ABAQUS are used to analyze the macroscopic deformations and microscopic stresses of symmetric, antisymmetric, and complex-structured beams. The results demonstrate that the proposed multiscale model accurately describes both macroscopic deformations and microscopic stresses.

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abst. 1342
**TIGELLIO**
Tuesday
June 23
15h50

## Data-driven-AI and Component-Wise-based Unified Models for the free vibration analysis of sandwich spherical panels with auxetic lattice core

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Equivalent-Single-Layer (ESL) and Layer-Wise (LW) models are uncapable of capturing local effects of auxetic-cored structures due to the use of homogenization techniques, leading to neglection of relevant phenomena, especially in high-frequency bandwidth. Therefore, in this work, the high-fidelity Component-Wise (CW) approach is employed as the variable description for building two-dimensional models within a Unified Formulation framework in order to study the free vibration behavior of sandwich shells with auxetic lattice core and isotropic skins. The cross-sections of both the auxetic core and skins are discretized employing higher-order Lagrange polynomials. Weak-form solutions are obtained by using the Finite Element Method (FEM) with MITC9 elements. Moreover, a surrogate deep-neural-network (DNN) is trained and tested using hyperparameter tuning, cross-validation, regularization technique. Several parametric studies are developed with the DNN model in order to analyze the influence of the geometric dimensions of the plate and the auxetic unit cell.

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## A SCA-DNN multiscale model for 3D woven composites based on the damage evolution genome database

abst. 1380
**TIGELLIO**
Tuesday
June 23
16h10

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The damage mechanisms of 3D woven composites are characterized by multiscale and multimode features, necessitating the development of efficient and accurate multiscale damage evolution models to reveal their damage behavior. However, current macro-meso-micro concurrent multiscale damage evolution models suffer from the "curse of dimensionality", which requires the integration of AI models to resolve. The study proposes an SCA-DNN multiscale model based on the material damage evolution genome database to predict the meso-micro damage evolution behavior of 3D woven composites in parallel. In the model, the mesoscale problem is solved using the Self-Consistent Clustering Analysis (SCA) method, while the microscale problem is addressed through a Deep Neural Network (DNN) to achieve equation-free solutions. A SCA-driven high-fidelity damage information compression method is introduced to obtain the homogenized stress and microscopic damage evolution data of the microscopic representative volume element. A total of 200000 datasets are collected in the damage evolution genome database for training the DNN. The simulation analyses of 3D woven composites under four typical loading conditions using the SCA-DNN method demonstrate three key advantages: (1) The stress-strain curves and dominant failure modes predicted by the SCA-DNN method are in excellent agreement with experimental results; (2) The meso-micro multiscale damage evolution processes predicted by the SCA-DNN method are highly consistent with those obtained from the SCA2 method; (3) Compared to the SCA2 model, the SCA-DNN model achieves a 2-4 times improvement in computational efficiency.

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## Micromechanics multiscale damage model for soil-based composites: experimental and numerical analysis

abst. 1424
**TIGELLIO**
Tuesday
June 23
16h30

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This work presents a multiscale micromechanical damage model for predicting the nonlinear mechanical behavior of soil-based composite. Due to the similarity of these materials with concrete, the material is treated as a heterogeneous multi-phase composite. The Mori–Tanaka homogenization scheme is used within a three-level multiscale framework, progressively homogenizing cement porous paste, mortar, and concrete phases. To extend the model to soil-based composites, the concept of Fictitious Element Inclusion (FEI) is employed, addressing the limitations of classical mean-field homogenization in

presence of large stiffness differences between matrix and inclusions. This represents a key challenge when incorporating soft soil phases into a stiff cementitious matrix. A nonlinear damage evolution law driven by the porosity of the composite as an internal variable is introduced to capture stiffness degradation under compressive loading, consistent with a thermodynamically admissible continuum damage mechanics framework. The predictive capability of the model is validated against experimental data from unconfined compression tests, demonstrating good agreement for various composite configurations, from standard concrete to mixtures with up to 50% earth content. The proposed approach offers a computationally efficient and physically grounded framework for the mechanical characterization of innovative sustainable composite materials. Acknowledgements: Materials and Structures Testing Laboratory of the University of the Republic of San Marino is gratefully acknowledged for the support during the experimental campaign. The financial support of the Italian Ministry of University and Research (MUR) through the research grant FISA-2022-00183 "EARTH-TECH" (code 00183; CUP: E93C24000250001) is gratefully acknowledged. The financial support of the University of the Republic of San Marino through the research grant PRIU2024 "Progettazione Sostenibile e Tecnologie Avanzate per il Settore delle Costruzioni: Caratterizzazione e Analisi di Materiali e Sistemi Strutturali Innovativi ed Ecocompatibili" is gratefully acknowledged.

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abst. 1427
**TIGELLIO**
Tuesday
June 23
16h50

## Numerical and experimental study on the tensile behavior of C/SiC mini-composites

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Carbon fiber reinforced silicon carbide composites are ideal candidates for aerospace components serving in high-temperature environments due to the excellent thermomechanical properties. Prediction of the complex nonlinear failure behavior of the C/SiC composites typically requires multiscale analysis, for which the accurate modelling at the microscale level lays the foundation for meso- and macroscale prediction of material behavior. Theoretical models at the microscale, for example the Bridging model and Chamis model, necessitate simplified assumptions which limit their predictive capacity. While representative volume element (RVE) models are better suited for refined microscale modelling of yarn behavior, they typically lack direct experimental validation. On the other hand, experimental results from mesoscale woven composites can hardly be used to validate the micro-RVE accuracy due to the effect of fabric architecture. Mini-composite specimens enable direct experimental characterization of microscale mechanical behaviors. A series of tensile tests on C/SiC mini-composites were conducted in the current research. Utilizing data obtained from X-ray computed tomography (X-CT), micro-RVEs were developed with porosity and fiber volume fraction accurately reflected. The simulation results showed reasonable agreement with the mini-composite test results, verifying the rationality of the progressive damage constitutive behavior adopted in the micro-RVE models. Furthermore, energy dissipation mechanisms, including interface debonding and fiber pull-out, were observed via scanning electron microscopy (SEM) fractography. These observed features reveal the microscale toughening mechanisms and provide a basis for understanding the nonlinear mechanical behavior of the composite. The experimental validation ensures the accuracy of microscale behavior inputs, improving the reliability of the subsequent multiscale analyses.

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## Optimization techniques and methods

### Neural Network-based Strength Constraint Implementation for Composite Optimization in the Lamination Parameter Design Space

abst. 1077
CIMA
Thursday
June 25
09h40

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*Kriegesmann, Benedikt (), Hamburg University of Technology, Germany*

Using lamination parameters for the optimization of composite structures provides various advantages compared to the optimization considering layer angles, such as the convexity of the problem and the independence of the number of layers. However, it is difficult to consider the strength of a laminate in the lamination parameter space. Accurate estimation of reserve factors in composite laminate design is essential for ensuring structural safety while avoiding excessive conservatism. The current state-of-the-art analytical lower bound of strength in the lamination parameter space given by Ijsselmuiden et al. (AIAA Journal, 2008), provides valid but overly conservative estimates that are not attained for laminates with a bounded number of layers. This stems from the ambiguity inherent in the back transformation from lamination parameters to stacking sequences, which complicates direct calculation of the reserve factor based on classical failure criteria such as Tsai-Wu. Specifically, for bending-dominated problems where the stacking order has a significant influence, the current state of the art is overly conservative. In this work, we introduce a novel approach to derive a less conservative yet realizable lower bound on the reserve factor for laminates parameterized by lamination parameters. Our approach employs a neural network trained on attained reserve factors computed from stacking sequences with a bounded number of layers and can be applied to different degrees of conservatism. This data-driven model effectively learns attainable reserve factors, bridging the gap between theoretical analytical bounds and practical laminate realizations. The reserve factor is evaluated via the Tsai-Wu failure criterion, ensuring compatibility with standard composite failure assessments. We implement the neural network–based bound as a constraint within a composite structural optimization workflow, enabling direct integration into automated laminate design processes. Numerical examples demonstrate that this approach significantly tightens reserve factor predictions compared to existing analytical bounds, reducing unnecessary safety margins without compromising structural integrity.

