Integrated Design, Simulation, and Experimental Validation of Advanced Cellular Metamaterials

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Abstract *Cellular metamaterials offer supreme properties for engineering, medicine, and defence, but their transition to industrial use faces design, fabrication, and characterisation challenges. This review provides an overview of 20 years of advancements in cellular structures, from open-cell foams to triply periodic minimal surfaces (TPMS), presenting novel fabrication techniques (e.g., explosive compaction for UniPore structures) and demonstrating validated computational models for optimising graded auxetic and hybrid TPMS lattices. The study indicates that porosity and base material primarily govern energy absorption, with closed-cell foams and TPMS outperforming other geometries. Additive manufacturing enables spatially graded designs with tailored mechanical properties. This work accelerates the development of next-generation metamaterials for crash absorption, blast protection, and biomedical devices.*

Keywords *cellular structures, metamaterials, experimental testing, computational simulations, mechanical properties*

Highlights
- *Modern metamaterials are set to revolutionise engineering, transportation, medicine, and sports.*
- *Design, fabrication, modelling, and characterisation of cellular structures are covered.*
- *The article offers a comparative analyzis of mechanical responses of various cellular structures.*
- *Validated computational models are crucial for optimising metamaterial design.*

1 INTRODUCTION

Modern engineering faces dual challenges: escalating material costs and stringent sustainability requirements. Cellular metamaterials—engineered porous structures with tunable mechanical, thermal, and acoustic properties—have emerged as a transformative solution. These materials leverage hierarchical architectures spanning nano- to macro-scales to achieve unprecedented performance-to-weight ratios, making them indispensable for aerospace (impact-absorbing components), biomedical (tissue scaffolds), and defence (blast-resistant panels) applications [1,2]. Cellular materials excel in mechanical and thermal properties and enable multifunctionality. They serve as structural components (cores for sandwich panels, enhancing stiffness and damping [3]), functional systems (heat exchangers, acoustic isolators, and fluid filters [4]) and energy absorbers (crashworthy fillers in automotive and protective gear [5]).

Despite their potential, widespread deployment is hindered by fabrication limitations (traditional methods like powder foaming) lack precision for complex geometries), knowledge gaps (incomplete data on shear/dynamic behavior and graded porosity effects), design barriers (absence of standardised guidelines for application-specific optimisation) and scepticism towards new materials. However, advanced fabrication technologies, such as additive manufacturing, are overcoming these hurdles. All of the additive manufacturing technologies offer precise control over cell shape, size, and distribution on a certain level of the scale, depending on the printing accuracy. These methods surpass traditional methods like melt/powder foaming and replication techniques in terms of fabrication accuracy and adaptability, while in some cases, the costs and fabrication speed are still in favour of the traditional methods [6]. They also enable the integration of digital twins using three-dimensional (3D) models obtained from computed tomography (CT) for iterative design..

As the use of cellular structures grows, it is essential for engineers, material scientists, and commercial entities to understand their behavior under various loads to optimise performance through customised designs. Combining different base materials with tailored internal structures can achieve unique mechanical and thermal properties [7]. Advanced additive manufacturing enables the creation of complex cellular metamaterials designed for specific applications through computational simulations and topological optimisation [8].

The mechanical properties of cellular (meta)materials depend on factors like relative density (porosity), base material (metal or non-metal), morphology (pore size and shape), topology (pore distribution) and fillers [1]. The most important factor is relative density, which is calculated as the ratio of the bulk density of the foam to the solid density of the material, while the porosity is then determined by subtracting relative density from 1. In general, the higher the porosity, the lower the mechanical properties, which can also be analytically calculated using the empirical equations given in [4]. Careful selection of these parameters and proper fabrication can yield desired mechanical, damping, and thermal properties [4,5]. Detailed geometry and mechanical behavior of fabricated structures can be evaluated using CT scanning [9]. High-quality 3D data acquisition is crucial for building precise digital twins, which aid in developing new cellular structures with advanced material engineering techniques.

Standard mechanical tests like compression, tension, and bending are well-documented, but data on shear and dynamic testing are limited. Recent studies have explored cellular structures' dynamic and impact behavior, but a detailed analyzis of functionally graded porosity is still needed [10–12]. Specifically designed internal structures can optimise mechanical responses for applications in safety, defence, and crashworthiness [13].

In general, the cellular metamaterial's unit cell size is in the range of millimetres, while also micro-architected cellular structures and

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nano-lattices with unit cell sizes below 1 μm have been developed, driven by the need to control band gaps in phononic metamaterials [14,15]. These structures offer unique properties like tailorable stiffness and auxetic behavior. However, further research is needed on their mechanical behavior, fabrication optimisation, and biocompatibility for medical applications [16].

This review systematically investigates the design, fabrication, and mechanical behavior of cellular metamaterials under various loading conditions, with a focus on their specific energy absorption (SEA) capabilities and its relationship to the base material, geometry and loading conditions. Understanding these relationships and the distinct deformation mechanisms of cellular metamaterials is crucial, as it enables the tailored design of high-performance cellular materials for diverse engineering applications. This study's significance lies in providing critical insights for optimising metamaterial design, which is essential for advancing fields such as automotive crashworthiness, aerospace impact resistance, and biomedical engineering. In summary, there is a clear need for more research on detailed geometry characterisation and the development of digital twins to create new geometries and optimised fabrication processes. The group at the University of Maribor is working to address these gaps in metamaterials research.

2 METHODS AND MATERIALS

The following section categorises (meta)materials based on their topology and manufacturing processes. Figure 1 illustrates the progression from primitive to advanced geometries over the last two decades in the research group at the University of Maribor.

The geometry and properties of cellular metamaterials presented in Fig. 1 are provided in the next paragraphs. The fabrication methods are given as follows: investment casting (IC), (aluminium), selective electron beam melting (SEBM) (titanium), powder bed fusion (PBF) (stainless steel), photopolymerisation (VAT) (photopolymer), gas injection (GI) (aluminum), powder metallurgy (PM) (aluminium), explosive compaction (EC) (copper).

2.1 Open-cell Foams

Open-cell foams are materials characterised by an interconnected network of pores, which allow air or fluids to pass through (Fig. 1b). These foams are highly versatile and are used in various applications due to their unique properties. In the furniture industry, polymeric open-cell foams are commonly used for sofa cushions, foam mattresses, and car seats because they can be easily compressed and then naturally return to their original shape. Additionally, they are employed in acoustic and soundproofing applications. Metal open-cell foams, produced through methods like investment casting, are valued for their lightweight and high-strength properties, making them suitable for use in automotive, aerospace, and other engineering fields [17]. The mechanical properties of open-cell foams can be further enhanced by introducing fillers, such as polymers, into the cellular structure. Additionally, open-cell foams can be used as fillers for foam-filled tubes [18]. This adaptability and multifunctionality make open-cell foams necessary in modern engineering and design.

The impact of the base material on the mechanical properties of open-cell foams is well-documented, with numerous empirically established relationships linking the base material and cell morphology to the properties of the cellular material. The metals and alloys used for metal foams must also be lightweight to retain the advantage of low relative density over conventional solid materials. Therefore, the most commonly used metals for cellular materials include aluminium, magnesium, titanium, and their alloys.

The influence of cell morphology on the mechanical properties of regular and irregular open-cell materials has been extensively studied using representative unit cells. However, since the geometry of fabricated open-cell foams often deviates from geometric regularity, many researchers have also examined the cell morphology of these fabricated foams [19]. The mechanical behavior of open-cell foam can be further enhanced by introducing polymer fillers into the cellular structures [18].

