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Auxetics and related systems

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ABSTRACT BOOK

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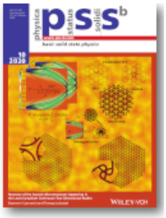

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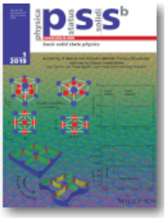

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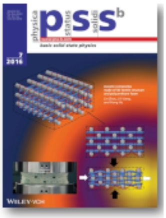

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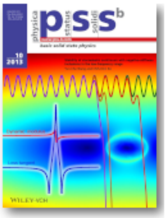

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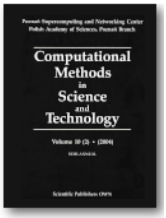

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CONTENTS

ABSTRACTS

Foam-filled auxetic absorbers: working mechanisms and preliminary studies

A. Airoldi[1], N. Novak[2], H. Al-Rifaie[3], C. Chen[4], A. M. Caporale[1], and S. Di Mauro[1]

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Energy absorption properties of auxetic metamaterials have been studied by several authors [1]. It should be observed that auxetic metamaterials are typically characterized by the presence of voids, which occupy most of the volume, like in other cellular structures. Such characteristic suggests the development of very lightweight energy absorbers, exploiting the possibility of filling the void with foam materials, to enhance energy absorption performances. Although some authors have explored this possibility, as for instance in [2], very few studies have been conducted in the case of localized impacts, where the beneficial effects of negative Poisson's ratio can be maximized with respect to more conventional materials [3].

This work reviews the progresses made moving from the promising results obtained in [3], where it was shown that the energy absorbed by a foam-filled auxetic frame may be higher than the sum of the energies absorbed by the same frame and the same volume of foam tested separately. In the activity presented, the performance of foam-filled absorbers was investigated more systematically. As a first step, an hexachiral frame made of 3D-printed unreinforced polyetherimide (ULTEM 1000) and filled by open-cell urethane foam (Confor® CF-45) was manufactured and tested to validate a modelling approach (Fig 1-a).

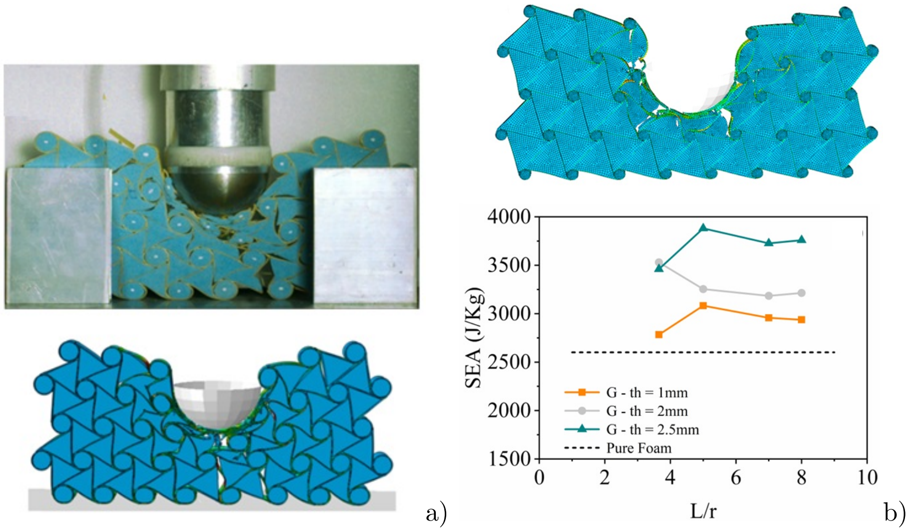

Figure 1. Experiments and numerical model of a foam-filled polymeric elements (a) and effects of the variation of L/r ratio of the chiral geometry and ligament thickness on the Specific Energy Absorbed (b).

Once validated, the modelling technique was adopted to investigate the performance of the absorbers by varying the interaction between the frame and the filler (considering glued insert or simple contact interactions) and the effects of brittle failure in the frame materials. A definition of the Specific Energy Absorption (SEA) based on the mass displaced by the impactor was adopted to provide a proper quantification of the performances, which resulted in all cases higher with respect to absorbers made of the unfilled frame and of an equivalent block of foam both in terms of energy absorbed per unit mass and per unit volume. These studies highlighted a synergistic effect of the two components in the composite absorbers, based on the capability of the auxetic frame to compress the foam, thus maximizing the energy extracted, and the support offered to the ligaments of the frame by the compressed foam, which delays the buckling of the auxetic frame. Other configurations of foam-filled auxetic frame have been investigated numerically and experimentally, pointing out the beneficial effect of the foam filler on the overall performances.

Finally, a sensitivity studied was performed to analyse the effect of the variation of the ratio between the ligament length, L, and the node radius, r, on the SEA level as well as the effect of varying the ligament thickness. The results, shown in Fig. 1-b for a configuration with glued foam inserts, indicate that the SEA levels can significantly exceed the ones of a pure foam block and suggest a non-trivial relationship between the geometrical parameters and the performances, which is probably dependent also on the dimension of the indentor and of the specific impact scenario.

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Models for the prediction of temperature- and pressure-dependent Poisson's ratios in the α-cristobalite and α-quartz tetrahedral frameworks

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The α-cristobalite polymorph of crystalline silica (SiO_2) is the stable phase (tetragonal space group $P4_12_12$) below $\sim 267°C$, and is known to display on-axis auxetic (negative Poisson's ratio) behaviour under ambient conditions [1]. The related α-quartz polymorph (trigonal space group $P3_121$)) of crystalline silica is known to be auxetic in certain off-axis directions under ambient conditions [2], and attains auxetic on-axis response at elevated temperature [3-5]. The structures of both α-cristobalite and α-quartz consist of a corner-sharing framework of SiO4 tetrahedra (with oxygen atoms occupying the 4 corners of each tetrahedron and a silicon atom located at the centre of each tetrahedron). We have previously reported the development of analytical models for the prediction of Poisson's ratio in the α-cristobalite and α-quartz tetrahedral framework under ambient conditions [6,7].

In this paper we report a detailed study into the thermo-mechanical response of the α-cristobalite and α-quartz polymorphs of crystalline silica, and also the germania equivalents to establish the effect of changing the central atom species on the mechanical properties. Molecular modelling simulations have been employed to predict the structure and elastic constants under pressure and temperature loading. Semi-empirical analytical models have been developed to enable prediction of pressure- and temperature-dependent Poisson's ratio response from knowledge of experimental variations in structure under these loading cases. The analytical model predictions are compared with the molecular modelling simulation results and experimental/modelling data in the literature where available.

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A numerical study to deepen the potential of auxetic materials in the design of novel fixation systems

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Studies have proven that auxetic structures' properties are undoubtedly a promising resource for engineers and designers. In particular, the odd behaviour that characterises auxetic meta-materials and structures is expected to offer the chance to re-think the way common mechanical systems work and, in some cases, to re-design them to reach unprecedented performances [1]. In this context of further extending the design boundaries of mechanical systems, auxetic inserts have gained popularity in recent years [2]. The ability of an auxetic insert to shrink when compressed and expand under tension makes it an ideal material for the design of fixation systems (e.g., orthopaedic screws [3]): this insert can be inserted into a cavity with relative ease, but simultaneously, it is also difficult to extract.

This potential of auxetic structures has led to manufacture and test different auxetic inserts, confirming their superiority to more conventional solutions [4]. This new field of application now opens questions about the way these auxetic inserts should be designed to maximise the negative Poisson ratio impact on the overall system's performance. In fact, despite the studies available on the manufacturing and the properties of auxetics, their behaviour under operational conditions still remains an open issue.

To contribute to this field of research, Finite Element Analyses (FEA) were carried out on a virtual bulk auxetic paired with a regression model. These numerical analyses were used to evaluate the potential of defect-free bulk auxetic inserts to be used as a reference and a target for subsequent experimental evaluations. First, the responses of an auxetic and a conventional material inserted in a cavity were compared. The comparison was based on the force required to pull the insert into the cavity and the one required to pull it out. Results proved the superiority of the auxetic insert compared to the conventional one, confirming what was already discussed in the literature [4]. Besides, the nail deformations obtained by the simulations also provided insights into the effect that a negative Poisson ratio has on inserts' ability to stay in the cavity. Auxetics' transversal shrinking when compressed allows them to adapt to the cavity, in contrast to the tendency of conventional materials to escape the cavity once the pushing force ends (Figure 1). Investigations on the size and shape of auxetic inserts were also conducted, providing numerical evidence for designing almost cylindrical fixation devices. Finally, a comparison of the behaviour of auxetic nails in different operational conditions (i.e., when inserted into rigid or soft cavities) has been performed to verify the auxetic nail superiority with rigid cavities.