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### Optimization and enhancement of nano/ultrafine grained structure in cryo-rolled FeMnCoCr HEA through machine learning

abst. 1269
CIMA
Friday
June 26
15h50

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Among various plastic deformation approaches, cryogenic rolling process has been widely recognized as a highly successful technique, particularly for producing nano/ultrafine-grained structures, which can consequently lead to production of HEAs with a great balance among their strength and ductility. In this study, the formation of ultrafine-grained structures in FeMnCoCr HEAs is investigated. The studied alloys were processed through cryo-rolling process which is followed by annealing process to promote significant microstructural refinement. Meanwhile, different characterization techniques such as XRD, EBSD and TEM, were performed to evaluate the microstructural refinement. Due to the complicated nature of this process as well as the presence of various parameters, performing time-consuming experimental tests will not be an efficient method of optimization. In this context, machine learning can provide a powerful framework for accelerating the optimization of microstructure, thereby enhancing the ultimate performance of cryo-rolled HEAs. In fact, appropriate microstructure modification can provide an in-depth insight into designing and customizing next-generation of HEAs for advanced structural applications, in cases where a balance among strength and ductility is needed. The findings can confirm the important role of thermomechanical processing to design next generation of HEAs with significant performance.

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abst. 1413
**CIMA**
Thursday
June 25
10h00

## Optimization-Based Regularization of Voronoi-Based Lattice Structures for Improved Mechanical Performance

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The inherent structural randomness of Voronoi-based lattice structures often leads to geometric irregularities, resulting in performance dispersion and localized failure, which limits their applications in reliability-sensitive engineering scenarios. To address this issue, this work proposes an optimization-oriented regularization framework that enables effective geometric control for both uniform and gradient Voronoi lattice structures. First, a data-driven analysis is conducted to identify the relationship between cell geometric features and mechanical performance. The results reveal that the minimum solid angle and the variance of edge lengths are the dominant geometric descriptors governing the mechanical behavior of Voronoi cells. Based on these findings, a Cell Regularization Method (CRM) is developed to optimize uniform Voronoi lattice structures by adjusting the positions of Voronoi seeds, thereby reducing geometric irregularities and improving structural uniformity and mechanical reliability. Furthermore, an Adaptive Gradient Cell Regularization Method (AGCRM) is proposed to extend the optimization framework to gradient lattice designs. By performing Voronoi tessellation in a higher-dimensional space followed by projection into three-dimensional space, AGCRM enables controlled spatial variation of cell sizes and improves performance distribution. Numerical results demonstrate that the proposed framework provides an effective and scalable optimization strategy for regulating randomness in Voronoi-based lattice structures.

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abst. 1437
**CIMA**
Thursday
June 25
10h20

## Towards an optimization method for sustainable autoclave processing of composite materials

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Fibre-reinforced composite materials are in widespread use due to their unique combination of mechanical properties, light weight and design flexibility. From a sustainability point of view, however, they pose significant challenges. In fact, not only are repairing and recycling of composites complex tasks, but also their manufacturing is a very energy-intensive process, which leads to substantial environmental concerns and costs. In particular, autoclave processing is especially critical due to its high specific energy consumption. In this work, we propose a method for optimizing the curing cycle of a composite part. The method aims to compute the optimal temperature profile which needs to be applied in the autoclave, while minimizing the energy consumption, which is regarded as an indicator of the environmental impact of the manufacturing process. The curing process is modelled as a thermo-chemical phenomenon by coupling the temperature evolution of the composite part and its degree of cure. Heating is assumed to occur primarily by forced convection inside the autoclave, while also taking into account the heat generation due to exothermic polymerization reactions during resin curing. For simplicity, the temperature distribution inside the part is assumed to be homogeneous, which is reasonable for thin laminates. The cure kinetics of the resin is modelled using Kamal's law, with reaction rate constants of Arrhenius type. Curing optimization is formulated as a fixed-time optimal control problem, with the part temperature and degree of cure regarded as state variables and the applied temperature profile as a control variable. We define an objective functional consisting of a linear term, which represents energy consumption, plus a quadratic regularization term. The bounds on the applied temperature and temperature rate, as well as the required degree of cure at the final time, are enforced as constraints on the state and control variables. Two approaches are considered for the solution of the optimization problem: one based on direct discretization of the control variable, the other based on the dynamic programming principle. In the first approach, the control variable is approximated by

a linear combination of basis functions, transforming the original functional minimization into a finite-dimensional constrained optimization problem. This is solved numerically by an iterative algorithm; the state dynamics are computed at each step using a Runge-Kutta method. In the second approach, the optimal temperature profile is computed as a feedback control by means of the dynamic programming principle. By defining the minimum objective functional as a value function and solving the corresponding Hamilton-Jacobi-Bellman (HJB) equation, we derive the optimal state variables and hence the optimal feedback control. In particular, the HJB equation is solved using a Semi-Lagrangian approximation scheme. For both approaches, we simulate the curing cycle corresponding to the computed optimal temperature profile and evaluate the final cure state of the part and the energy consumption. By comparing the results with those of a reference temperature profile, we establish the effectiveness of the proposed method in reducing the energetic impact of the autoclave process. Acknowledgements This publication was made with funding from the Ministry of University and Research (MUR) under the FIS 2 Grant, Project TOSSTO, no. FIS-2023-01465, CUP: J53C25000610001.

# Probabilistic models for composites

abst. 1052
**CIMA**
Friday
June 26
13h10

## Adaptive entropy-weighted ensemble surrogate framework for reliability analysis of composite structures

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Composite structures in aerospace and marine applications exhibit significant variability in material properties, layup configuration, geometry, and loading, which makes probabilistic design and reliability assessment highly demanding when direct finite element analysis is embedded in Monte Carlo simulation. This contribution presents an adaptive reliability framework for composite structures that combines an entropy-weighted ensemble of surrogate models with a local Markov chain Monte Carlo learning strategy. Kriging and artificial neural network surrogates are first constructed from an initial design of experiments and then combined using weights that account for local prediction error, global accuracy and entropy-based measures of output dispersion. A modified Metropolis-Hastings algorithm with delayed rejection is used to generate candidate samples in the vicinity of the limit state surface, so that new training points are added only where they most improve the reliability estimate. The proposed method is benchmarked on classical engineering examples and then applied to two finite-element-based composite structures: a carbon-epoxy laminated plate subjected to combined in-plane compression and transverse pressure, and a C/SiC composite bolted joint under tensile loading. In these applications, the framework delivers reliability indices in close agreement with direct Monte Carlo simulations while reducing the number of limit state evaluations from 106 to 107 to fewer than 50 calls to the high-fidelity models. These results demonstrate that the adaptive entropy-weighted ensemble surrogate strategy provides an accurate and computationally efficient tool for probabilistic analysis and reliability-based design of complex composite structures.