2.2 Closed-cell Foams

Closed-cell foam's interconnected, sealed cells provide higher stiffness and water resistance, are suitable for shock absorption and thermal insulation (Fig. 1a). Powder metallurgy is a standard method for producing closed-cell aluminium foams [20]. This involves heating a precursor (aluminium, silicon, and titanium hydride) within a mould, allowing it to expand and fill the cavity. After cooling, the foam is extracted and sectioned. The mechanical behavior of these foams has been thoroughly investigated under free and laterally constrained compression, and it was proved that the behavior of the cell material could be adequately described with a single,

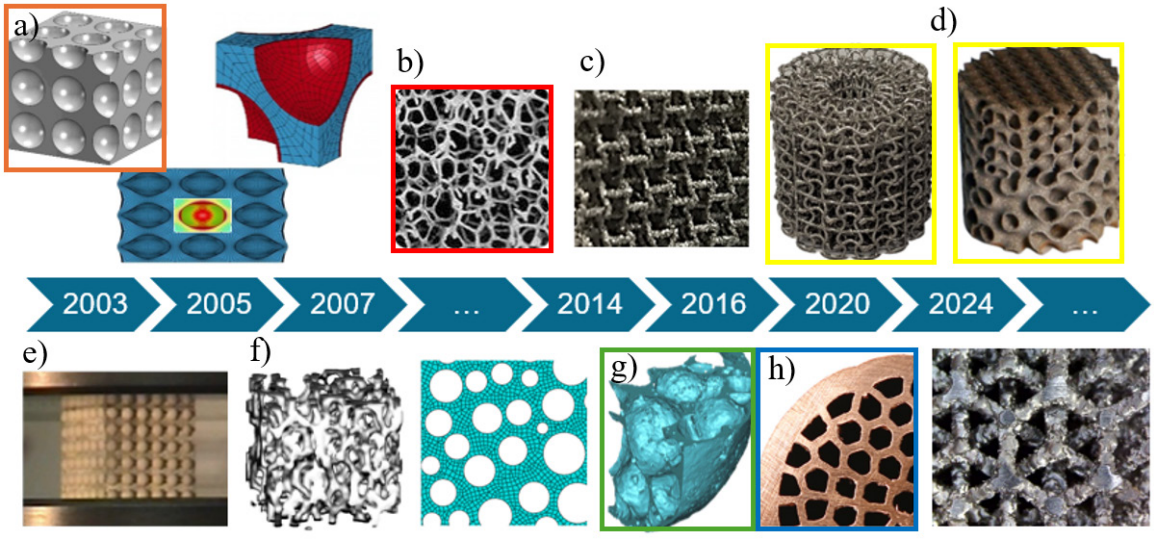

Fig. 1. Research of cellular metamaterials in recent years: from primitive to advanced cellular geometry; a) closed-cell foams, b) IC, C) SEBM, d) PBF, e) VAT, f) GI, g) PM, and h) EC

geometrically uniform cell [21]. Applications include ex-situ and in-situ foam-filled tubes, where the latter, produced directly within the tube, demonstrates enhanced stiffness due to improved bonding [22]. Furthermore, closed-cell foam can be integrated into auxetic aluminium alloy panels to improve their mechanical performance [22].

2.3 UniPore Structure

The UniPore structure, characterised by longitudinal pores, is fabricated by explosively welding thin-walled inner tubes within an outer tube (Fig. 1h) [23]. This process involves densely packing the outer tube with smaller diameter inner tubes along its length, resulting in a uniform porous cross-section. However, variations in collision angles during welding due to the inner tubes' curvature can lead to inconsistent interface formation, a phenomenon supported by computational simulations [24].

To address these limitations, a novel UniPore fabrication method has been recently developed [25]. This approach utilises rolling thin metal foil with acrylic spacer bars, followed by explosive compaction. This technique ensures a stable collision angle, similar to conventional explosive welding, leading to more uniform welding interfaces. The production process, demonstrated with copper, allows for the use of various metallic foils. Notably, this method offers flexibility in tailoring external dimensions, pore size, internal wall thickness, and porosity to meet specific application requirements.

2.4 Advanced Pore Morphology (APM) Foam

Advanced Pore Morphology (APM) foam, a hybrid cellular material featuring interconnected, sphere-like closed-cell pores within a solid outer skin, was pioneered at Fraunhofer IFAM in Bremen, Germany (Fig. 1g) [26]. This unique structure offers a balance of high surface area and structural integrity, making it attractive for applications requiring energy absorption and thermal management. The fabrication begins with the compaction and rolling of an AlSi7 alloy combined with a TiH2 foaming agent, yielding an expandable precursor. This precursor is subsequently granulated and subjected to thermal decomposition of the TiH2 in a continuous belt furnace, resulting in spherical foam elements. The internal structure of APM foam has been extensively characterised [9,27], revealing its tailored pore distribution and connectivity. Notably, APM elements have demonstrated efficacy as filler material in foam-filled tubes [28,29], enhancing their mechanical performance under impact loading.

2.5 Predesigned Structures

Advanced fabrication techniques, particularly additive manufacturing, enable the creation of complex, pre-designed cellular structures with tailored mechanical properties (Fig. 1d) [6,30,31]. This includes the development of three-dimensional auxetic cellular materials, such as those built from interconnected inverted tetrapods [32,33] and chiral auxetic designs [34]. Inverted tetrapod structures are constructed by stacking unit cells in layers, resulting in a layered 3D auxetic architecture [35]. These structures, along with chiral auxetic designs based on the 10th eigenmode of a regular cubic unit cell [36], are typically modelled using computer aided design (CAD) software and fabricated using additive manufacturing technologies. The mechanical performance of these auxetic structures can be further enhanced by incorporating polymeric fillers [37], offering a route to multi-functional materials.

Furthermore, triply periodic minimal surfaces (TPMS) represent a class of periodic cellular materials with significant potential in diverse engineering applications. TPMS are intricate 3D topologies that minimise surface area within defined boundaries and exhibit periodicity in three orthogonal directions [38,39]. They partition space into interconnected domains without enclosed voids, leading to unique topological characteristics. This makes them highly suitable for applications ranging from tissue and structural engineering to thermal management and fluid transport [38,40]. Their optimised thermal and electrical conductivity and controlled fluid permeability make them promising candidates for advanced heat exchangers, filters, and catalytic reactors. The ability to precisely control the geometric parameters of TPMS through additive manufacturing opens up new avenues for designing materials with tailored functional properties.

3 DESIGN AND CHARACTERISATION

Cellular metamaterials are engineered materials with cellular structures that exhibit unique mechanical, thermal, acoustic, or electromagnetic properties not found in conventional materials. Their design involves careful selection of the unit cell geometry, size, arrangement, and constituent material to achieve the desired macroscopic behavior. This often entails intricate topologies like lattices, honeycombs, or triply periodic minimal surfaces, which are carefully examined using CT scanning. These can be optimised using computational methods like finite element analyzis and topology optimisation to tailor properties like stiffness, strength-to-weight ratio, energy absorption, and wave propagation characteristics. The ability to precisely control the microarchitecture allows for creating materials with unprecedented functionalities, opening doors for applications in diverse fields ranging from aerospace and automotive to biomedical engineering and soft robotics.

A critical aspect of metamaterial design and research involves developing and validating robust computational models, essential for accurately predicting their behavior. These models, often employing techniques like finite element analyzis, must be rigorously validated against experimental data to ensure reliability. The complexity of these models can vary significantly, with simplifications tailored to the specific geometry of the metamaterial and the intended application of the simulation. For instance, simplified models might be used for preliminary design studies. In contrast, more detailed models are necessary to predict complex phenomena like non-linear deformation or dynamic response accurately. Moreover, these validated numerical models can serve as powerful tools for parametric studies, allowing researchers to explore the influence of geometric variations and material properties on the overall performance of the metamaterial, thereby accelerating the design and optimisation process.