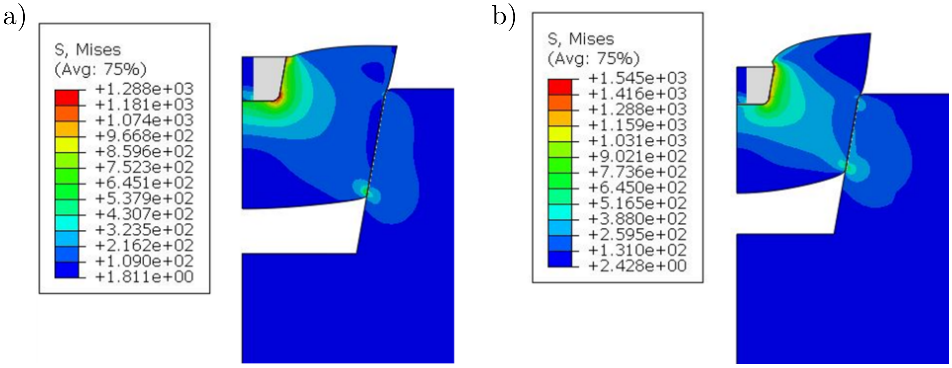

Figure 1. Von Mises stress distribution (MPa) in (a) an auxetic and (b) a conventional insert. An axisymmetric model was used to evaluate the behaviour of auxetic and conventional fixation devices.

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Investigation of wave propagation in auxetic material rods

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Many physical phenomena can be modeled by nonlinear partial differential equations (NLPDE), such as, for example, plasma physics, solid state physics, mechanics, electromagnetism, chemical physics, etc. Exact solutions of nonlinear differential equations play an important role in the study of nonlinear physical phenomena. In this paper, starting from the equation built by Porubov based on Murnaghan's free energy model [1], we investigate wave propagation in auxetic material rods. In particular, we study the influence of Poisson's ratio on the amplitude and velocity of soliton waves when propagating in an auxetic rod by both analytical methods and numerical simulation methods. The obtained results are compared with results published in other papers [2-5].

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A 3D BCC chiral auxetic structure

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Auxetic materials, metamaterials, and structures have negative Poisson's ratio (PR), which means that when subjected to a longitudinal strain, they show a transversal strain with the same sign [1]. These materials are appealing for their increased energy absorption and shear modulus, tuneable vibration and acoustic damping. Auxeticity has been observed not only in foams and crystalline materials but also in a wide range of metamaterials, where it can be tailored through meticulous design of the internal structure. Among the most known auxetic geometries there are re-entrant structures, rotating units, chiral and anti-chiral structures, missing ribs, star, and double arrowhead structures. In recent years, several 3D auxetic patterns were designed and studied [2-13].

In this study, a 3D auxetic chiral structure based on spheres and ligaments is presented, as an example of an entire class of spheres-based auxetic structures. An example of the structure is shown in Figure 1, in which the spherical units are placed following a Body Centred Cubic (BCC) lattice and joined by ligaments which connect each sphere to its eight first-neighbours. Those ligaments are tangentially connected to the spheres surface, and they are oriented to form a chiral pattern. This geometry creates a coupling between the axial displacement of the spheres and their rigid rotation, similarly to what happen in hexachiral pattern, but in a three-dimensional domain. This coupling causes an auxetic effect in all the directions with a transversally isotropic distribution [11], where the isotropy axis is the rotation axis of the spheres. A numerical study was conducted to investigate the PR of the structure and its dependence on the geometrical parameters of the structure, such as the spheres diameter, the ligaments length and thickness, and of the edge effects.

An exemplificative geometry was designed and 3D-printed in Nylon12 using MJF technique. It was tested in quasi-static compression along different axes. An image-processing Matlab code was used to measure the displacement of the spheres of one face of the structure, allowing the determination of the PR. The structure showed the auxetic behaviour in all the directions with a stable PR $= -0.3$ when compressed in longitudinal direction.

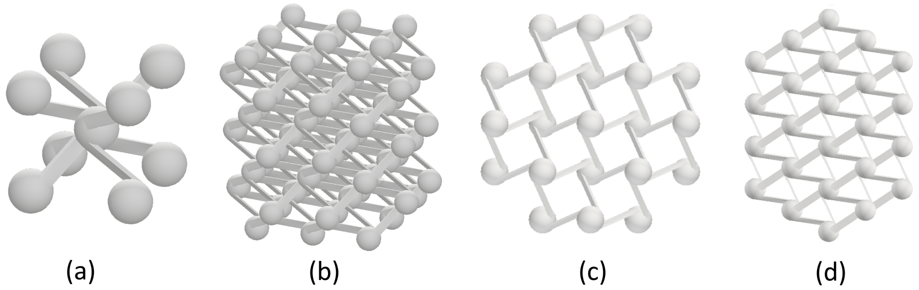

Figure 1. The BCC chiral structure under investigation: (a) unit cell, (b) multicell structure and its morphology form (c) the top view and (d) and along the main diagonal axis.

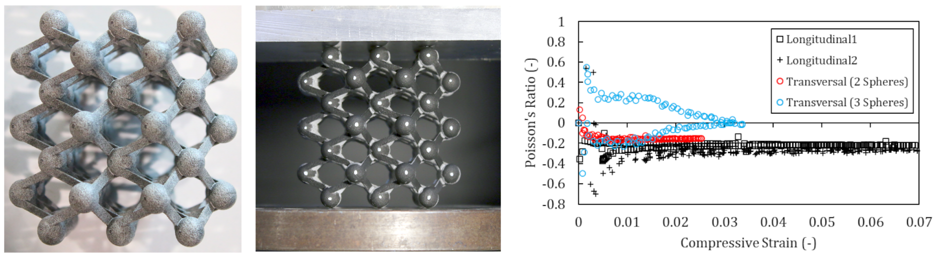

Figure 2. (a) 3D-printed geometry, (b) PR evolution during quasi-static compression tests.

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Towards the Synthesis of Auxetic Molecular Networks; Preparation of Precursors

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The pursuit of intrinsically auxetic synthetic materials has been a recent focus within the field of auxetics[1]. This effort seeks to incorporate chemical tunability and broaden the applications of auxetic materials[2]. Presently, only one single liquid crystalline elastomer has been successfully synthesized and demonstrated to exhibit a negative Poisson's ratio under certain conditions[3]. However, theoretical studies have predicted several molecular structures that would possess a negative Poisson's ratio upon successful synthesis, including a polymeric network built from calix[4]arenes which mimics an "egg-rack" structure[4]. The synthesis of such structures has, however, been considered too complex, as yet. This presentation will review recent advancements in covalent molecular auxetics and discuss a novel approach being investigated in our laboratory for the synthesis of a potential molecular auxetic based on calix[4]arenes.

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The supramolecular route to 3D auxetic materials

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Auxetics are uncommon materials characterized by the counterintuitive property of lateral expansion upon longitudinal stretching, corresponding to a Negative Poisson's Ratio (NPR). The major unresolved issue in auxetics is represented by the design and synthesis of 3D isotropic auxetic materials. Despite several theoretical studies, experimental evidence of 3D molecular auxeticity in synthetic materials is still lacking. The solution reported in this lecture (Fig. 1) relies on a completely novel approach based on the mechanically-driven conformational expansion of a cavitand, which has the unique property to switch between two well-defined conformations: the compact vase and the extended kite. The macroscopic expression of the cavitand conformational expansion is obtained by embedding the auxetic units as crosslinker in a polymer of intrinsic microporosity (PIM). The auxetic behavior of the reported polymer is fully reversible and reproducible, in the presence of a small amount of auxetic unit.[1] The extension to the non-crosslinked version of this class of 3D auxetics will also be presented.