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## Application of Shape Memory Polymer in Low-Viscosity, High-Thermal-Conductivity Underfill Material

abst. 1105
**CIMA**
Thursday
June 25
15h10

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The advancement of high-speed computing technologies, such as artificial intelligence and autonomous driving, has necessitated high-performance interconnection and chip stacking technologies, resulting in a rapid increase in the degree of chip integration. However, as chips become highly integrated, increases in current densities and tighter structural constraints have posed a challenge in heat dissipation design, necessitating the development of high-thermally conductive packaging materials. Underfill, a key packaging material, mechanically and chemically protects electrical joints and dissipates heat generated during chip operation. Conventional underfills are reinforced with ceramic particles to achieve high thermal conductivity, electrical insulation, and a low coefficient of thermal expansion (CTE). However, increasing the content of reinforcing particles leads to a rapid increase in the viscosity of underfill, which can result in problems such as longer gap-filling times and increased void formation, consequently lowering production yields. Therefore, the primary research challenge is to resolve the trade-off between the enhanced material properties and the low viscosity required for manufacturing processability. In this study, we address this trade-off by incorporating thermally conductive shape memory polymer composite (SMPC) particles as functional fillers. In underfill materials, which are primarily based on thermoset resin composites, the shape and content of reinforcing particles are key factors in determining the viscosity of a suspension and thermal conductivity. A more spherical shape helps maintain low viscosity, while a high-aspect-ratio shape increases thermal conductivity. During the dispensing process, SMPC particles can maintain a spherical shape to improve flowability. As the curing process begins, heat induces their transformation into a permanent high-aspect-ratio shape, thereby enhancing particle connectivity and forming thermally conductive pathways. To fabricate the shape memory polymer precursor polycaprolactone-based polymer, which has photo-curable functional groups at both ends, was synthesized as previously reported. Microsphere particles were produced via an emulsion process using a high-speed mixer (L5M-A, Silverson, USA). A thin-film stretching-based shape programming method was applied to control their permanent and temporary shapes using a universal testing machine (Instron 5969, Instron, USA) equipped with a temperature chamber and a UV spot curing machine (Inno-Cure 5000, Lichtzen, Korea). To shorten UV curing time, diphenyl(2,4,6-trimethylbenzoyl) phosphine oxide (TPO, Sigma-Aldrich, Germany) is added as a photo initiator. The polymer particles were mechanically coated with hexagonal boron nitride (DT-BN-M05, Ditto Technology Co., Ltd., Korea). Hexagonal boron nitride (h-BN), a ceramic with electrically insulating properties and exceptionally high thermal conductivity along the in-plane direction (751 W/m·K), was used as a filler material to increase the thermal conductivity of the particles by forming a heat conduction path along h-BN particles on the outer surface. The structural characteristics of the fabricated SMPC particles were analyzed using a scanning electron microscope (SEM), and it was confirmed that the h-BN coated SMPC

particles formed a stable core-shell structure. To formulate the underfill composite, the fabricated SMPC particles were incorporated into a mixture of epoxy resin and curing agent. Viscosity was measured using a rotational rheometer (MCR102e, Anton Paar, Austria), and a hot disk thermal conductivity measurement system (TPS 3500, Hot Disk, Sweden) was used to measure thermal conductivity. The viscosity and thermal conductivity of the underfill changed according to the shape recovery of the SMPC particles. Consequently, this approach demonstrates the potential to overcome the trade-off between viscosity and thermal conductivity in advanced underfill material.

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abst. 1150
**CIMA**
Thursday
June 25
15h30

## Development and optimization of fbg smart sensors for composite structures

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Smart structures represent a fundamental advancement in composite structures, particularly sensorized systems developed for aeronautical applications aimed at implementing Health and Usage Monitoring Systems (HUMS). Among the various sensing technologies considered for these structures, optical fibers have emerged as a highly promising solution. Their main advantages include low invasiveness, reduced weight and immunity to electromagnetic interference. The possibility of placing sensors that enable local measurements at any point within a structure, including through its thickness, and with a desired orientation would represent a significant advantage for monitoring strategies. Such solutions are currently under investigation and development. In this work, the integration of Fiber Bragg Grating (FBG) sensors into composite materials is considered. This solution, however, presents several challenges related both to sensor positioning along complex geometric paths and to the risk of optical fiber damage or fracture during manufacturing. Indeed, embedding of optical fibers often results in handling difficulties, misalignment and fiber breakage during lay-up and curing operations. To overcome these limitations, a pre-assembled smart sensing solution, called quick-pack, was developed. The smart sensor consists of multiple thin layers, including neat epoxy resin layers and epoxy resin reinforced with glass fiber fabric, within which the optical fiber is embedded prior to integration into the composite structure. This configuration enhances sensor robustness and handling while facilitating accurate positioning of FBG sensors along predefined paths, thus improving measurement repeatability and reliability. However, the effectiveness of the quick-pack embedment is influenced by the processing conditions adopted during the production, requiring a dedicated investigation of the integration strategy. In particular, the effect of partial epoxy resin crosslinking on the adhesion and peeling behaviour of the quick-pack within the composite laminate was examined. Experimental results demonstrate that improved peeling performance is obtained when partially crosslinked quick-pack sensors are employed rather than fully cured ones. When a partially cured quick-pack sensor is embedded into the composite laminate, resin crosslinking continues during the curing cycle of the composite, resulting in a co-curing mechanism that promotes improved interfacial bonding. Moreover, the degree of epoxy resin crosslinking must be carefully controlled. Indeed, low degree of crosslinking can cause optical fiber displacement from the predefined path, compromising sensor positioning and measurement accuracy. To support the identification of an optimal curing conditions, a detailed study of the epoxy resin curing kinetics was performed through Differential Scanning Calorimetry (DSC). Both model-based and model-free kinetic approaches, such as Kamal-Sourour and nth order, were used to monitor the evolution of crosslinking and study the degree of cure as a function of time and temperature. In addition, gel point identification was performed to exclude curing degrees characterized by insufficient polymer network formation, which could result in optical fiber displacement from the intended geometric path. The optimal degree of crosslinking can be therefore determined by combining peeling tests with thermal and rheological analyses, enabling a correlation between interfacial mechanical performance and resin curing behaviour. Finally, quick-pack sensors with embedded FBG sensors cured at different degrees of crosslinking were tested under ambient temperature storage conditions (25°C) and at 125 °C. The aim of these tests was the determination of the influence of ambient storage during the embedding process, as well as the evolution of resin crosslinking and viscoelastic behaviour at temperatures representative of typical composite manufacturing cycles.

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## Evaluation of Carbon Capture Characteristics of Mortar with Rhodopseudomonas palustris

abst. 1254
**Repository**

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This study developed a mortar mixed with photosynthetic bacteria for carbon capture capabilities to continuously absorb atmospheric carbon. The bacteria mixed mortar demonstrated up to twice the carbon capture performance of conventional mortar, driven by the Calvin cycle mechanism. Additionally, the bacterial growth sustainability within the mortar was evaluated.