3.1 Experimental Testing

Experimental characterisation of cellular metamaterials has predominantly focused on compression testing, revealing a characteristic mechanical response: an initial elastic region, followed by a plateau phase denoting progressive cell collapse, and finally, a densification regime. To gain deeper insights into deformation mechanisms, micro-computed tomography (μCT) has been employed to visualise and quantify internal structural changes during the compression of closed-cell aluminium foams [41]. This technique has facilitated detailed analyzes of pore collapse and crack propagation, contributing to a fundamental understanding of foam behavior under load [42].

Beyond compression, extensive studies have investigated the mechanical response of various closed-cell foams under diverse loading conditions, including bending [43–47]. Similarly, Advanced pore morphology (APM) foams and APM-filled tubes have been

subjected to both compression [28] and bending tests [29], with in-situ geometric analyzis conducted to track deformation evolution [48].

The influence of loading rate on mechanical behavior has also been of considerable interest. High-strain-rate compression testing, utilising the split Hopkinson pressure bar (SHPB) apparatus, has been used to assess the dynamic response of closed-cell aluminium foams [49]. Studies employing powder guns have further extended the investigation of high-strain-rate behavior to both open-cell [43] and closed-cell foams [50] as well as auxetic structures [33,51], revealing rate-dependent phenomena such as inertial effects and material strengthening.

Furthermore, three-point bending tests have been instrumental in evaluating the flexural performance of foam-filled tubes [29,44,45], providing data on bending stiffness, energy absorption, and failure modes. Recent investigations have also explored the shear response of open-cell foams [52] and auxetic cellular structures [53], contributing to a more comprehensive understanding of their anisotropic mechanical behavior.

The combined use of these experimental techniques, complemented by advanced imaging and analyzis, allows for a thorough characterisation of the mechanical behavior of cellular metamaterials, providing critical data for the design and optimisation of these materials for diverse engineering applications.

3.2 Homogenised Computational Models

For computational modelling of closed-cell foam behavior, a simplified yet practical approach employed within Abaqus finite element (FE) software involves a homogenised material model, specifically the crushable foam model with volumetric hardening. Leveraging the axial symmetry of the experimental specimens, axisymmetric boundary conditions were applied, significantly reducing computational cost while maintaining accuracy. An explicit solver was utilised to capture the dynamic nature of foam deformation [50].

The crushable foam constitutive model parameters were determined through an optimisation algorithm, where the computational response was iteratively matched to the experimental quasi-static (Q-S) compression data (Figs. 2 and 3). This optimisation ensured that the model accurately represented the foam's behavior under low strain rate conditions. Subsequently, the optimised material model was employed for high strain rate (HSR) simulations, demonstrating a remarkable agreement with experimental HSR data (Fig. 2).

The difference between the experimental and computational results across quasi-static and high-strain rate regimes is noteworthy. The only observable discrepancy occurs at the initial stages of the HSR response, where the computational model fails to capture the initial stress peak observed experimentally. This stress peak, a direct consequence of the impact-induced collision in the experimental setup, represents a transient phenomenon characteristic of the initial impact phase. However, as demonstrated by the subsequent correlation between experimental and simulated data, this initial peak does not significantly influence the overall global deformation behavior of the foam [33]. The use of this simplified model allows for efficient simulations while still retaining the overall mechanical response of the closed-cell foam.

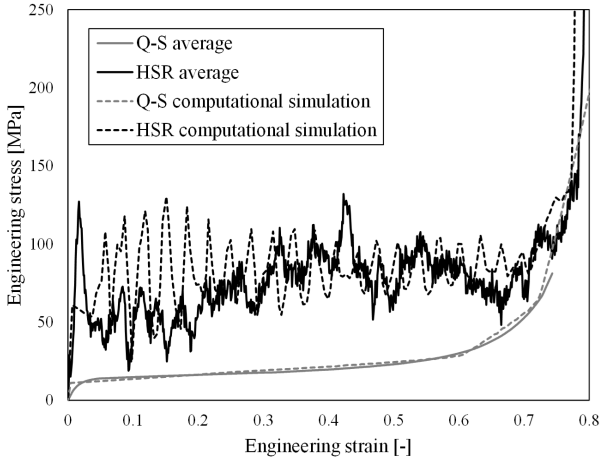

Fig. 2. Comparison between the computational and experimental results under Q-S at loading velocity 0.01 mm/s and HSR at loading velocity 250 m/s

Under quasi-static loading, the specimen exhibits a uniform deformation pattern, indicative of a homogeneous stress distribution throughout the sample (Fig. 3). In contrast, HSR loading induces a distinct shift in the deformation mode, characterised by localised deformation concentrated at the impact interface between the loading plate and the specimen. This localisation signifies the influence of inertial effects and stress wave propagation at high strain rates, leading to a non-uniform deformation profile. The observed difference in deformation patterns highlights the significant impact of loading rate on the material's mechanical response.

This can be further used to develop modern crash absorbers, where the validated FE models enable the development of new foam-filled auxetic panels with a tailored response, where different geometries, sheet thicknesses, densities and distributions of the foams can be virtually tested before fabrication. The deformation behavior of that

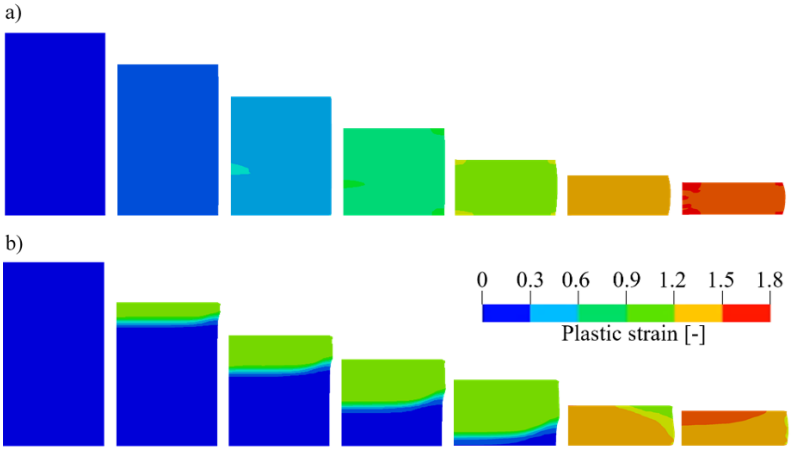

Fig. 3. Comparison between the Q-S and HSR deformation responses of closed-cell foam modelled with homogenised computational model (PEEQ - equivalent plastic strain)