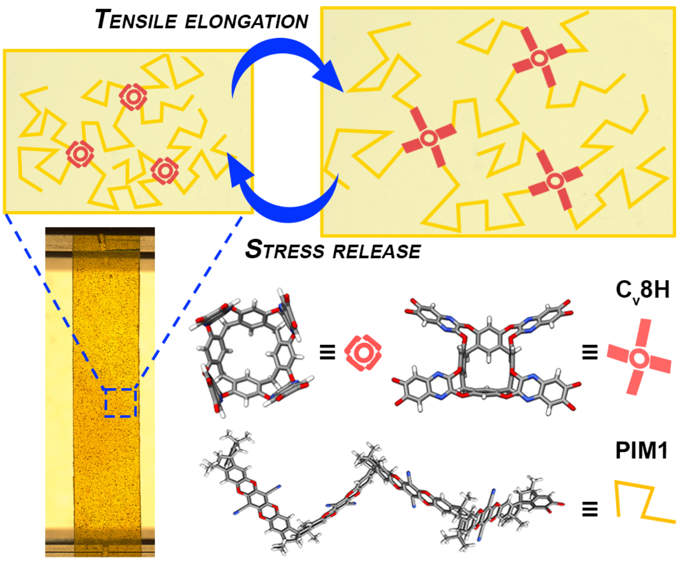

Figure 1. Schematic representation of the working mechanism of the cavitand-based molecular auxetic polymer.

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Foam-filled auxetic absorbers: materials and applications

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The work describes the design of an impact energy absorber, based on a foam-filled auxetic frame and is focused on the identification of the material combinations and of the geometrical parameters for the fulfilment of the requirements in a pre-defined application scenario. The innovative absorber is based on a concept described in [1], i.e. an auxetic hexachiral structure filled with foam. To investigate the importance of material choice, numerical simulations previously conducted on a 3D-printed polymeric hexa-chiral frame filled with open-cell soft polyurethane foam inserts have been repeated considering a metallic frame filled with an aluminium foam [2]. In the present work, the metallic combination of frame material and foam is described, and the energy absorption performances have been evaluated numerically in a localized impact condition, considering two quantitative indices, namely the total absorbed energy and the Specific Energy Absorbed (SEA). The performances indicated an increase up to 25% of the specific energy absorbed with respect to an equivalent mass of aluminium foam.

The comparison with the previous results obtained with polymeric foam-filled frames, highlights the importance of the material choice in the achievement of desired performance in terms of forces and impact energy referred to specific application cases. Moreover, the use of a material with a high elongation at break, such as an elastomeric material, deserves investigation since it could guarantee the preservation of the auxetic property for the whole duration of the localized impact, as the early breakage of ligaments or nodes, which induce the loss of the auxetic property, could be avoided.

All these aspects have been considered in the design of an absorber concept in a specific crash scenario, represented by the impact between a Vulnerable Road User (VRU) and the bumper of a vehicle. In particular, different polymeric materials were considered, including the usage of a thermoplastic polyurethane (TPU) with micronized waste tire-rubber (WTR), which exhibits a very large strain at failure [3], can be 3D-printed to obtain auxetic topologies, and involves the use of recycled material. Additionally, the use of fibre-glass reinforced inserts was assessed, and the role performed by the external cover of the absorbing system on the auxetic effect was investigated (Fig. 1). Finally, an optimization procedure based on a genetic algorithm is presented. The aim is to find an optimal solution of foam-filled auxetic hexachiral structure, considering desired levels of forces and impact energy as target and using as variables in the design space all the geometrical parameters of the auxetic frame and some of the proposed material combinations.

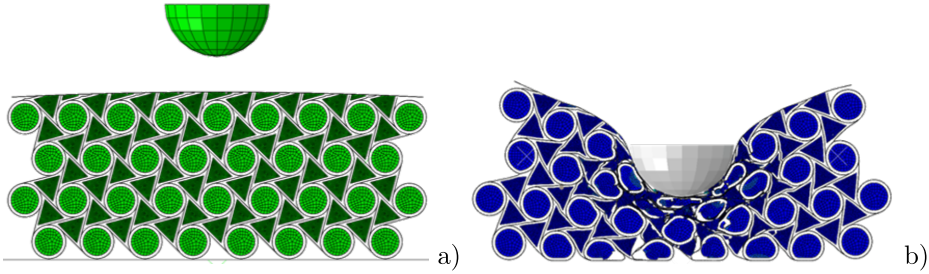

Figure 1. Behaviour of the energy absorber with composite materials: a) undeformed and b) deformed numerical model.

Acknowledgements

This study was carried out within the MOST - Sustainable Mobility National Research Center and received funding fron the European Union Next-Generation EU (Piano Nazionale di Ripresa e Resilienza (PNRR) - Missione 4. Componente 2, Investimento 1.4 - D.D. 1033 17/06/2022, CN00000023). This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them.

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Active control over static and dynamic properties of magneto-mechanical metamaterials

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Over the years, it has been possible to observe numerous studies devoted to the design of mechanical metamaterials capable of exhibiting unusual static mechanical properties such as negative Poisson's ratio (auxetic behavior) or negative stiffness. These studies have been of great practical importance as they were implemented in numerous applications ranging from biomedical to protective devices. However, despite the various advantages that such metamaterials have to offer, they often share one limitation. Namely, once they are fabricated, it is very difficult to significantly change their properties without reconstructing the system. The answer to this problem turned out to be active mechanical metamaterials, i.e. composite structures that can be remotely controlled via changes in the external stimuli such as the temperature or magnetic field. In recent studies, it has been shown that through changes in the magnetic field, it is possible to observe a significant change in the static mechanical properties of the system. More specifically, in one of such studies [1], it was shown that based on the change in the external magnetic field, a magneto-mechanical system may undergo a transition from the configuration characterized by the positive Poisson's ratio to the highly auxetic configuration and vice versa. However, the same could not be done in terms of the dynamic properties of the system.

Given the above, in this work [2], a new magneto-mechanical metamaterial was proposed that allows simultaneous control over the static and dynamic mechanical properties of the system based solely on the changes in the external magnetic field. Similarly to previous studies, the considered metamaterial can exhibit very different Poisson's ratio depending on the externally induced reconfiguration. However, what makes this work particularly interesting, is that in addition to the control over the Poisson's ratio, the active reconfiguration leads to significant changes in the phononic band structure of the system. This, in turn, makes it possible to fine-tune the wave propagation through the system based solely on the changes in the external magnetic field.

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Fast optimisation of honeycombs for impact protection

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Cellular solids such as honeycombs and are often used in impact protection. Product development cycles for those with precisely defined geometries, that allow responses to be programmed to specific functions, can be costly. Desirable functions can include auxetic behaviour - with potential to mitigate risk during impacts with concentrated loads [1-3], or programable, non-linear stress vs. strain relationships that can be tailored to specific impact conditions. This lecture will describe an analytical model that allows fast, parametric optimisation of such honeycombs [4,5]. The analytical model is based on similar principles to the established honeycomb models, extending these to larger strains substantially beyond the point of cell wall buckling during compression/impact [1-3].

The analytical model, and a numerical one (ANSYS Mechanical/LS-DYNA), were validated against experimental data for three thermoplastic polyurethane honeycomb variants. Quasistatic compression tests to 80% engineering strain, and flat-plate impact tests at 1, 3 and 5 J, were applied. The numerical model force readings remained within 5% of the experiments, so this model was then used to verify the analytical one across a broader range of conditions. Honeycomb parameters (cell geometry, orientation, and end constraints) were varied during 5 and 15 J impacts. The analytical model predicted energy absorption at all displacement increments to be (on average) 3% higher than the numerical one. The limits of agreement (with 95% confidence) were between +15 and −9% of the numerical model. While this level of error is higher than most numerical models, it is comparable to those based on artificial intelligence (e.g. [6]). Further work could reduce error by including terms to simulate the force fluctuations during the force plateau (Figure 1).

As the analytical model provided solutions almost instantly, it was used in a demonstrative parametric optimisation study, for a 10 J impact (Figure 1). The input and output solutions were verified in the numerical model, showing a four-fold reduction in peak force (from ~ 2000 to ~ 500N). The 32 cycle optimisation procedure took ~ 0.6s on a standard laptop with 16 GB RAM, while each numerical simulation took between one and four hours, indicative of substantial reductions in computational costs. As such, this model could be used before numerical or experimental optimisation to reduce the number of iterations, and the overall cost of product development cycles.