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## Numerical prediction and experimental analysis of the buckling loads of smpc cylindrical shells

abst. 1315
**Repository**

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At present, the applications of shape memory polymers (SMPs) and shape memory polymer composites (SMPCs) in the aerospace field mainly include space deployable hinges, trusses and antennas. Most of these structures are SMPC plates; SMPC cylindrical shells, which are excellent load-bearing structures, have not been widely used. The reason for their lack of use is that the structure and external load conditions of the SMPC cylindrical shells are relatively more complex than those of the SMPC plates, which makes it difficult to analyze the load-bearing capacity (the buckling load). In addition, as a temperature-sensitive material, the mechanical properties of SMPCs will change dramatically with temperature, so the buckling behaviors of SMPC cylindrical shells are quite different from those of general fiber reinforced polymer composite cylindrical shells. It is found that the theoretical buckling loads of cylindrical shells are always quite different from the experimental results due to the geometric, loading and material imperfections. The practical buckling loads of cylindrical shells are always much lower than the theoretical values. The load-bearing capacities are insufficient if the cylindrical shells are designed according to the theoretical calculation results, which leads to premature destruction of the structures. Therefore, the concept of the knock-down factor (KDF) is proposed to quantify such errors, which is the ratio of the maximum axial load-bearing capacity of a cylindrical shell in practical applications to its theoretical critical buckling load. There has been much research on the imperfection sensitivities of cylindrical shell structures, while only a few of them are related to FRPC cylindrical shells (they mainly focus on isotropic materials, such as steel). To the best of our knowledge, few studies have been conducted on the geometric imperfection sensitivity of SMPC cylindrical shells under axial compression. In this study, the influence of temperature on the buckling behavior of SMPC cylindrical shells is studied in a novel way. The temperature is divided into a low-temperature region and a high-temperature region. The compressive failure mode of SMPC cylindrical shells in the low-temperature region is dominated by brittle fracture, while that in the high-temperature region is dominated by buckling. The numerical and experimental methods are combined to study the buckling behaviors of SMPC cylindrical shells. The single perturbation displacement imperfection (SPDI), multiple perturbation displacement imperfection (MPDI) and linear buckling mode imperfection (LBMI) techniques are introduced in this study to verify the geometric imperfection sensitivities of SMPC cylindrical shells at different temperatures and obtain the corresponding buckling loads, KDFs and post-buckling patterns. In this section, these numerical methods are investigated. To ensure the quality of the specimens, carbon fiber-reinforced SMPC prepreg tapes were used as raw materials instead of carbon fiber and liquid shape memory epoxy resin. The technology of two-step automated tape laying was applied to manufacture the prepreg tapes. The resin was shape memory epoxy resin with a glass transition temperature of prepared by Leng's group, and the fiber was Toray T300s 12K carbon fiber (Toray Industries Inc., Tokyo, Japan). The specimens were prepared by the hand lay-up process assisted by the autoclave. The fiber stacking configuration of all the specimens is the same as that of the above numerical analyses.The load-bearing capacities

at different temperatures are tested and compared with the numerical results. The results demonstrate that the buckling loads of the SMPC cylindrical shell obtained by numerical techniques are sensitive to temperature, while the KDFs are insensitive to temperature. Meanwhile, the experimental results indicate that brittle fracture is the main failure mode instead of buckling at low temperature, so there is a risk when using any numerical technique to design SMPC cylindrical shells in low-temperature region. At high temperatures, the SPDI method overestimates the KDFs, while the KDFs calculated by the MPDI and LBMI techniques are in good agreement with the experimental results. However, only the LBMI method can distinguish the influence of temperature on the post-buckling patterns, and the corresponding post-buckling pattern is more consistent with the experiment.

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abst. 1322
**CIMA**
Thursday
June 25
15h50

## Design and application of deployable hinges based on shape memory polymer composites

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Hinges play a critical role in deployable structures by providing controlled rotational movement between two connected components. Shape memory polymer composites combine the shape-memory effect with excellent strength-to-weight ratio of composites, offering an ideal material for smart deployment applications. This study investigates the design, fabrication, and application of a novel deployable hinge with an L-shaped initial configuration. A parametric design framework is proposed, enabling the systematic tuning of hinge geometry, composite layup, and shape memory programming to achieve desired deployment performance. The driving torque of hinge is predicted by deformation energy analysis. And finite element simulations are employed to study the thermo$_x001E_mechanicalbehaviorandshapememorycharacteristicsofthehinge.Ex$
$scalethickplatedeploymentsystems, particularlyinspacemechanismsthatrequiretheintegrateddesignofhingeandpan$

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abst. 1328
**CIMA**
Thursday
June 25
16h10

## Real-time In-situ monitoring of deformation and defect generation in dry glass-fiber preforms using piezopolymer sensors

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During the processing of organic matrix composites, the fibrous reinforcement experiences complex in-plane and out-of-plane deformations that can induce various types of defects such as wrinkling, fiber misalignment, or sliding ultimately compromising the mechanical performance of the final composite structure. It is therefore crucial to develop tools capable of accurately monitoring the deformability of dry preforms. In this study, flexible and ductile piezopolymer transducers were embedded directly within dry glass-fiber preforms to enable in-situ, real-time monitoring of reinforcement deformation mechanisms and to identify the onset and evolution of defects generated during pull-out tests. Beyond defect detection, this sensing strategy also offers valuable insight into the reproducibility of the manufacturing process, allowing quantitative comparison of deformation patterns and defect-generation pathways across repeated experiments. The proposed methodology demonstrates both originality and relevance, providing high-resolution, time-resolved data that elucidate the mechanisms of defect formation during composite processing.

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## Smart healable cotton nanocomposites for next-generation wearable strain and temperature sensors

abst. 1373
**CIMA**
Thursday
June 25
16h30

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Smart textiles represent a key pathway for the widespread adoption of wearable multifunctional electronics, requiring materials that are not only flexible and functional, but also scalable, robust, and washable. Here, we introduce an industry-compatible method for producing conductive, hydrophobic, and healable cotton fabrics using thermoplastic polyurethane (TPU) matrices doped with carbon nanotubes (CNTs). Through a simple two-step extrusion and hot-pressing process, cotton fibers are impregnated with TPU–CNT nanocomposites, achieving conductivities up to  40 S/m, high sensitivity to both strain and temperature (gauge factor  3 for  < 5%; R/R·T  0.001 across 10–80 °C), and water contact angles above 100°. The resulting multifunctional fabrics exhibit outstanding durability under mechanical, thermal, and laundering stresses, retaining electrical performance over 20 washing cycles and enabling post-damage recovery through hot pressing. These engineered cotton textiles provide high-fidelity motion and temperature sensing, positioning them as strong candidates for next-generation wearable technologies that are scalable, reliable, resilient, and well-suited for real-world applications.