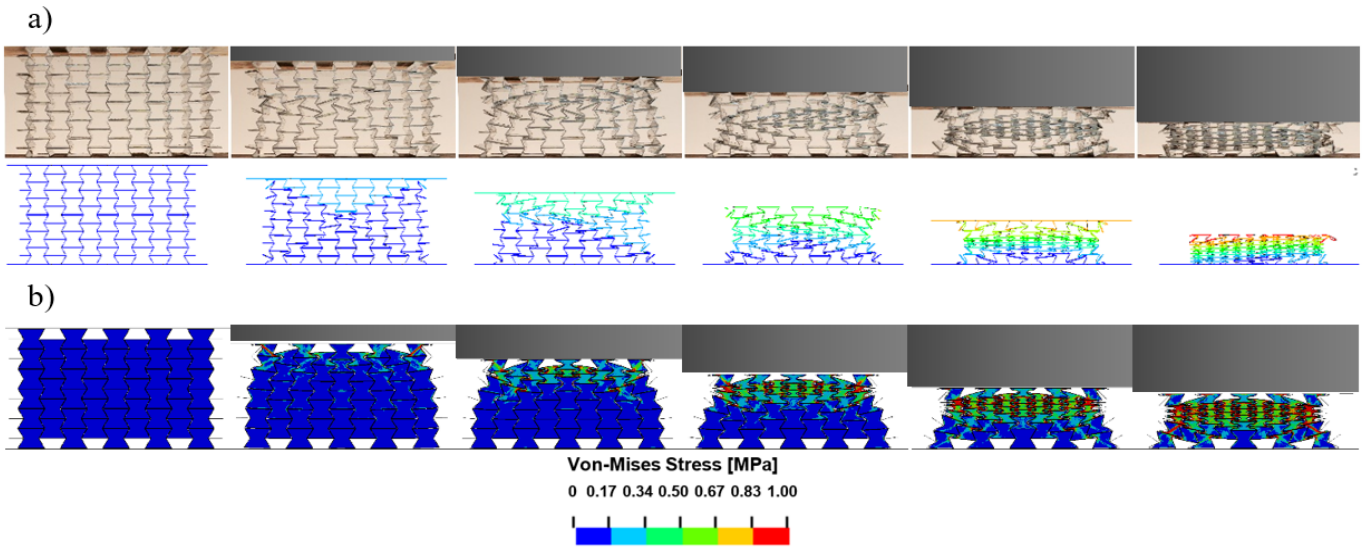

Fig. 4. Comparison of deformation behaviour of: a) empty, and b) foam-filled crash absorber [55]

kind of absorber is shown in Fig. 4b, where the crash absorber is filled with Polyurethane (PU) foam. This will hopefully lead to the application of modern crash absorption systems on newly built roads or blast protection elements in buildings [54].

3.3 Discrete Computational Models

Discrete computational models, while demanding higher computational resources than homogenised models, provide a more accurate representation of metamaterial deformation behavior. Beam finite elements are predominantly employed for strut-based cellular structures, such as open-cell foams and auxetic designs [11,56,57]. This approach allows for a detailed analyzis of individual strut deformation and interaction.

The generation of TPMS lattice computational models is facilitated by shell finite elements, utilising the MSLattice code [58] to define the fundamental lattice geometry. Subsequently, meshing is performed using PrePoMax software, and boundary conditions are defined within the LS-PrePost environment. Inverse parametric computational simulations are conducted to refine material parameters to account for manufacturing imperfections, particularly plate thickness variations. This indirect incorporation of imperfections enhances the model's fidelity.

The validation of these discrete TPMS lattice models involves comparing their mechanical response, specifically stress-strain relationships and deformation patterns, to quasi-static experimental data from reference [59] for each analyzed geometry and relative density. Furthermore, the computational deformation behavior is validated through comparisons with experimental observations recorded by high-definition video cameras. Figure 5 illustrates the comparative deformation behavior of diamond TPMS lattices with varying relative densities, demonstrating a high correlation between experimental and computational results.

Volume finite elements could also be employed for the discretisation of open-cell foams. Achieving an accurate geometric representation of fabricated aluminium open-cell foam samples necessitates high-resolution micro-computed tomography (μCT) scans. These high-resolution scans are crucial for capturing the intricate geometric details of the foam's porous structure and enabling precise segmentation of the metallic phase from the void space. This precise segmentation is essential for generating reliable volume finite element meshes and critical for accurate computational modelling of the foam's mechanical behavior.

4 OPTIMISATION AND DEVELOPMENT OF NEW GEOMETRIES

Validated computational models provide a powerful platform for developing and optimising novel metamaterials. For instance, topology optimisation techniques have been employed to generate

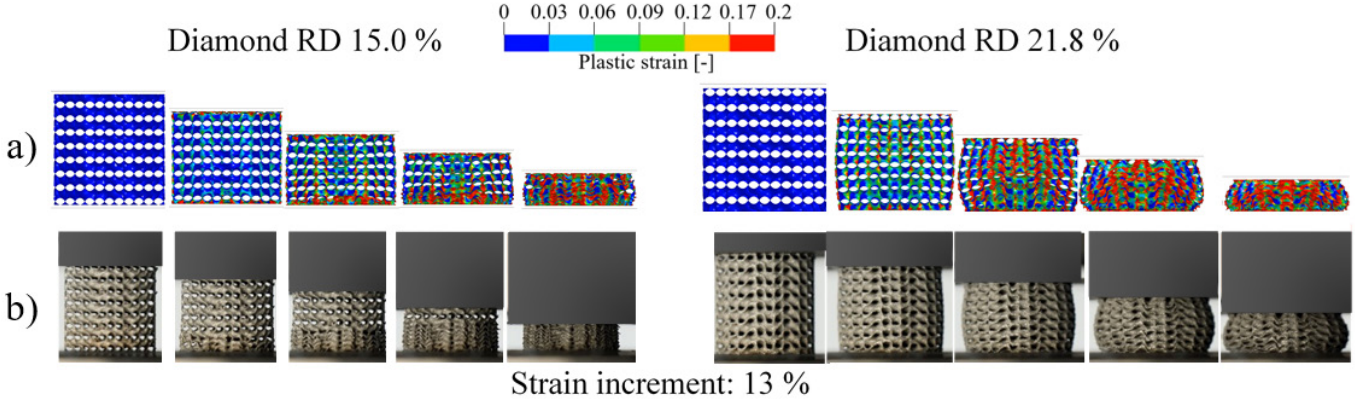

Fig. 5. Comparison between a) computational, and b) experimental results in case of TPMS structures modelled with shell finite elements

new auxetic geometries [60]. These studies used a 2D plane stress state simplification to model the auxetic structure, focusing on a single unit cell of the periodic structure as the optimisation domain. To further reduce the computational cost, only one-quarter of this unit cell was modelled, with the remaining portion represented by appropriate double symmetry boundary conditions. This simplification is justified by the prevalence of double symmetry in many existing auxetic structures, including re-entrant hexagons, symmetric chiral designs, and sinusoidal ligament configurations.

Triply periodic minimal surface (TPMS) lattices, inherently mathematical designs, benefit significantly from advanced fabrication methods. These methods enable the creation of graded or hybrid structures, where diverse TPMS geometries are strategically combined to enhance topological features and achieve desired properties. To accurately predict the mechanical behavior of additively manufactured uniform TPMS lattices made of stainless steel 316L under quasi-static and dynamic loading, a FE computational model was developed in LS-DYNA. This validated model was then used to simulate the performance of a newly designed hybrid TPMS cellular lattice featuring spatially varying gyroid and diamond cells in both longitudinal (the diamond and gyroid cells are on top of each other) and radial (the diamond and gyroid cells are concentric) directions (Fig. 6). Experimental validation of the fabricated hybrid lattices demonstrated a high correlation with the computational predictions [61], confirming the model's accuracy and predictive capabilities.

Building upon existing 3D conventional chiral unit cell designs [57,62], novel 3D axisymmetric chiral structures exhibiting negative and zero Poisson's ratios have been developed. This innovation involves mapping the conventional tetra-chiral unit cell into an axisymmetric space, resulting in a new class of 3D axisymmetric chiral architectures (ACS structures). These structures are fabricated using additive manufacturing techniques (Fig. 7), enabling the precise realisation of complex geometries.