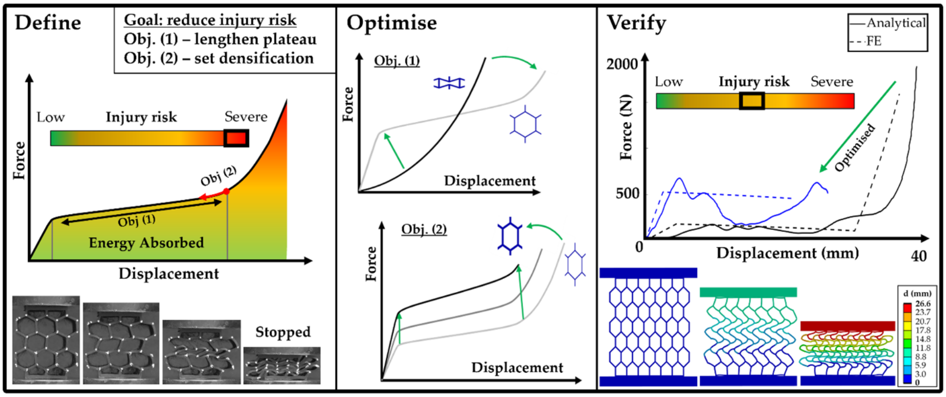

Figure 1. Example optimisation steps for honeycomb impacts.

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Negative stiffness produced by lateral constraint

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Some mechanical systems and structures under displacement-controlled loading can exhibit apparent negative stiffness (stress reduction caused by strain increase). Such structures include buckling beams, rotating levers and non-spherical grains as well as the inverted pendulum. The main feature of these structures is that they do not exist on their own but are a part of a bigger structure. The structure absorbs the energy released by deformation of negative stiffness elements thus making the total elastic energy positive definite.

So far, the negative stiffness elements were considered under uniaxial load presuming that the mechanism of negative stiffness exists within the element. We now consider a situation when the load is multiaxial: the axial load inducing negative stiffness and the constraint in one or two normal directions. In this case it is the constraining system that provides energy to be released by the negative stiffness deformation.

As examples we consider the following systems

1. A sandwich-type configuration whereby the material (conventional or auxetic) is squeezed by two parallel frictionless platens which provide the lateral constraint. Depending upon elastic properties of the material the negative stiffness in a direction parallel to the platens can be observed.

2. A straight beam under axial load smaller than the buckling load and bent by a point load. If the beam is thin or soft enough there exists a critical deflection after which the forces needed to continue deflection will start decreasing thus exhibiting negative stiffness. The easiest way to ensure the low stiffness is to make the beam of blocks without binder.

3. Plates assembled from topologically interlocking blocks which hold together by the virtue of kinematic constraint. Such a plate requires peripheral constraint (e.g. peripheral frame) for its stability, while the fragmentation ensures low bending stiffness. Experiments show that under indentation at the centre the negative stiffness stage is achieved. It can be concluded that negative stiffness is a feature of the movement of some elements of a structure characterised by a specific internal energy redistribution.

Auxetic behaviour from semi-rigid rotating units

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One of the earlier and most well-known auxetic mechanism is that of the rotating rigid units whereby rigid elements are connected at the corners or edges. These connecting parts act as pivots allowing the rigid units to rotate relative to each other without changing shape themselves. Various geometries have been considered including rotating squares [1–3] and equilateral triangles [4] as well as other shapes [5–8]. Rotating rigid units have also been designed in 3D using a variety of polyhedra [9–18].

In reality no system is perfectly rigid and some degree of deformation of the unit is always present. If the extent of deformation affects the mechanical behaviour but the structure is still auxetic then such structures are referred to as having semi-rigid units. Various such systems were considered, including the square [19], triangles [20], and tetrahedra [18]. The mechanism proved to be useful in explaining the auxetic behaviour of interacting atoms. However, it seems that, beyond this application, these systems have attracted very little attention. One of the few exceptions is given by the studies on the cross system [21]. Given the relatively slender ligaments making up the cross system investigated by Wang [21], this is expected to deform primarily through the bending of the ligaments. In this way, it is expected that the changes in the distance between hinging points is small for small deformations.

This work starts by considering variants of the cross system illustrating how there is a transition from prevalently rigid units to the semi-rigid units mechanisms. Subsequently, a novel way of attaining a semi-rigid system will be introduced. It consists of diamond perforations carried out on a lamina having a curvilinear side profile in such a way that as view from above it looks like the rotating square system. The side profile chosen for further investigation consists of semicircles that alternate in direction. A parametric investigation that has been carried out indicates that the system can be auxetic in three orthogonal directions. Finally, the fabrication of auxetic systems using biomaterial will be discussed.

Acknowledgements

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Auxetic Mechanical Metamaterials: Towards the consumer marketplace

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Current innovations in auxetic and related systems will be highlighted. Magneto-mechanical active metamaterials, based on an accordion system and controlled via an external magnetic field, will be discussed. Two different configurations of these systems will be presented: one which functions like a linear actuator, and another which can expand in multiple directions. Experimental and numerical studies demonstrating the behaviour of these systems under an external magnetic field will be presented. Additionally, the potential of stacking these structures to create larger systems that may exhibit auxetic properties across multiple planes will be explored. This will be complemented by a discussion on the use of magnetorheological elastomers to construct these systems.

Another significant topic that will be discussed is that of auxetic polyurethane foams. Foams having a negative Poisson's ratio were first produced in the 1980s by Prof. Rod Lakes using a post-processing thermomechanical technique. During the past four decades, numerous studies have shown that such auxetic foams have considerable potential uses, ranging from comfort products to protection equipment. Despite their benefits, the market presence of auxetic foams has remained limited due to challenges in scaling up the conversion techniques and associated costs. Here we will present an innovative method that is not based on a post-processing technique, and which produces auxetic foams directly from synthesis.

The first attempts to scale up this process will be highlighted. It will be shown that this method enables the scalable production of auxetic foams with tuneable mechanical properties and densities, thereby broadening the spectrum of potential applications for these materials.

Macromolecular Approaches to Auxetic Materials

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Liquid crystalline polymers (LCPs) are attractive targets as auxetic materials due to their combination of intrinsic short-range positional ordering and long-range orientational ordering when uniaxially stretched. Inclusion of appropriate structural motifs in these LCPs by synthetic design offers the possibility to achieve local non-affine deformation leading to a negative Poisson's ratio. The unique features of LCPs that make them well- suited as a platform for macromolecular auxetic materials will be examined.

We have designed, synthesized, and studied several transverse rod containing main-chain LCPs. They were examined in both the powder and fiber forms by wide angle x-ray diffraction. Data from the diffraction experiments were consistent with our site-connectivity driven transverse rod reorientation mechanism for intrinsic auxetic character in these macromolecules. Shifts in peak maxima, intensity distributions in the interchain interaction region, and calculated volume increase accompanying fiber formation were all in line with expectations from considerations of this mechanism. The narrow window for experimental conditions necessary for fiber preparation and subsequent x-ray observation of this phenomenon will be discussed. A close examination of CPK molecular models revealed details of local packing of rods and connected polymer chains in the quiescent nematic polymer melt prior to fiber drawing. It was found that two rod reorientation possibilities exist - each of which leads to increased interchain separation as required for auxetic response. We will conclude with suggestions for future experiments and materials design for new liquid crystalline polymers.

Auxetics and Their Properties

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Auxetics are "materials" that exhibit the unusual property of becoming thicker when stretched, characterized by a negative Poisson's ratio. This unique behaviour arises from their specific nano/microstructural design and the manner this deforms when a uniaxial load is applied. The design often involves re-entrant or chiral geometries, rotating units, or other complex architectures, implemented in 2d or 3d.

The present work will review and compare some of the more commonly known mechanistic models which are known for auxetic behaviour. It also explores how auxetics can be applied in various fields, including but not limited to biomedical devices, protective gear, sports, aerospace applications, flexible electronics, etc. where their distinctive properties can be leveraged to improve performance and durability.

Acknowledgements

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A novel double arrowhead auxetic coronary stent

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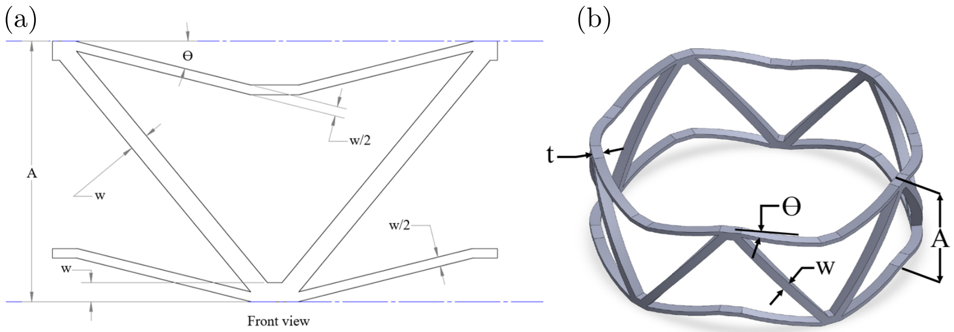

Figure 1. (a) DA auxetic unit cell structure, (b) 3D model of the DA unit ring.