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## Special Session: Composite Pressure Vessels Design and Manufacturing (chaired by P.M. Weaver, S. Daghighi)

abst. 1111
**RIVA**
Tuesday
June 23
15h10

### Failure Pressure Tailoring in Conformable Composite Pressure Vessels

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Pressure vessels are widely used in the transportation industry for fuel storage. Structural weight reduction in pressure vessels, along with the efficient use of available space, are two attractive design features. In this context, composite materials offer a great opportunity to enhance design and achieve these goals by tailoring the stiffness of pressure vessels by varying the fibre tow trajectory across the structure. This technique, known as Variable Angle Tow (VAT), has previously been used to improve the design of pressure vessels. Failure is an important factor in the design of pressure vessels, and its accurate prediction is essential to ensure structural safety. In this study, an analytical expression for failure performance in a family of conformable pressure vessels is developed. The developed expression is fully analytical and removes the need for using computationally expensive numerical analysis. Therefore, it is possible to control the failure performance of the composite pressure vessel at the design stage. The developed expression for failure pressure is then used to tailor failure pressure performance across the structure, ensuring that a conformable pressure vessel exhibits consistent failure performance throughout its geometry. This could be especially interesting in applications where a pressure vessel is integrated into a larger system, and failure must be directed to a specific location or follow a controlled pattern.

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abst. 1211
**RIVA**
Tuesday
June 23
15h30

### A Manufacturing-Consistent Multiscale Framework for the Design of Nanomodified Composite Pressure Vessels

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This work presents an optimisation framework for Type IV composite overwrapped pressure vessels (COPVs) for high-pressure hydrogen storage, integrating multiscale modelling, experimental characterisation, and manufacturing-consistent design. Three carbon fibre reinforced polymer (CFRP) systems were investigated: a reference neat-epoxy composite, a nanosilica-modified epoxy composite, and a graphene nanoplatelet (GNP)-modified epoxy composite. Manufacturing studies confirmed that both nanofillers can be incorporated into the epoxy matrix without detrimental agglomeration or excessive void formation. Mechanical testing showed improved stiffness, flexural response, and damage tolerance for the modified systems compared to the reference composite. These improvements directly address matrix-dominated damage mechanisms governing Type IV COPV performance. A multiscale modelling strategy combining micromechanical homogenisation, finite-element lamina modelling, and laminate-level simulations with realistic filament-winding architectures was developed to transfer material-scale enhancements to the structural level. Numerical results indicate delayed damage initiation and improved burst pressure predictions for the nanosilica- and GNP-modified systems, with the GNP-reinforced composite showing the highest performance gains. The results demonstrate that nanofiller-modified CFRPs offer a viable and scalable solution for improving safety margins and reducing material usage in hydrogen storage vessels. The proposed CADWIND–ABAQUS-based methodology provides a transferable design framework for composite structures operating under severe loading conditions.

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abst. 1420
**RIVA**
Tuesday
June 23
15h50

### Multi-Objective Layout Optimization for Robotic Filament Winding Systems Using a Refined NSGA-II Algorithm

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As a key enabling technology in composite manufacturing, robotic filament winding systems offer high adaptability and flexibility, demonstrating significant application potential in the production of advanced composite structures. The spatial layout between the robot and the mandrel plays a critical role in determining system performance. However, existing optimization approaches lack efficient and systematic algorithms to achieve a coordinated balance between manipulability and operational efficiency. These methods often fail to simultaneously ensure solution accuracy and computational efficiency, thereby limiting their practical applicability. To address this issue, this paper proposes a comprehensive two-phase optimization framework, consisting of a multi-objective optimization model based on an improved NSGA-II algorithm and an optimal solution selection model based on a weighting function. The proposed framework aims to simultaneously enhance both manipulability and efficiency in robotic filament winding systems. In the first phase, the layout optimization problem is formulated as a multi-objective optimization problem, with the objectives of minimizing cycle time and maximizing motion flexibility, while incorporating reachable workspace constraints. An improved NSGA-II algorithm is developed by introducing an adaptive elitist strategy and an enhanced crowding distance mechanism based on neighboring individuals, effectively balancing convergence speed and solution quality. Binary encoding is adopted to represent layout configurations, and efficient exploration of the solution space is achieved through tournament selection and adaptive crossover and mutation operators, with a dynamically adjusted elitism ratio to ensure convergence. In the second phase, an optimal layout configuration is selected from the obtained Pareto front using a weighting function model, providing an effective solution to the trade-off between time efficiency and motion flexibility. Experimental results demonstrate the effectiveness of the proposed method. Compared with the conventional NSGA-II algorithm, the improved algorithm reduces cycle time by approximately 2.8–3.0 seconds and increases the manipulability index by 0.10–0.15, while also exhibiting improved convergence stability. Under the optimal layout configuration, the robot joint trajectories are smooth and continuous without encountering singular configurations, all joint angles remain within their physical limits, and kinematic simulations indicate coordinated and stable motion between the robot and the external rotational axis. The proposed layout optimization method provides a robust theoretical foundation for the design of robotic filament winding systems. It effectively resolves the trade-offs among efficiency, flexibility, and workspace constraints, and offers a systematic solution for automated system design.

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## Special Session: Nonlocal and Peridynamic Modeling of Composites (chaired by M. Dorduncu, E. Oterkus)

abst. 1321
SANT'EFISIO
Tuesday
June 23
15h10

### Base Excited Axially Functionally Graded Timoshenko-Ehrenfest Nanobeams with Axial Loading

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Axially functionally graded nano materials are one of the most promising structures for engineering applications. Material grading throughout length affects the dynamics of the nanobeam. Base excited cantilever nanobeam with axial loading on the free end will be considered in the present study. Besides material properties, also Poisson's ratio of the nanobeam will be considered in the functionally grading form. Nanobeam will be modeled with using Timoshenko-Ehrenfest beam model and Nonlocal Elasticity theory. Ritz method will be used in the solution of weak energy formulation. Effect of the base excitation, axial loading, Poisson's ratio and material grading to the dynamics of nanobeam will be investigated. Present study can contribute to design and manufacture of nano structural elements.

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abst. 1406
SANT'EFISIO
Tuesday
June 23
15h30

### Peridynamic Differential Operator for Reconstruction of Displacement Fields in Composite Structures

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Accurate reconstruction of full-field displacement and strain from limited sensor data remains a major challenge in the structural health monitoring of composite structures. In practical applications, sensor layouts are often sparse and irregular due to weight, cost, accessibility, and operational limitations. As a result, measured data provide only partial information about the structural response, which restricts reliable assessment of the global deformation state. These difficulties are more critical in composite structures, where anisotropy, coupling effects, and spatially varying deformation patterns require robust and physically consistent reconstruction procedures. This study presents a nonlocal inverse reconstruction framework based on the Peridynamic Differential Operator (PDDO) for the simultaneous recovery of displacement and strain fields from sparse strain measurements in composite structures. The proposed approach first populates discrete sensor data into continuous spatial fields using nonlocal smoothing, which reduces the influence of noise and irregular sensor distributions. Subsequently, a PDDO-consistent weighted least-squares integration procedure is employed to reconstruct displacement fields directly from strain data by enforcing kinematic compatibility through nonlocal integral operators. Unlike element-based inverse approaches, the formulation is meshfree, horizon-based, and independent of predefined shape functions or mesh topology. In contrast to sequential methods in which strain and displacement are recovered in separate stages, the proposed framework provides both fields within a unified nonlocal setting. The formulation is purely kinematic and does not require assumptions regarding constitutive behavior or external loading, which enhances its flexibility for inverse analysis of composite structural components. Owing to its nonlocal character, the method is expected to offer improved robustness under sparse sensing conditions and to provide an efficient basis for shape sensing and structural state estimation in aerospace composite applications.