Experimental compression tests were conducted to validate the computational modelling of these axisymmetric chiral structures. The resulting experimental data was used to refine and validate the computational models. Subsequently, these validated models were employed to evaluate the performance of new axisymmetric chiral structures featuring graded cell configurations.

The analyzis revealed that these newly developed axisymmetric structures demonstrate significantly enhanced mechanical properties compared to conventional 3D chiral structures (the SEA is comparable to structures made of titanium and much higher than in structures made of copper). This improvement is attributed to the optimised geometry and graded cell arrangements, offering potential advantages in applications requiring tailored mechanical responses.

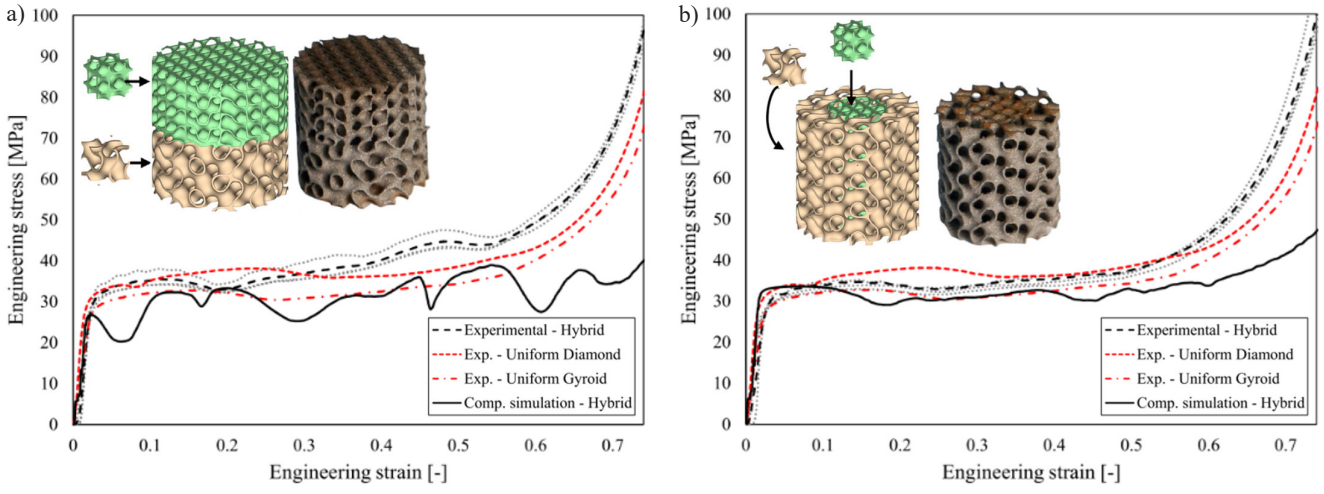

Fig. 6. Comparison between the computational and experimental results for: a) linear, and b) radial hybrid TPMS lattices [61]

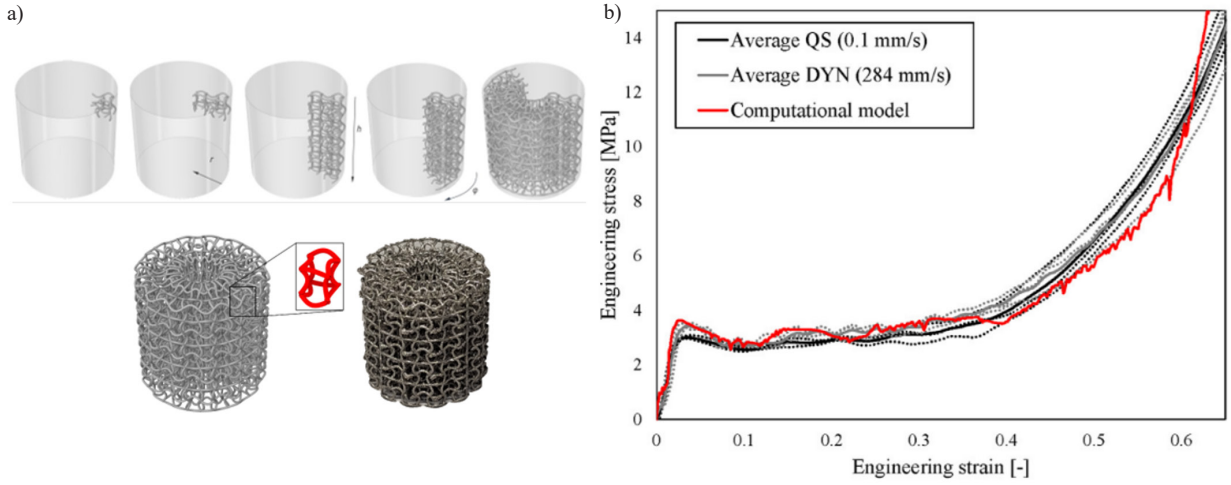

Fig. 7. Design of the: a) axisymmetric auxetic structure, and b) comparison between the computational and experimental results under quasi-static (QS) and dynamic (DYN) loading conditions [57]

5 CONCLUSIONS AND OUTLOOK

This review systematically examined cellular metamaterials' design, fabrication, and mechanical behavior across quasi-static and dynamic loading regimes. Figure 8 illustrates the SEA up to 50 % strain for these structures under compression loading to facilitate a comparative analyzis of energy absorption capabilities.

In Figure 8, darker shading corresponds to specimens with lower porosity within each analyzed group of cellular structures, while lighter shading indicates higher porosity specimens. A clear trend emerges: porosity and base material significantly influence SEA capacity. Lower porosity structures and stiffer base materials (e.g., high Young's modulus alloys) exhibit superior SEA.

Notably, closed-cell foams, TPMS structures, and UniPore structures exhibit consistently high SEA values at 50 % strain, suggesting their suitability for applications requiring efficient energy dissipation within this strain range. However, a key distinction arises with UniPore structures, where densification initiates at 50 % strain (Fig. 8). Consequently, the SEA reported for UniPore structures at this strain level represents their total SEA capacity, limiting their applicability in higher strain scenarios. In contrast, closed-cell foams (Fig. 8) and other analyzed cellular structures exhibit densification at significantly higher strain levels, enabling them to achieve greater total SEA capacity beyond 50 % strain. This demonstrates that while UniPore structures provide good energy absorption at low strain, closed-cell foams and TPMS structures outperform UniPore structures at strains >50 % due to delayed densification.

Furthermore, the observed differences in SEA capacity can be attributed to the distinct deformation mechanisms exhibited by these structures. Closed-cell foams, for example, undergo progressive cell wall buckling and crushing, leading to sustained energy absorption over a wider strain range. TPMS structures, with their complex interconnected geometries, exhibit a combination of bending, stretching, and buckling, contributing to their high SEA and controlled deformation behavior. UniPore structures, with their unidirectional pore channels, primarily deform through axial compression, leading to rapid densification and limited energy absorption at higher strains.

Understanding these deformation mechanisms and their influence on SEA capacity is crucial for the tailored design of cellular structures for specific applications. For instance, materials with high SEA at high strain rates are essential for occupant protection in automotive crashworthiness. In aerospace applications, lightweight structures with high SEA are desirable for impact resistance and vibration damping. By leveraging the insights gained from experimental and computational analyzes, researchers can optimise the design of cellular metamaterials to meet the stringent demands of various engineering applications, driving innovation in transportation, construction, and biomedical engineering.

Future research directions encompass expanded shear and high-strain-rate testing protocols for anisotropic metamaterials and integrating thermal/electrical conductivity into TPMS designs for innovative applications. We also envisage that we will accelerate the discovery of novel architectures using machine learning and AI-driven optimisation.