A stent implantation is a standard medical procedure for treating coronary artery diseases [1]. Over the years, various different designs have been explored for the stents, which come with a range of limitations, including late in-stent restenosis (due to low radial strength) [2], foreshortening [2-4], radial recoil [3], etc. Contrary, stents with auxetic [5] design, characterized by a negative Poisson's ratio, display unique deformation characteristics that result in enhanced mechanical properties in terms of radial strength, radial recoil, foreshortening, and more [6-9]. In this study, we have analyzed a novel double arrowhead (DA) auxetic stent with an outer diameter of 3mm and wall thickness of 100 microns that aims to overcome the limitations associated with traditional stents, specifically in terms of radial strength, foreshortening, and radial recoil [10]. The parametric analysis was done initially on the DA's unit ring structure (shown in Fig. 1.) to optimize the design by evaluating the effect of three design parameters (angle, amplitude, and width) on the mechanical characteristics (radial strength and radial recoil) using finite element analysis, as shown in Fig. 2. The width of the strut was found to be the primary determinant of the stent structure's properties. Consequently, the angle and width were found to have the least effect on altering the stent's mechanical properties. Moreover, region A was found to have the highest distortion due to which the region experienced the highest equivalent stresses, region B is the subsequent zone to experience stresses after region A (as shown in Fig. 3.), and region C experiences the least von-mises. After performing the parametric analysis, optimal design factors were selected to design the full-length DA auxetic stent. The mechanical characteristics of the DA auxetic stent were assessed and compared in a case study with the Cypher^{TM} commercial stent, as shown in Fig. 4. The radial strength of the DA auxetic stent was found to be 7.26 N/mm, which is more than double the Cypher^{TM} commercial stent's radial strength. Additionally, the proposed stent possesses reduced radial recoil property and completely eliminates the stent foreshortening issue, as shown in Fig. 5, which shows the superior mechanical properties of the proposed auxetic stent and its potential as a promising candidate for future stent designs.

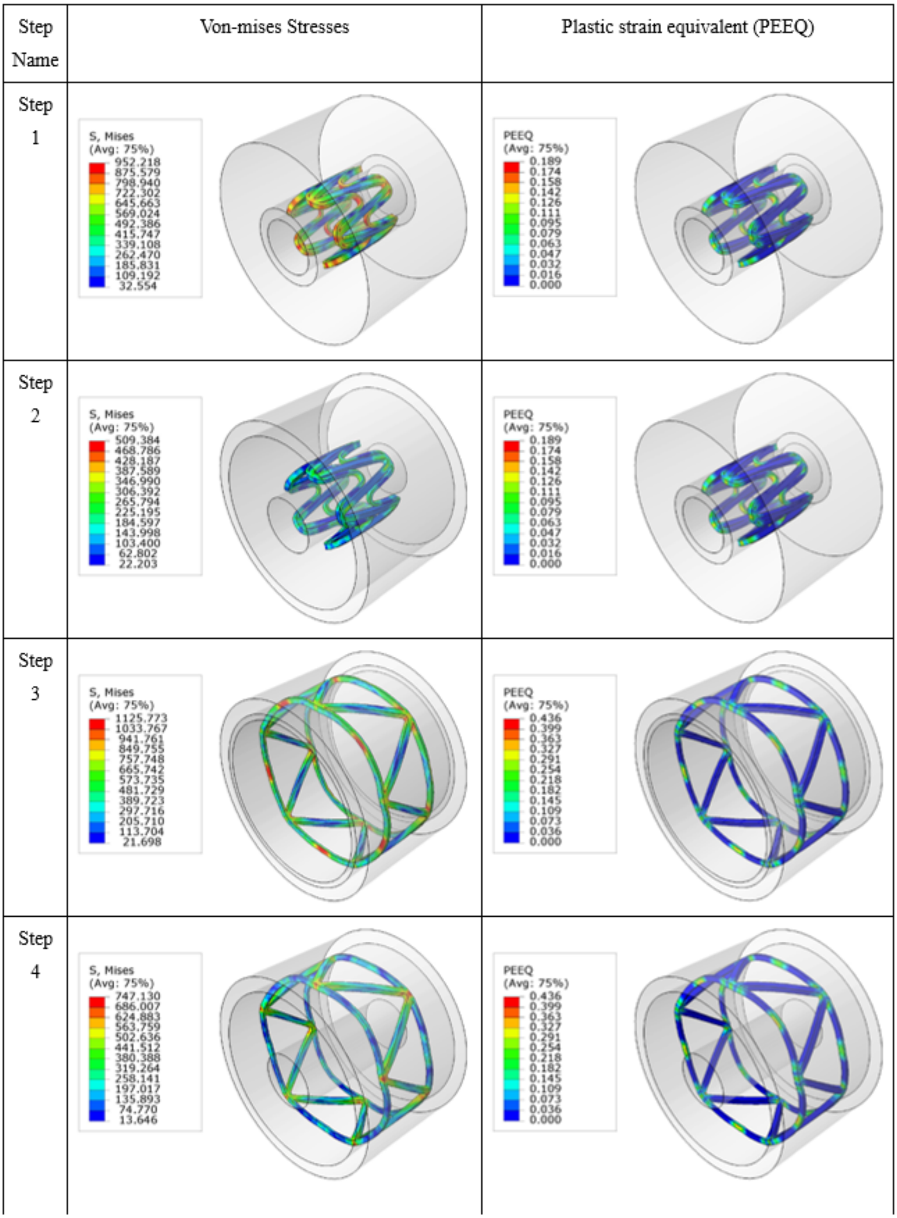

Figure 2. Von-mises and plastic strain in stent structure at (a) Step 1, (b) Step 2, (c) Step 3, (d) Step 4.

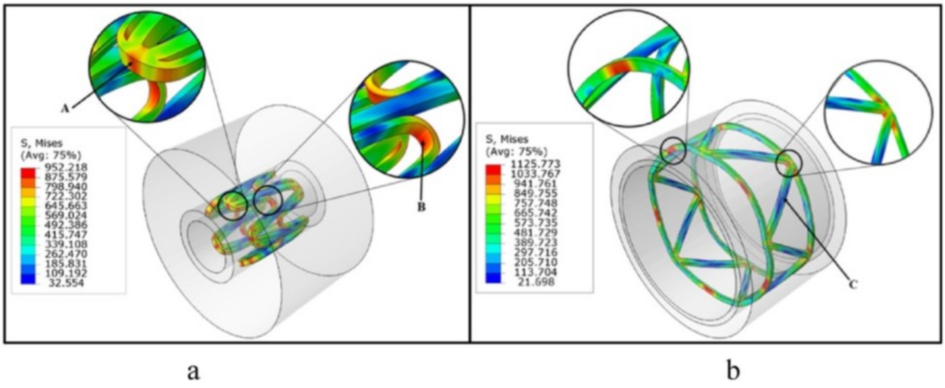

Figure 3. Areas of maximum von-mises during (a) crimping and (b) expansion of the stent's unit ring.

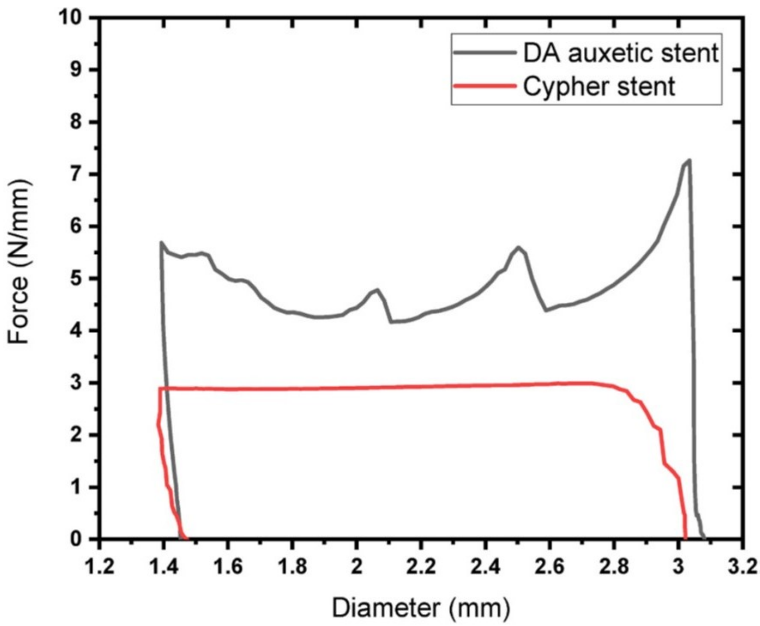

Figure 4. Force per unit length vs change in diameter graph for DA auxetic and Cypher stent.