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## Special Session: Recent Advancements in Morphing Composite Structures (chaired by P.M. Weaver, A.P.M. Nair, A. Haldar)

### Numerical Modeling of an Efficient Four Corner Simply Supported Piezoelectric Energy Harvester

abst. 1148
**RIVA**
Tuesday
June 23
16h10

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Bistable structures, such as cured shapes of unsymmetrical composite laminates, have been extensively studied due to their wide-ranging applications in morphing and energy harvesting. These laminates exhibit a double-well potential energy landscape, which can be either symmetric or asymmetric, depending on various factors. When bistable composite laminates are employed for energy harvesting, piezoelectric materials like Macro Fiber Composite (MFC) are to be bonded to their surface. The bonding of MFC patches affects both the bistable behavior of the laminate and its static and dynamic characteristics effecting the power harvesting capability. This study investigates the potential energy landscape and power harvesting ability of a four-corner simply supported (FCSS) square bistable composite laminate bonded with an MFC. The FCSS square bistable composite laminate inherently possess a symmetric double-well potential energy landscape which gets distorted after the attachment of MFC patch. To analyze this effect and to quantify the induced asymmetry in the static and dynamic characteristics, a fully non-linear finite element (FE) model is proposed. The FE model is then used in connection with electronic simulation software, to extract the open-circuit voltage and the power output from the FCSS bistable harvester. The model is then further utilized to conduct parametric studies examining the influence of varying the size and distribution of the MFC on the potential energy landscape, the static and dynamic characteristics and the power harvesting ability of the FCSS bistable harvester. From the parametric study, the best MFC configuration is selected for the energy harvesting analysis. The findings of this study can be utilized for selecting the appropriate size and distribution of MFC for optimum power harvesting from FCSS bistable harvesters.

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### Sequential actuation in tessellated smart multistable laminates using macro fiber composite actuators

abst. 1212
**RIVA**
Tuesday
June 23
16h30

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Adaptive structures capable of changing shape in response to varying requirements are in high demand for a wide range of deployable structure applications. The cured shapes of unsymmetrical composite laminates have significant application potential in this context due to their ability to exhibit two stable

configurations at room temperature. By assembling these laminates in series and parallel within a tessellated arrangement, multistable configurations can be achieved. A major design challenge lies in developing an actuation strategy that can intelligently induce transitions between multiple stable configurations while imposing minimal practical constraints. Triggering snap-through using mechanical loads in such complex systems would require selective changes in loading locations and could lead to weight penalties if performed using mechanical equipment. In this study, macro fiber composite (MFC) actuators are employed to meet the shape-changing requirements. Several MFC configurations are investigated in conjunction with tessellated laminate arrangements using finite element simulations. The smart composite system discussed in this study can exhibit up to six stable configurations, with multiple energy paths available to reach these configurations from a given stable state. A carefully designed actuation strategy is developed by systematically analysing different actuation paths arising from various sequences of MFC activation. The actuation path requiring the minimum voltage for shape transformation between configurations is selected. The out-of-plane displacement, strain energy requirements, and snap-through voltages associated with different stable states are examined. The findings of this study provide valuable insights for the preliminary design of multistable composite laminates with smart actuation strategies suitable for practical applications.

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abst. 1345
**RIVA**
Tuesday
June 23
16h50

## On tailoring morphing mechanics of a bistable composite tape-spring structure

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A bistable composite tape-spring (CTS) structure is stable in both extended and coiled configurations, which can be fully coiled or folded following the positive Gaussian curvature deformation mechanics. Its bistable coiling feature has been employed in a Roll-Out Solar Array and successfully deployed in space; its inherent foldable characteristics is analogous to a flexible mechanical hinge, showing great potential for flexible hinge applications. Both the structural coiling and folding mechanics are dependent on tape geometries, whilst the correlated morphing mechanics has not been fully revealed, which significantly constrains its shape morphing designs and smart driving strategies in order to further reduce weight and complexity for space deployable mechanisms. This talk will mainly cover our continuous research on tailoring the morphing mechanics of the bistable CTS structure. The main findings include: (i) a typical CTS folding process consists of linear bending, torsional buckling, localisation and then folding at large displacements, the folded tape shape is dominated by axial shear strains and transverse curvature changes; (ii) the morphing mechanics of a CTS is dependent on its internal stress level, which can be tailored by applying fibre prestressing, where the prestressed fibres generate compressive stresses to alter the internal stress, and thus controlling the structural bistability and deployable mechanics, as well as improving its load-carrying capabilities; (iii) smart driving of a CTS can be achieved under thermal energy, magnetic field, as well as composed with shape memory polymer through two layered design, there is a minimum energy constraint to initiate the shape morphing process, and the critical shape driving boundaries are dependent on scale effects; (iv) the bistable principle of the CTS can be extended to produce bistable torsional structures, as well as multistable hinge structures with tailorable stabilities. These findings enrich the diversities of functional structures to benefit novel requirements for various deployable applications, and enable customised design, as well as smart driving for flexible and multifunctional space explorations.

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abst. 1347
**RIVA**
Tuesday
June 23
17h10

## Design of Bi-stable Composite Laminated Domes for Lightweight Modular Morphing Structures

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A typical example of bistability can be observed in the metal lid of a tin can, which can be pressed into a stable inverted configuration and subsequently returned to its original shape. Notably, restoring

the lid to its upright state can be achieved either by applying a force near its base, exploiting a local instability to induce a global shape change, or at its centre. Inspired by this behaviour, the present work demonstrates that the underlying mechanism provides a simple yet robust route to achieving bistability, enabling the design of lightweight, modular morphing structures that can be assembled and reconfigured through geometric constraints and localised actuation [1]. The design space of the metallic dome is further expanded by using composite laminates with unsymmetric layups [2]. Numerical results from finite element analysis of the proposed composite laminated domes are presented, showing that their equilibrium paths exhibit snap-through behaviour and two distinct stable equilibria corresponding to minima in the strain-energy landscape. References: [1] Zucco G., Weaver PM., "Design of a Bi-stable Dome for Lightweight Modular Structures," AIAA 2026-0843. AIAA SCITECH 2026 Forum. January 2026. [2] Lachenal, X., Daynes, S., and Weaver, P. M., "Review of morphing concepts and materials for wind turbine blade applications," Wind Energy, 2013, 16(1), 1-16.

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## Viscoelastic mechanics of a bistable composite tape-spring structure

abst. 1376
**RIVA**
Tuesday
June 23
17h30

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Bistable composite structures hold significant application value in fields such as aerospace, automotive, wind turbine blades, and deployable space structures. Carbon fiber reinforced polymer (CFRP) composites have attracted considerable attention due to their high specific strength and specific stiffness. To clarify the influence of the viscoelastic behavior of CFRP on the bistable characteristics and long-term performance of structures, a study was conducted using carbon fiber plain weave/PLA as the research object. Laminates and CTS structures with different volume fractions were prepared, and experiments on static mechanical properties, dynamic mechanical properties, and stress relaxation were carried out to characterize their mechanical performance and viscoelastic behavior. Representative volume element (RVE) models and macroscopic finite element models were established to simulate the multiscale mechanical response of the composites. By combining the minimum strain energy path model, the effect of viscoelasticity on the evolution mechanism of structural bistability was revealed. This study is expected to provide a theoretical basis for the time-dependent design and performance prediction of composite materials in deployable aerospace structures.