Computational simulations have emerged as an indispensable tool for the preliminary evaluation of novel cellular designs and for gaining a deeper understanding of the complex deformation behavior exhibited by various cellular structures. This article has showcased a spectrum of computational approaches, ranging from simplified and computationally efficient homogenised models to intricate and time-intensive discrete models employing volume finite elements to represent the entire cellular architecture.

The ongoing advancement of computational power and software capabilities heralds a significant evolution in computational modelling. Specifically, the implementation of mesoscale modelling approaches holds immense promise, enabling the incorporation of fabrication defects and microstructural features into simulations. This enhanced level of detail will lead to more precise virtual prediction capabilities, allowing researchers to accurately anticipate the deformation behavior of cellular metamaterials under diverse loading conditions. Consequently, the optimisation of their mechanical response will become more efficient and reliable, facilitating the development of high-performance cellular materials tailored to specific engineering applications.

Furthermore, the integration of machine learning and artificial intelligence techniques into computational modelling workflows will further accelerate the design and optimisation process. These techniques can be used to perform parametric studies, predict trends, and optimise geometries based on the simulation results. The use of these techniques will lead to faster development times and higher-performing materials.

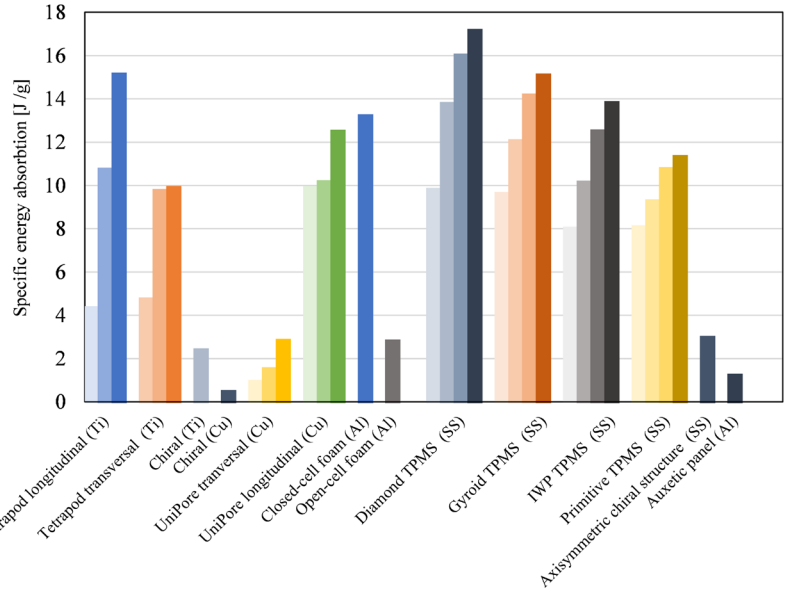

Fig. 8. Comparison of SEA for different cellular metamaterials made from different base materials (Ti-titanium, Cu-copper, Al-aluminium, SS-stainless steel)

This work lays the foundation for the design of multifunctional metamaterials with application-specific performance characteristics. Future research will explore fatigue behavior, adaptive structures, and integration with sensing technologies. The modelling tools and methodologies established here can be used to accelerate innovation in structural materials across a broad spectrum of industries, including aerospace, automotive, defence, and biomedical engineering.

References

[1] Gibson, L.J., Ashby, M.F. *Cellular Solids: Structure and Properties*, Cambridge University Press, Cambridge (1997) **DOI:10.1017/CBO9781139878326**.

[2] Banhart, J. Light-metal foams - History of innovation and technological challenges. *Adv Eng Mater* 15 82-111 (2013) **DOI:10.1002/adem.201200217**.

[3] Vesenjak, M., Fiedler, T., Ren, Z., Öchsner, A. Behaviour of syntactic and partial hollow sphere structures under dynamic loading. *Adv Eng Mater* 10 185-191 (2008) **DOI:10.1002/adem.200700325**.

[4] Ashby, M.F., A. Evans, Fleck, N.A., L.J. Gibson, L.J., Hutchinson, J.W., Wadley, H.N.G. *Metal Foams: A Design Guide*. Elsevier Science, Burlington (2000) **DOI:10.1016/S0261-3069(01)00049-8**.

[5] Lehmhus, D., Vesenjak, M., de Schampheleire, S., Fiedler, T. From stochastic foam to designed structure: Balancing cost and performance of cellular metals, *Materials (Basel)* 10 922 (2017) **DOI:10.3390/ma10080922**.

[6] Körner, C. Additive manufacturing of metallic components by selective electron beam melting - a review. *Int Mater Rev* 61 361-377 (2016) **DOI:10.1080/09506608.2016.1176289**.

[7] Surjadi, J.U., Gao, L., Du, H., Li, X., Xiong, X., Fang, N.X., Lu, Y. Mechanical metamaterials and their engineering applications. *Adv Eng Mater* 21 1800864 (2019) **DOI:10.1002/adem.201800864**.

[8] Gado, M.G., Al-Ketan, O., Aziz, M., Al-Rub, R.A., Ookawara, S. Triply periodic minimal surface structures: Design, fabrication, 3D printing techniques, state-of-the-art studies, and prospective thermal applications for efficient energy utilization, *Energy Technol* 2301287 (2024) **DOI:10.1002/ente.202301287**.

[9] Ulbin, M., Vesenjak, M., Borovinšek, M., Duarte, I., Higa, Y., Shimojima, K., Ren, Z. Detailed analysis of closed-cell aluminum alloy foam internal structure changes during compressive deformation. *Adv Eng Mater* 20 1800164 (2018) **DOI:10.1002/adem.201800164**.

[10] Zheng, Z., Yu, J., Wang, C., Liao, S., Liu, Y. Dynamic crushing of cellular materials: A unified framework of plastic shock wave models. *Int J Impact Eng* 53 29-43 (2013). **DOI:10.1016/j.ijimpeng.2012.06.012**.

[11] Novak, N., Vesenjak, M., Ren, Z. Computational simulation and optimization of functionally graded auxetic structures made from inverted tetrapods. *Phys Status Solidi B* 254 (2017) **DOI:10.1002/pssb.201600753**.

[12] Fíla, T., Koudelka, P., Falta, J., Zlámal, P., Rada, V., Adorna, M., et al. Dynamic impact testing of cellular solids and lattice structures: Application of two-sided direct impact Hopkinson bar. *Int J Impact Eng* 148 (2021) **DOI:10.1016/j.ijimpeng.2020.103767**.

[13] Novak, N., Borovinšek, M., Vesenjak, M., Wormser, M., Körner, C., Tanaka, S., et al. Crushing behavior of graded auxetic structures built from inverted tetrapods under impact. *Phys Status Solidi B* 256 1800040 (2018) **DOI:10.1002/pssb.201800040**.

[14] Mieszala, M., Hasegawa, M., Guillonneau, G., Bauer, J., Raghavan, R., Frantz, C., et al. Micromechanics of amorphous metal/polymer hybrid structures with 3D cellular architectures: Size effects, buckling behavior, and energy absorption capability. *Small* 13 1602514 (2017) **DOI:10.1002/smll.201602514**.

[15] Al-Ketan, O., Rezgui, R., Rowshan, R., Du, H., Fang, N.X., Abu Al-Rub, R.K. Microarchitected stretching-dominated mechanical metamaterials with minimal surface topologies. Adv Eng Mater 20 1800029 (2018) **DOI:10.1002/adem.201800029**.