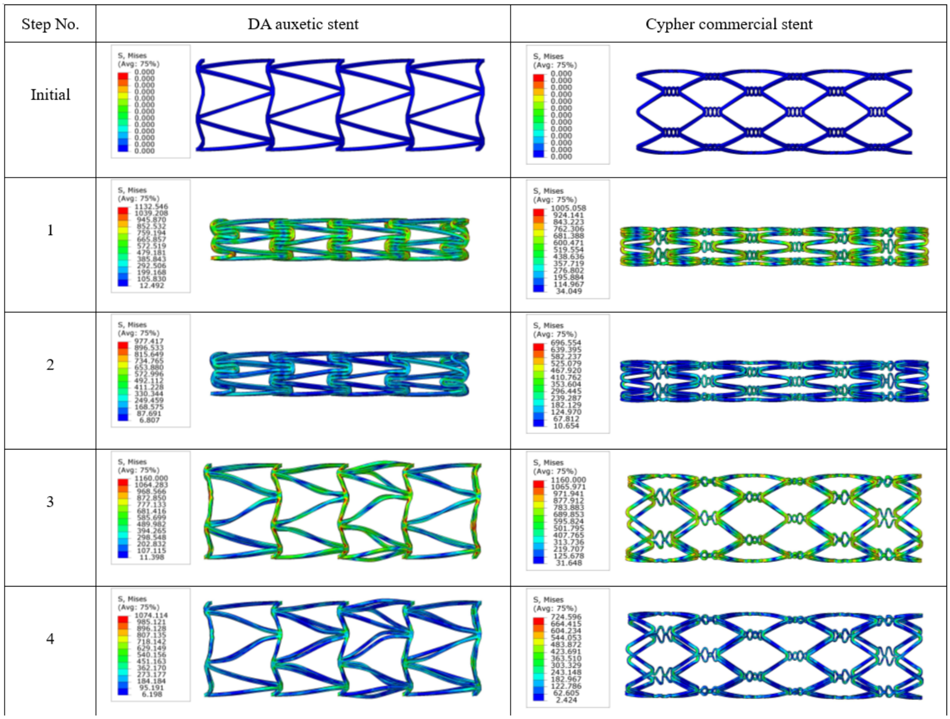

Figure 5. Deformation behavior of the DA auxetic stent and Cypher stent structure at its initial stage, Step 1, Step 2, Step 3, and Step 4.

Acknowledgements

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Excess Entropy of Fluids: Isomorphs and Isodynes

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Auxetic behaviour is the consequence of a specific solid structure leading to a negative Poissons Ratio. This presentation is focussed mainly on the fluid state, which can be separated into liquid and supercritical fluid regions. The thermodynamic quantity, the excess entropy, which is the difference between the total entropy of the system with that of the ideal gas (were it to exist) at the same state point. This is another negative quantity which is closely linked to the structural state, this time of fluids. In recent decades it has been demonstrated that lines of constant excess entropy (a 'configurational adiabat') within the phase diagram of some real and model molecule fluids exhibit a collapse of their structure and some physical properties into the same value when scaled by simple powers of the density and temperature. Such a line, which is called an isomorph [1,2], exhibits properties which can be specified to a very good approximation from data evaluated at only a *single* state point on that line. This reduces the complexity or dimensionality of the description of the fluid state, which follows in the tradition of the van der Waals equation of state where the scaling is performed instead from the strength of attraction and size of a given molecule.

Isomorphs are lines of hidden scale invariance and are approximately parallel to the freezing line [3]. An isomorph is a configurational adiabat but a configurational adiabat is not necessarily an isomorph. For example for Lennard-Jones fluids the shear viscosity forms an isomorph but the bulk viscosity is not an isomorph along the same configurational adiabat line [4].

This subject stems from the pioneering work of W. G. Hoover and collaborators [5] on the properties of inverse power fluids, whose pair potential is purely repulsive and varies as the inverse power of the pair separation raised to an exponent, n.

This presentation covers some recent developments in the isomorph field, and in particular the scaling of the shear viscosity and the self-diffusion coefficient of Lennard-Jones fluid states (see Refs. [6,7] and references quoted in those articles). There are some chemical systems in which the molecules contain many internal degrees of freedom where the transport coefficients collapse just as for a typical isomorph but the fluid assembly structure does not scale or collapse. These are called isodynes, and Ref. [8] presents the results of a molecular dynamics simulation investigation of a model low temperature ionic liquid which behaves as an isodyne.

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Performance improvement of heat exchangers utilizing gyroid TPMS structure

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The first description of minimal surface, dating back to the 19th century, was given by Schwartz and Neovius. A minimal surface is a surface that has zero mean curvature at every point and minimizes its total surface area for a given boundary. The minimum surface of an infinite, created by duplicating the elementary formation in three main directions, is called the triply periodic minimal surface (TPMS) [1-3]. TPMS is a surface-type cellular structure with continuous internal channels and a large surface area-to-volume ratio. This unique geometry results, making them recently applied for heat exchangers (HX) to enhance heat transfer performance [4,5]. The most common TPMS types used for heat exchanger cores are gyroid, diamond, and Schwartz structures [6]. In the present work, gyroid TPMS HX was chosen for enhanced heat transfer because of its helical flow pattern and symmetrical periodic surfaces. These characteristics of the gyroid TPMS contribute to creating a helical flow path and ensuring a uniform distribution of fluid flow [7-9].

The presentation concerned on fluid flow and thermal analysis of gyroid TPMS HX under finite element method. In the first section of this work, the block-type geometry of TPMS-HX was modeled in an ntopology computational tool where Boolean operations were implemented in order to obtain the hot, cold, and hex core domains. Besides structure type, TPMS thickness, unit cell size, and aspect ratio also determine the overall performance of the heat exchanger. In the next section, the conjugate heat transfer method was implemented using computational fluid dynamics (CFD) ANSYS fluent to analyze heat exchanger-coupled fluid flow and thermal performance. The appropriate boundary conditions were applied to the model, specifying the flow rates and temperatures at the inlet and outlet of the fluid streams. In this study, the fluid flow through the heat exchanger was assumed to be incompressible and steady-state. Additionally, a realizable K-epsilon turbulence model is used for fluent flow and the energy method governing equation was implemented to determine the analysis result. Simulation result of the state-of-the-art of heat exchanger that utilized the TPMS structure is compared with a traditional plate heat exchanger. Finally, the results were presented and discussed.

Acknowledgements

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An analysis of mechanical properties of selected composites with auxetic phase

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Nowadays, research on auxetics is already widespread. There are also more and more works devoted to the analysis of composite materials in which one or more components is an auxetic [1-3]. Auxetic materials and structures exhibit unusual properties due to negative value Poisson's ratio.The influence of NPR might be also significant when auxetic (or semiauxetic) materials are used as constituents of multiphase composite. This work presents several selected composite structures built from two or more materials or structures, somee of which exhibits auxetic properties. The study investigate the effect of auxeticity on the properties of the entire composite. The effect of the orientation of the constituent materials in the composite was also analyzed when the constituent materials or structures are characterized by anisotropy of mechanical properties (in particular, Poisson's ratio). Example results of the stress field for geometries close to the classical rotating squares are shown in the following illustration.