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# Stability of nano, micro and macro composite structures

abst. 1061
CIMA
Friday
June 26
10h20

## Buckling performance of composite panels with multiple cutouts using streamline-based fibres and stiffeners

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Recent studies have shown that the buckling capacity of composite panels containing a single cutout can be significantly enhanced by aligning fibers and stiffeners along curvilinear trajectories that follow the streamlines of fluid flow around arbitrarily shaped cutouts. This paper extends the streamline-based design methodology to composite panels with multiple cutouts, thereby addressing more complex structural configurations. In particular, the potential flow around two circular cylinders of equal radius is derived analytically using conformal mapping and complex variable theory. Finite element models are developed to perform buckling analyses of unstiffened, longitudinally stiffened, and grid-stiffened panels. Results are obtained for various stacking sequences, cutout sizes and arrangements, boundary conditions, and loading scenarios. The findings confirm that curvilinear fiber and stiffener layouts based on streamline trajectories substantially improve buckling performance compared with conventional straight configurations.

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abst. 1227
CIMA
Friday
June 26
10h40

## Stability Analysis of Delaminated Composite Beams and Plates Using Advanced 2D Finite Elements

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In order to capture the effects of orthotropic material behaviour caused by reinforced layers, 2D models are required even for beam structures. The most expedient way to model these problems is to employ plate theories and the concept of equivalent single layers. With the presence of delamination, structural stability loss can be divided into two main scenarios: local and global instability. The local stability loss occurs as the opening phenomenon of the delamination, on the contrary, global instability is related to the stability loss of the whole structure. Basically, local instability can appear if the structure contains a shallow-depth delamination. On the other hand, deep delaminations cause a significant reduction in the structural stiffness, which can lead to the failure of the global structure. In particular cases, both phenomena can occur at the same time. The prevalent modelling procedure for these problems is to apply finite element method with 3D solid elements with contact conditions. Analyses can be simplified by employing improved plate-theory-based finite elements, which include delamination as a geometric property. This technique requires a set of special element types: intact, delaminated and transition. Using these element families, the analysis of local and global stabilities can be separated (mixed problems can also be investigated). The developed framework can be employed for static linear stability analysis, linear dynamic stability analysis and post-buckling analysis. In addition, these models can be modified in order to examine aeroelastic problems of delaminated composite plate structures.

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# Sustainable and recyclable and recycled composite materials

## Mechanical and Thermal Transport Characterization of Hot-Pressed Mycelium-Based Composite Materials for Semi-Structural Mobility Applications

abst. 1129
**TIGELLIO**
Friday
June 26
14h30

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Mycelium-based composites (MBC) present a promising sustainable alternative to conventional foam and chipboard materials by combining fungal mycelium with lignocellulosic substrates. These bio-composites offer significant environmental advantages including biodegradability, independence from fossil resources, resource conservation through utilization of industrial waste as substrates, a low carbon footprint and the use of raw materials that do not compete with the food industry. Like many bio-materials, MBC face the inherent challenge of highly variable material properties, which depend on numerous factors such as fungal species, substrate composition, and cultivation conditions. Current applications of MBC are limited to non-structural uses such as packaging materials, acoustic panels, and insulation materials. This study investigates the mechanical characterization of MBC for potential use as core materials in sandwich structures. Furthermore, thermal transport properties, particularly thermal diffusivity, were evaluated using infrared thermography. The objective is to optimize MBC properties and combine them with additional bio-based materials in sandwich configurations suitable for semi-structural mobility applications. Seven fungal species (Cyclocybe aegerita, Fomes fomentarius, Ganoderma lucidum, Lentinula edodes, Pleurotus eryngii, Pleurotus ostreatus, and Trametes versicolor) were cultivated on various lignocellulosic substrates including alder, beech, maple, hemp shives and oak. The grown materials were subsequently processed using hot-pressing with systematically varied parameters: temperatures of 160 °C, 180 °C, and 200 °C, pressures of 2 and 4 MPa, and durations of 20 and 40 minutes, starting from literature-based reference conditions (160 °C, 4 MPa, 20 min). Mechanical characterization was performed using three-point bending tests, impact bending tests, compression tests and Shore-D hardness measurements, supplemented by optical analysis. Thermal diffusivity was assessed using infrared thermography, where the temperature evolution in a defined region of interest was monitored and analyzed to determine the heat transfer characteristics. Initial results indicate significant variations in mechanical properties depending on fungal species, substrate type, and hot-pressing parameters. This comprehensive characterization aims to establish MBC as viable core materials for semi-structural bio-based sandwich components in sustainable mobility applications.

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## Pyrolysis Recycled Carbon fabric, Mass Productive, Circular Recyclable Crosspreg® prepregs based production of Safety Shoes Toe caps

abst. 1261
**TIGELLIO**
Friday
June 26
15h10

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Within the frame of GIANCE project, and in support of C-UP (Re-use of recycled Carbin Fiber for Upcycled applications in the general industry) Ecosister Project for the Ecological Transition in the

Emilia Romagna Region of Italy, Crossfire is directly involved in the development and prototyping of some structural parts by the usage of the Recycled Carbon fabric patches to get important Extra Lightweight in a Circular Recyclable, Mass Productive environment. The Crosspreg® resin system is used to impregnate the recycled carbon fabric without any need of new sizing treatments. Furthermore, the Crosspreg® Graphene added version is developed to show additional important mechanical improvements. Recycled Carbon fabric is produced through a thermal pyrolysis process from an existing industrial line at HERAmbiente (FIB3R plant), built with technical support of the Department of Industrial Chemistry at the University of Bologna. The Crosspreg® Resin system is a RT solid, Crossfire patented hybrid (TS/TP) reactive prepreg, epoxy based and capable to impregnate by capillarity and create chemical bonds with Oxidized Graphene, supplied by Graphenea, and with the reactive groups on the fabrics surface. The study shows the easy and perfect recycled fabric impregnation by Crosspreg® and the important mechanical improvements obtained by the addition of very little % of Graphene Oxide. Thanks to its very low viscosity at molten stage, Crosspreg® resin demonstrates its capacity to easily impregnate the carbon fabric and make the Graphene Oxide particles enter and chemically bond the fabric active sites. The FIB3R Recycling technology does not affect the carbon fabric quality and offers great opportunities for its re-use at the highest mechanical level. The presence of chemically bonded Graphene offers additional advantages in Shear resistance, leading to higher E-Modulus and lower deflection under load. All technical aspects, from the production of parts up to their final Circular Recycling technologies, will be discussed. GIANCE Project is a European Union's Horizon Europe research and innovation program under Grant Agreement No 101119286 and UKRI under Grant Agreement No 10090645 and No 10101683, Graphene Flagship sponsored, dedicated to developing technical advantages by the 2-D materials adoption inside Composite Materials.