[16] Kolken, H.M.A., Fontecha Garciam, A., Du Plessis, A., Rans, C., Mirzaali, M.J., Zadpoor, A.A. Fatigue performance of auxetic meta-biomaterials. *Acta Biomater* (2021) **DOI:10.1016/j.actbio.2021.03.015**.

[17] Borovinšek, M., Vesenjak, M., Jože, M., Ren, Z. Computational reconstruction of scanned aluminum foams for virtual testing. *J Serbian Soc Comput Mech* 2 (2008) 16-28.

[18] Duarte, I., Krstulović-Opara, L., Dias-de-oliveira, J., Vesenjak, M. Axial crush performance of polymer-aluminium alloy hybrid foam filled tubes. *Thin-Walled Struct* 138 124-136 (2019) **DOI:10.1016/j.tws.2019.01.040**.

[19] Vesenjak, M., Veyhl, C., Fiedler, T., Analysis of anisotropy and strain rate sensitivity of open-cell metal foam. *Mater Sci Eng A* 541 105-109 (2012) **DOI:10.1016/j.msea.2012.02.010**.

[20] Duarte, I., Vesenjak, M., Vide, M.J. Automated continuous production line of parts, *Metals (Basel)* 9 (2019) 531 **DOI:10.3390/met9050531**.

[21] Duarte, I., Vesenjak, M., Krstulović-Opara, L., Compressive behaviour of unconstrained and constrained integral-skin closed-cell aluminium foam. *Compos Struct* 154 231-238 (2016) **DOI:10.1016/j.compstruct.2016.07.038**.

[22] Duarte, I., Vesenjak, M., Krstulović-Opara, L., Ren, Z. Static and dynamic axial crush performance of in-situ foam-filled tubes. *Compos Struct* 124 128-139 (2015) **DOI:10.1016/j.compstruct.2015.01.014**.

[23] Hokamoto, K., Vesenjak, M., Ren, Z. Fabrication of cylindrical uni-directional porous metal with explosive compaction. Mater Lett 137 323-327 (2014) **DOI:10.1016/j.matlet.2014.09.039**.

[24] Nishi, M., Oshita, M., Ulbin, M., Vesenjak, M., Ren, Z., Hokamoto, K. Computational analysis of the explosive compaction fabrication process of cylindrical uni-directional porous copper. *Met Mater Int* 24 1143-1148 (2018) **DOI:10.1007/s12540-018-0059-x**.

[25] Vesenjak, M., Hokamoto, K., Matsumoto, S., Marumo, Y., Ren, Z. Uni-directional porous metal fabricated by rolling of copper sheet and explosive compaction. Mater Lett 170 39-43 (2016) **DOI:10.1016/j.matlet.2016.01.143**.

[26] Stöbener, K., Lehmhus, D., Avalle, M., Peroni, L., Busse, M. Aluminum foam-polymer hybrid structures (APM aluminum foam) in compression testing. *Int J Solids Struct* 45 5627-5641 (2008) **DOI:10.1016/j.ijsolstr.2008.06.007**.

[27] Ulbin, M., Borovinšek, M., Higa, Y., Shimojima, K., Vesenjak, M., Ren, Z. Internal structure characterization of AlSi7 and AlSi10 advanced pore morphology (APM) foam elements. Mater Lett 136 416-419 (2014) **DOI:10.1016/j.matlet.2014.08.056**.

[28] Duarte, I., Vesenjak, M., Krstulović-Opara, L., Ren, Z. Compressive performance evaluation of APM (Advanced Pore Morphology) foam filled tubes. *Compos Struct* 134 409-420 (2015) **DOI:10.1016/j.compstruct.2015.08.097**.

[29] Vesenjak, M., Duarte, I., Baumeister, J., Göhler, H., Krstulović-Opara, L., Ren, Z. Bending performance evaluation of aluminium alloy tubes filled with different cellular metal cores. *Compos Struct* 234 111748 (2020) **DOI:10.1016/j.compstruct.2019.111748**.

[30] Biasetto, L., Franchin, G., Elsayed, H., Boschetti, G., Huang, K., Colombo, P. Direct ink writing of cylindrical lattice structures: A proof of concept. *Open Ceram* 7 100139 (2021) **DOI:10.1016/j.oceram.2021.100139**.

[31] Bronder, S., Adorna, M., Fíla, T., Koudelka, P,. Falta, J., Jiřroušek, O., Jung, A. Hybrid auxetic structures: Structural optimization and mechanical characterization. *Adv Eng Mater* 23 2001393 (2021) **DOI:10.1002/adem.202001393**.

[32] Novak, N., Vesenjak, M., Ren, Z. Auxetic cellular materials - a Review. *Stroj Vestn-J Mech E* 62 485-493 (2016) **DOI:10.5545/sv-jme.2016.3656**.

[33] Novak, N., Hokamoto, K., Vesenjak, M., Ren, Z. Mechanical behaviour of auxetic cellular structures built from inverted tetrapods at high strain rates. *Int J Impact Eng* 122 83-90 (2018) **DOI:10.1016/j.ijimpeng.2018.08.001**.

[34] Novak, N., Starčevič, L., Vesenjak, M., Ren, Z. Blast response study of the sandwich composite panels with 3D chiral auxetic core. *Compos Struct* 210 167-178 (2019) **DOI:10.1016/j.compstruct.2018.11.050**.

[35] Schwerdtfeger, J., Heinl, P., Singer, R.F., Körner, C. Auxetic cellular structures through selective electron beam melting. *Phys Status Solidi B* 247 269-272 (2010) **DOI:10.1002/pssb.200945513**.

[36] Körner, C., Liebold-Ribeiro, Y. A systematic approach to identify cellular auxetic materials. *Smart Mater Struct* 24 025013 (2014) **DOI:10.1088/0964-1726/24/2/025013**.

[37] Novak, N., Krstulović, L., Ren, Z., Vesenjak, M. Mechanical properties of hybrid metamaterial with auxetic chiral cellular structure and silicon filler. *Compos Struct* 234 111718 (2020) **DOI:10.1016/j.compstruct.2019.111718**.

[38] Kapfer, S.C., Hyde, S.T., Mecke, K., Arns, C.H., Schröder-Turk, G.E., Minimal surface scaffold designs for tissue engineering *Biomaterials* 32 6875-6882 (2011) **DOI:10.1016/j.biomaterials.2011.06.012**.

[39] Diachenko, S.V., Balabanov, S.V., Sychov, M.M., Litosov, G.E., Kiryanov, N.V. The impact of the geometry of cellular structure made of glass-filled polyamide on the energy-absorbing properties of design elements. *Strojn Vest-J Mech E* 70 607-619 (2024) **DOI:10.5545/sv-jme.2024.975**.

[40] Al-Ketan, O., Rowshan, R., Abu Al-Rub, R.K.R. Topology-mechanical property relationship of 3D printed strut, skeletal, and sheet based periodic metallic cellular materials. *Addit Manuf* 19 167-183 (2018) **DOI:10.1016/j.addma.2017.12.006**.

[41] Peroni, L., Avalle, M., Peroni, M. The mechanical behaviour of aluminium foam structures in different loading conditions. *Int J Impact Eng* 35 644-658 (2008) **DOI:10.1016/j.ijimpeng.2007.02.007**.

[42] Tomažinčič, D., Nečemer, B., Vesenjak, M., Klemenc, J. Low-cycle fatigue life of thin-plate auxetic cellular structures made from aluminium alloy 7075-T651. *Fatigue Fract Eng Mater Struct* 42 1022-1036 (2019) **DOI:10.1111/ffe.12966**.