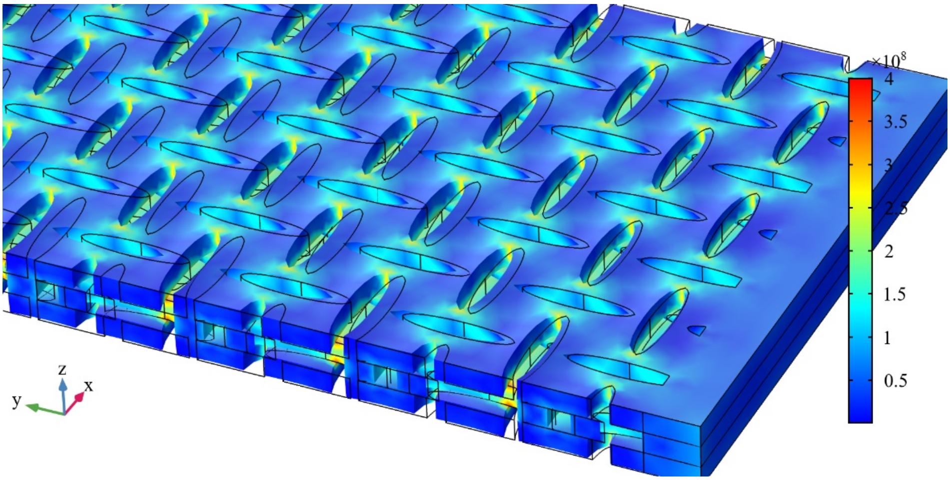

Figure 1. Sample composite consisting of three layers of auxetic sructure - stress field.

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Lattices and composites with unusual physical properties

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Poisson's ratio in chiral isotropic elastic solids can be larger or smaller than the classical thermodynamic bounds. Analysis shows that solids with weak coupling exhibit Poisson's ratio anomalies for larger specimen sizes than corresponding solids with strong coupling. Experiments on a quasi-isotropic composite with chiral inclusions show Poisson's ratio greater than 0.5. Lattices with truncated octahedron cells are studied via optical methods. Poisson's ratio is near 0.5 and strain distribution is nonclassical.

A novel 3D hybrid auxetic lattice structure with enhanced load bearing capacity

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This study presents novel 3D hybrid auxetic lattice structure based on stretching-dominated deformation mechanisms that exhibit excellent load-bearing capacity. The proposed hybrid auxetic unit cell was designed through the combination of a double arrowhead part with a modified re-entrant quadrilateral part. The 2D auxetic structure were first alternatively assembled into a 3D configuration via the interlocking assembly method. Four specimens with different geometric parameters were fabricated with high-modulus Carbon fibre-reinforced polymer (CFRP) laminate composites. Both quasi-static compression tests and finite element (FE) modelling was conducted to study their compressive properties along the loading direction, and good agreement was found between them. A parametric analysis was performed to investigate the effect and interactions of the design parameters on the mechanical properties of the structures using the Box–Behnken response surface method (RSM). Furthermore, the multi-objective optimization method is used to solve the optimized design parameters with the aim of maximizing both the stiffness and auxetic effect. The results indicated the novel CFRP composite 3D auxetic structures realized a significant improvement in structural stiffness compared to conventional auxetic structures. The proposed structure can be used for practical applications requiring high load-bearing capacity.

Static and Dynamic Mechanical Properties of 3D Gradient Petal-like Structures Prepared by Continuous CFRP Composites

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The study involved creating petal-like auxetic structures with linear/linear symmetrical gradients using lightweight and high strength continuous carbon fiber reinforced composites to prevent abrupt stress drops from fiber fractures. The mechanical behavior, deformation patterns, and energy absorption capabilities of these structures were examined through a combination of finite element analysis and experiments under quasi-static compression and low-speed impact conditions. The results indicated that the gradient design could induce a stress plateau in the structures, improve compression modulus in structures with smaller angles, and prevent buckling failure in structures with larger angles, leading to more predictable structural performance. Additionally, the novel composite gradient petal-like structures showed superior energy absorption properties compared to traditional multicellular structures, making them promising candidates for various industries such as construction, marine, and wind power.

Multi-cell structures are characterized by their lightweight and high strength, making them essential in fields like protective engineering[1]. Recent advancements in design and fabrication have led to the development of multi-cell structures, particularly with the introduction of auxetic metamaterials[2]. These materials can contract or expand laterally under certain loads, showcasing impressive deformations and energy absorption abilities. However, these enhancements often come at the expense of structural strength and stiffness, limiting their practical use in engineering[3].

To address this issue, a novel 3D petal-like multi-cell gradient structure is proposed in this study. This structure combines lightweight, auxetic characteristics, and excellent energy absorption capacity, all achieved through the use of continuous fiber-reinforced composite materials. The study investigates the mechanical properties, auxetic behavior, deformation modes, and energy absorption capabilities of these gradient structures designed with various stacking methods under both static and dynamic loads.

Results and Conclusions

The findings of this study demonstrate that the petal-like structures comprised of continuous carbon fiber reinforced composites exhibits favorable mechanical properties, including strength, stiffness, and energy absorption capabilities. The innovative design concept is visually illustrated in Fig. 1. Employing a systematic approach, it is possible to enhance the equivalent compression modulus of petal-like structures with smaller angles while mitigating the risk of buckling failure in structures with larger angles. Furthermore, the interaction between stacking units with varying deformation characteristics reveals that units with limited deformation capabilities impede the deformation of units possessing higher auxetic properties.

The impact of different energy levels on the failure process of gradient composite petal-like structures is systematically analyzed in Fig. 2, with finite element analysis proving to be an effective tool in comparison with experimental data. As observed in quasi-static compression and surface impact load, the structural response unfolds in a multi-stage deformation sequence involving contraction, contact, rotation, and eventual buckling. Notably, the initiation of buckling failure results in a peak load being reached. In HMLs structures, it is important to note that while failure is concentrated near the 60° unit, the strain experienced at maximum load surpasses that of other structures under low impact energy conditions. This disparity in strain levels can be attributed to the influence of smaller angle elements on the deformation behavior of larger angle elements.

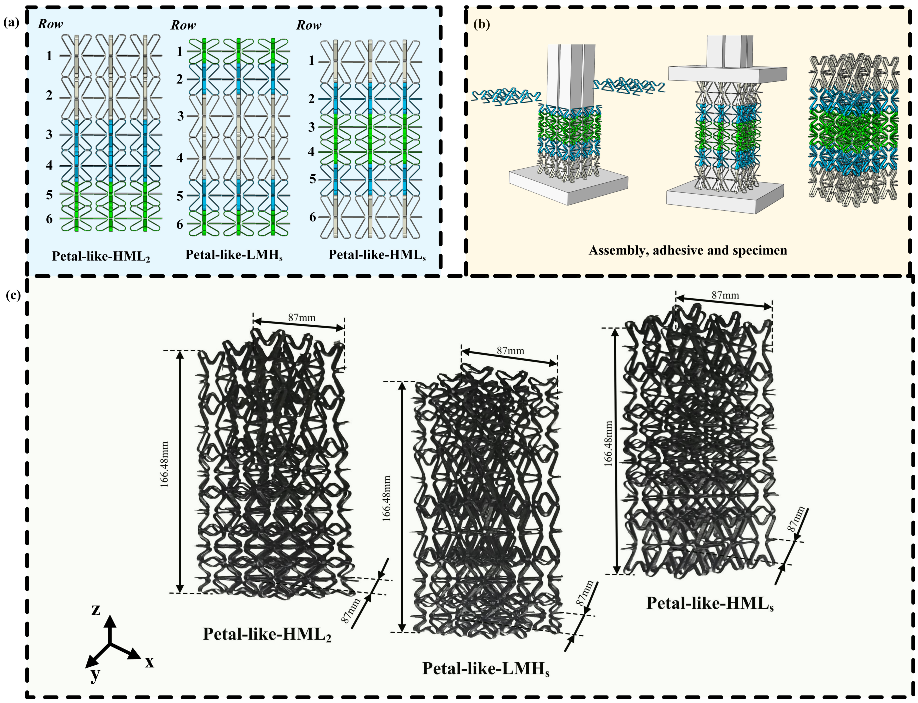

Figure 1. Design concept a) Gradient setting b) Preparation process c) Specimens.