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abst. 1318
**TIGELLIO**
Friday
June 26
14h50

## Comparative investigation of mechanical and thermal properties of polyamide 66 composites reinforced with waste nichrome and tungsten carbide powders

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This study evaluates and compares the reinforcing efficiency of two different industrial waste powders nichrome NiCr 80 20 and tungsten carbide WC Co Cr 86 10 4 within a polyamide 66(PA66) matrix. The investigation focuses on how these distinct fillers influence the structural mechanical and thermal characteristics of the engineering polymer when integrated through thermal molding processes. A comparative assessment shows that both NiCr and WC particles integrate effectively into the PA66 structure though they contribute different performance advantages. The incorporation of NiCr powders primarily enhances the tensile strength and provides a stable thermal response during phase transitions. On the other hand the addition of WC Co Cr powders at various weight ratios significantly increases the surface hardness and structural density of the composites. While NiCr serves as an effective metallic filler for improving general mechanical robustness the WC reinforcement provides superior resistance to deformation due to the high hardness of tungsten carbide particles. Thermal analysis reveals that both filler types improve the thermal stability of the PA66 matrix. The melting behavior and thermal conductivity show similar upward trends in both composite systems compared to the neat polymer. The results demonstrate that the choice between NiCr and WC as a reinforcement should be based on the intended application requirements where WC is more suitable for high hardness needs and NiCr is ideal for balanced mechanical strength. Ultimately both waste materials offer a sustainable and cost effective alternative for producing high performance PA66 composites proving that industrial by products can be successfully repurposed for advanced material engineering.

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## Thermal problems on composite structures

### Deformation and Damage Mechanisms of rGO-Containing PBX Simulants under Thermal Loading

abst. 1114
**RIVA**
Friday
June 26
12h30

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Polymer-bonded explosives (PBXs) are heterogeneous composites. They consist of a high volume fraction of explosive crystals embedded in a small amount of polymeric binder. Owing to the pronounced mismatches in thermal expansion coefficients, thermal conductivity, and mechanical properties between the crystalline phase and the binder, interfacial debonding and related damage can easily initiate under complex thermal loading. These damages tend to accumulate progressively. As a result, irreversible deformation occurs, which may pose potential safety risks during service.In this study, a small amount of reduced graphene oxide (rGO) was introduced into PBX simulants. The aim was to systematically investigate their deformation behavior and damage mechanisms under thermal loading. Based on the fundamental thermophysical and mechanical properties of the materials, the influence of rGO content on the thermal shock resistance factor was first evaluated. Subsequently, thermal shock experiments were designed and conducted. During the experiments, the deformation evolution of rGO-containing PBX simulants was measured in situ using digital image correlation (DIC).The results revealed that rGO effectively mitigates thermally induced damage in PBX simulants.Post-test microstructural characterization was performed using X-ray micro–computed tomography (micro-CT) and scanning electron microscopy (SEM). This allowed identification of thermal damage features within the materials. Furthermore, a finite element model incorporating a brittle material damage plasticity (CDP) framework was established. The model simulated the deformation and damage processes of rGO-modified PBX simulants under thermal loading. Based on these simulations, the effects of rGO content on the thermal shock resistance and damage evolution of the materials were systematically quantified.

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### Thermal Protection and Functional Integration Design for Thermoplastic Resin Matrix Composites via Two-Phase Aerogel

abst. 1126
**RIVA**
Friday
June 26
13h10

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Current fiber-reinforced thermoplastic composites (FRTP) thermal protection systems generally rely on ablative cooling or latent heat phase change mechanisms. These methods often result in components that are difficult to reuse, coupled with high manufacturing complexity and costly maintenance. To achieve long-term thermal protection for FRTP structures, this study designed a silica aerogel-carbon aerogel-matrix multilayer gradient composite material (SCMC). It effectively enhances the sustained thermal protection performance of the composite material and achieves multifunctional integration. For SCMC, the resin matrix serves as the precursor for carbon aerogel. Through laser-induced and layer-by-layer stacking techniques, it enables the integrated formation of laser-induced graphene (LIG) aerogel layers. This ensures strong interfacial bonding and high manufacturing efficiency. Additionally, an antioxidant silica aerogel was prepared on the surface of the carbon aerogel via a sol-gel process. The silica sol permeated into the porous interior of the carbon aerogel, followed by gelation and drying, enabling mechanical bonding between the two aerogels. This ensures the SCMC exhibits exceptional multi-interface strength. Simulation and experimental testing demonstrate that SCMC can elevate

the long-term operating temperature of composite materials by approximately 150°C while effectively suppressing out-of-plane heat conduction. Functionally, the LIG layer achieves rapid surface heating and de-icing through the Joule heating effect. The porous structure and high conductivity of LIG aerogel endow SCMC with electromagnetic interference shielding performance exceeding 50dB. Furthermore, hydrophobic treatment during silica aerogel fabrication imparts exceptional water resistance. This integrated structural-functional design and manufacturing strategy for SCMC demonstrates broad application prospects in intelligent hypersonic vehicles and spacecraft.

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abst. 1256
**Repository**

## Modeling of Ultrasonic Cutting of FRP Prepregs considering Temperature-dependent Viscoelasticity

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Conventional machining models for fiber-reinforced composites typically assume an elastic or elasto-plastic matrix behavior, which is fundamentally inadequate for uncured prepregs whose mechanical response is dominated by pronounced viscoelasticity arising from low cross-link density. Crucially, the resin's constitutive behavior is highly sensitive to both temperature and dynamic loading frequency. A third-order Prony-series-based viscoelastic model was proposed incorporating the time-temperature superposition (TTS) principle, rigorously calibrated for application in ultrasonic cutting simulations of carbon fiber prepreg laminates (CPL). The main works include as follows: (1) A micromechanically informed representative volume element (RVE) explicitly couples frequency-and-temperature-dependent resin viscoelasticity with fiber reinforcement, achieving an average prediction error of 12.1% with dynamic tensile tests across a range of temperatures (25-80 °C) and frequencies (1-100 Hz); (2) A coupled thermo-mechanical model accounting for viscoelastic hysteresis heating and transient heat conduction in ultrasonic cutting predicted peak surface temperature within 7.4% of experimental measurements; and (3) A physics-based ultrasonic cutting simulation considering localized temperature and frequency-modulated modulus softening yielded a mean absolute error of 17.2% in predicted cutting forces. Collectively, this work establishes a predictive, thermally aware, and frequency-resolved modeling paradigm for ultrasonic cutting viscoelastic composites, and provides a generalizable framework for failure modeling under combined thermal-dynamic loading.

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abst. 1276
**RIVA**
Friday
June 26
12h50

## Transpiration cooling of wedge shape nose cone with phase change

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To cope with the reality of higher and higher Mach number to hypersonic aircraft and the ultra-high aerodynamic heat that comes with, transpiration cooling with phase change is seen as an efficient method to deal with extreme high aerodynamic heat. Due to the cost of flight experiment is quite expensive, CFD method is seen as a useful way to research transpiration cooling with phase change. This paper describes the influence of relative porous structure, cone geometry and boundary condition parameters to half cone during transpiration cooling with phase change according to simulation approach with two-phase mixture model (TPMM) and local thermal non-equilibrium (LTNE) theory. The model is verified by comparing with analytical solution in previous study. The research proposed a trans-scale method to compute the permeability of porous medium and found the different distribution of particle has significant impact to the heat transfer in porous medium. In the comparison of different relative parameters, the results indicate the smaller diameter particle can efficiently decrease the temperature of stagnation point, smaller cone angle can improve the temperature distribution nears the cone trailing

end, the cooling effect and porous manufacturing cost needs to be balanced when it comes to thickness study and gradient pressure affects cooling effect which can be improved with different porosity and injection rate in various heat transfer status during transpiration cooling with phase change.

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