[43] Duarte, I., Krstulović-Opara, L., Vesenjak, M., Characterisation of aluminium alloy tubes filled with aluminium alloy integral-skin foam under axial compressive loads. *Compos Struct* 121 154-162 (2015) **DOI:10.1016/j.compstruct.2014.11.003**.
[44] Duarte, I., Vesenjak, M., Krstulović-Opara, L. Dynamic and quasi-static bending behaviour of thin-walled aluminium tubes filled with aluminium foam. *Compos Struct* 109 48-56 (2014) **DOI:10.1016/j.compstruct.2013.10.040**.
[45] Duarte, I., Vesenjak, M., Krstulović-Opara, L., Anžel, I., Ferreira, J.M.F.F. Manufacturing and bending behaviour of in situ foam-filled aluminium alloy tubes. *Mater Des* 66 532-544 (2015) **DOI:10.1016/j.matdes.2014.04.082**.
[46] Taherishargh, M., Vesenjak, M., Belova, I.V., Krstulović-Opara, L., Murch, G.E., Fiedler, T. In situ manufacturing and mechanical properties of syntactic foam filled tubes. Mater Des 99 356-368 (2016) **DOI:10.1016/j.matdes.2016.03.077**.
[47] Duarte, I., Krstulović-Opara, L., Vesenjak, M. Axial crush behaviour of the aluminium alloy in-situ foam filled tubes with very low wall thickness. *Compos Struct* 192 184-192 (2018) **DOI:10.1016/j.compstruct.2018.02.094**.
[48] Borovinšek, M., Vesenjak, M., Higa, Y., Shimojima, K. Ren, Z. Characterization of geometrical changes of spherical advanced pore morphology (APM) foam elements during compressive deformation, *Materials (Basel)* 12 1088 (2019) **DOI:10.3390/ma12071088**.
[49] Islam, M.A., Brown, A.D., Hazell, P.J., Kader, M.A., Escobedo, J.P., Saadatfar, M. et al. Mechanical response and dynamic deformation mechanisms of closed-cell aluminium alloy foams under dynamic loading. *Int J Impact Eng* 114 111-122 (2018) **DOI:10.1016/j.ijimpeng.2017.12.012**.
[50] Novak, N., Vesenjak, M., Duarte, I., Tanaka, S., Hokamoto, K., Krstulović-Opara, L. et al. Compressive behaviour of closed-cell aluminium foam at different strain rates. *Materials (Basel)* 12 4108 (2019) **DOI:10.3390/ma12244108**.
[51] Novak, N., Vesenjak, M., Tanaka, S., Hokamoto, K. Ren, Z. Compressive behaviour of chiral auxetic cellular structures at different strain rates. *Int J Impact Eng* 141 103566 (2020) **DOI:10.1016/j.ijimpeng.2020.103566**.
[52] Novak, N., Duncan, O., Allen, T., Alderson, A., Vesenjak, M., Ren, Z. Shear modulus of conventional and auxetic open-cell foam. Mech Mater 157 103818 (2021) **DOI:10.1016/j.mechmat.2021.103818**.
[53] Novak, N., Krstulović-Opara, L., Ren, Z., Vesenjak, M. Compression and shear behaviour of graded chiral auxetic structures. *Mech Mater* 148 103524 (2020) **DOI:10.1016/j.mechmat.2020.103524**.
[54] Al-Rifaie, H., Sumelka, W. Auxetic damping systems for blast vulnerable structures. in Voyiadjis, G.Z. (ed.) *Handbook of Damage Mechanics*. Springer, New York. 1-23 (2020) **DOI:10.1007/978-1-4614-8968-9_71-1**.
[55] Novak, N., Al-Rifaie, H., Airoldi, A., Krstulović-Opara, L., Łodygowski, T., Ren, Z., Vesenjak, M. Quasi-static and impact behaviour of foam-filled graded auxetic panel. *Int J Impact Eng* 178 104606 (2023) **DOI:10.1016/j.ijimpeng.2023.104606**.
[56] Novak, N., Vesenjak, M., Krstulović-Opara, L., Ren, Z. Mechanical characterisation of auxetic cellular structures built from inverted tetrapods. *Compos Struct* 196 96-107 (2018) **DOI:10.1016/j.compstruct.2018.05.024**.
[57] Novak, N., Mauko, A., Ulbin, M., Krstulović-Opara, L., Ren, Z., Vesenjak, M., Development and characterisation of novel three-dimensional axisymmetric chiral auxetic structures. *J Mater Res Technol* 17 (2022) 2701-2713 **DOI:10.1016/j.jmrt.2022.02.025**.
[58] Al-Ketan, O., Abu Al-Rub, R.K. MSLattice: A free software for generating uniform and graded lattices based on triply periodic minimal surfaces. *Mater Des Process Commun* 3 205 (2021) **DOI:10.1002/mdp2.205**.
[59] Novak, N., Al-Ketan, O., Krstulović-Opara, L., Rowshan, R., Al-Rub, R.K.A., Vesenjak, M., Ren, Z. Quasi-static and dynamic compressive behaviour of sheet TPMS cellular. *Compos Struct* 266 113801 (2021) **DOI:10.1016/j.compstruct.2021.113801**.
[60] Borovinšek, M., Novak, N., Vesenjak, M., Ren, Z., Ulbin, M. Designing 2D auxetic structures using multi-objective topology optimization. *Mater Sci Eng A* 795 139914 (2020) **DOI:10.1016/j.msea.2020.139914**.
[61] Novak, N., Al-Ketan, O., Borovinšek, M., Krstulović-Opara, L., Rowshan, R., Vesenjak, M., Ren, Z. Development of novel hybrid TPMS cellular lattices and their mechanical characterisation. *J Mater Res Technol* 15 1318-1329 (2021) **DOI:10.1016/j.jmrt.2021.08.092**.
[62] Vesenjak, M., Novak, N., Ren, Z. *Axisymmetric Chiral Auxetic Structure*, EP21197296.3, 2021.

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Data Availability *The data that support the findings of this study are available from the corresponding author upon reasonable request.*

Author Contribution *Nejc Novak: Conceptualisation, Formal analysis, Investigation, Methodology, Writing - original draft; Matej Vesenjak: Supervision, Investigation, Methodology, Writing – review & editing; Zoran Ren: Supervision, Funding Acquisition, Writing – review & editing.*

Celostni razvoj, simulacije in eksperimentalna validacija naprednih celičnih metamaterialov

Povzetek *Celični metamateriali nudijo vrhunske lastnosti za inženirstvo, medicino in obrambo, vendar njihov prehod v industrijsko uporabo otežujejo izzivi pri razvoju, izdelavi in karakterizaciji. Ta pregled ponuja povzetek 20 let napredka na področju celičnih struktur, od pen z odprtimi celicami do struktur s trojno periodičnimi minimalnimi površinami (TPMS). Predstavlja nove tehnike izdelave (npr. eksplozijsko varjenje za strukture UniPore) in prikazuje validirane računalniške modele za optimizacijo gradiranih avksetičnih in hibridnih TPMS metamaterialov. Študija kaže, da na absorpcijo energije vplivata predvsem poroznost in osnovni material, pri čemer se zaprto-celične pene in TPMS strukture izkažejo bolje kot druge geometrije. Dodajalne tehnologije omogočajo prostorsko gradiranje s prilagojenimi mehanskimi lastnostmi. To delo pospešuje razvoj metamaterialov naslednje generacije za absorpcijo trkov, zaščito pred eksplozijami in biomedicinske naprave.*

Ključne besede *celične strukture, metamateriali, eksperimentalno testiranje, računalniške simulacije, mehanske lastnosti*