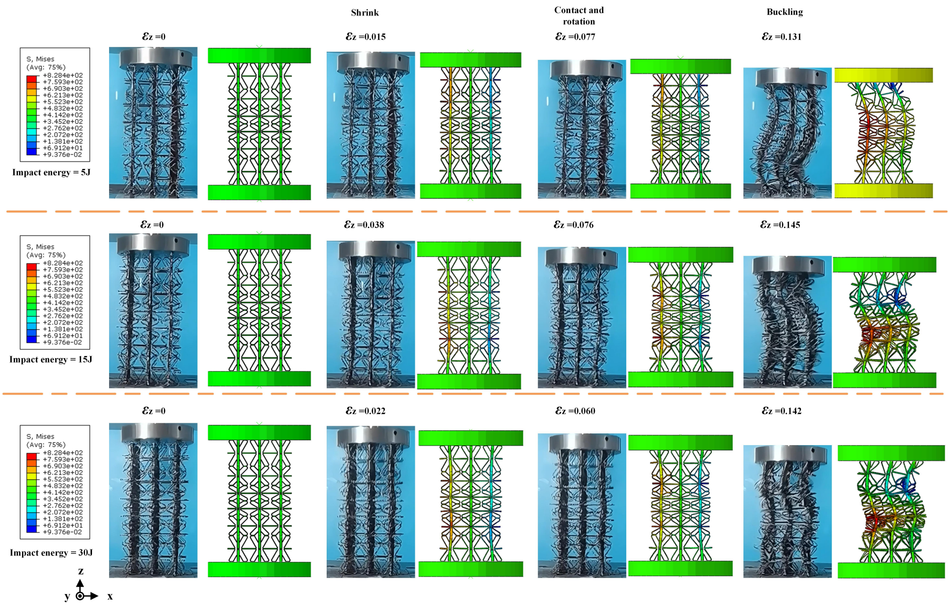

Figure 2. Failure forms of HMLs structure under different impact energies.

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Some remarks on two-dimensional mechanical metamaterials consisting of rotating rigid units of different shapes

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This presentation revisits and re-evaluates a few two-dimensional mechanical metamaterial models, whereby each consists of rigid units of different shapes. The scope includes:

- Metamaterial consisting of non-rotating rhombi with rotating right triangles
- Metamaterial consisting of non-rotating rhombi with rotating parallelograms
- Metamaterial consisting of rotating parallelograms and right triangles with its twin
- Metamaterial consisting of rotating trapeziums and right triangles with its twin
- Metamaterial consisting of rotating isosceles triangles and right triangles with its twin
- Metamaterials that include rotating hexagons

A brief overview of applications of Neuro-Symbolic AI, showcasing it as a promising way of creating explainable and effective models.

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Using neural networks to solve some given problems, although effective, comes with the drawback of low explainability of the generated solutions and usually requires a pretty large training set. On the other hand, using a symbolic approach requires structured data and some manual coding. Neuro-symbolic AI is an effort to combine both aforementioned approaches to leverage the advantages and combat the flaws of each one. Thus, combining the pattern recognition capabilities and scalability of neural networks with the reliability and explainability of symbolic AI.

A very impressive example of the implementation of Neuro-symbolic AI is AlphaGeometry, a tool for solving geometric problems from IMO (International Mathematical Olympiad) at an almost gold medallist level, published in January 2024 by Google DeepMind. It uses a language model (neural part) to guide a symbolic deduction engine solver (symbolic part) in finding solutions to the given geometric problems. Part of its success lies in the generation of a large amount of synthetic data, which is later used to train the language model. This subjcet will be reviewed in the presentation.

The Concept of Using 2D Self-Assembly of Magnetic Nanoparticles for Bioassays

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It can be observed that magnetic iron-oxide nanoparticles are increasingly used in bioassay methods. This is due to their stability in aqueous solutions, ease of functionalization, biocompatibility and very low toxicity. Here, we show that the recent discovery of the ability of magnetic nanoparticles to self-assemble into 2D structures of ordered chains may be exploited for bioassays. This would open up the possibility of controlled immobilization of proteins, enzymes, DNA or RNA and other molecular systems on spatially ordered nanostructures. In this work, fluorescein was used as an example. Also shown is the possibility of using Raman spectroscopy to analyze material accumulated on such structures. The observed formation of regularly spaced chains of magnetic nanoparticles takes place during the drying process of a thin layer of magnetic liquid placed on an appropriately prepared low-density polyethylene (LDPE) film.

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Thin auxetic films with magnetic nanoparticles for shielding electromagnetic radiation

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The growing number of new stretchable electronic materials is leading to the emergence of new strategies in the development of such materials, which must take into account the specific mechanical properties associated with elastic deformations and correspondingly changing physical properties. One example is flexible magnetoelectronic materials in the form of a thin layer of non-magnetic flexible polymer matrix with densely embedded magnetic nanoparticles. In this case, magnetic nanoparticles can be prepared by physicochemical methods of 2D printing in the form of flat agglomerates or uniform spatial structures of chains of single magnetic nanoparticles. Examples of ring and linear magnetic structures are presented in [1,2]. Different absorption of electromagnetic radiation energy by magnetic nanoparticles [3] in the deformed area is one of the consequences of elastic deformation of elastic thin films with magnetic nanoparticles. This creates an opportunity to use magnetic nanoparticles to prepare new materials that shield electromagnetic radiation in a controlled manner, depending on the intensity and direction of the radiation. The concept of such a system is presented based on preliminary experimental results and computer simulations.

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Unveiling Complex Mechanics of Kresling Origami

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Origami metamaterials offer a versatile framework for precisely tuning mechanical properties through intricate folding patterns. This lecture begins with an overview of the Kresling pattern, illustrating how twist buckling can spontaneously occur in thin cylindrical walls. By simply twisting a sheet of paper wrapped on two coaxial circular tubes separated by a specific gap, we will demonstrate the formation of the Kresling pattern.

Next, we explore the mechanics of Kresling cells, showing how selecting the right geometric parameters can lead to bistable behavior [1]. Our custom setup allows us to investigate the mechanical intricacies of Kresling tubes, with both even and odd numbers of Kresling units having varying chirality. This setup features fixtures that enable independent control of axial displacement (contraction/expansion) and twist, without restricting the chiral arrangement of individual cells within the Kresling origami array. This research has broad applications in fields such as soft robotics and mechanical computing.

The second part of the lecture examines the in-plane Poisson's ratio of various origami patterns, including the Miura- ori, Eggbox, and the newly devised Morph and Trimorph patterns [2,3]. Our studies show that the Morph pattern can uniquely reverse Poisson's ratio, displaying entirely positive or negative values through structural changes. We emphasize a triclinic metamaterial system derived from the Trimorph pattern, featuring a basic unit cell with four tilted panels and corresponding creases. This simple geometry provides valuable insights into the behavior of the material. Through mathematical analysis, numerical simulations, and experimental validation, we developed a manufacturing technique and a testing device called the Saint-Venant setup to measure the reversible auxeticity of the Trimorph pattern accurately. This setup helps us quantify the lattice Poisson's ratio and investigate line and point defects in the Trimorph-based metamaterial. Notably, we found that point defects cause significant stress, but this stress can be redirected into stable, distinct states by carefully choosing the defect locations.

Our research offers a deep understanding of origami metamaterials and highlights their potential for designing and controlling unique mechanical properties.

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Clockwise and Anti-Clockwise Chiral Metamaterials based on Axially Asymmetric 2D Euclidean Tessellations

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Chiral honeycombs are one of the main classes of auxetic metamaterials and are well-known for their ability to exhibit a wide range of negative Poisson's ratio which are retained over a relatively high strain range. As their name implies, these systems are characterized by a lack of axial symmetry. The classical chiral systems; which are hexachiral, tetrachiral and trichiral honeycombs; are all based on monohedral regular tessellations, namely triangular, square and hexagonal tilings, however, recently, other chiral systems based on polyhedral and irregular monohedral polygon tessellations have been proposed and shown to exhibit an even wider spectrum of mechanical properties and deformation behaviours. These include tessellations which are inherently 'chiral', i.e. tessellations which possess no axis of in-plane symmetry while retaining a rotational symmetry characteristic. In this work, we demonstrate how this geometric property imparts additional versatility to the metamaterial system upon 'chiralisation', i.e. the transformation of the base tessellation into a chiral metamaterial, since two distinct, unique geometries with different mechanical properties may be produced depending on whether clockwise or anti-clockwise chiralisation is applied.

Advancement in Molecular Modelling of Covalent Organic Frameworks and their Auxetic Potential

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Covalent Organic Frameworks (COFs) are a class of porous organic frameworks, composed of organic building blocks linked together via covalent bonds. These frameworks are defined by their large surface area, adjustable pore sizes, low density, and customisable structures, making them highly versatile for a wide range of applications [1]. To date such COFs have been synthesised in varying dimensionality- 1D [2], 2D [3] and 3D [4]. The majority of the studies have been carried out on 2D and 3D structures. 2D COFs like COF-1 [5], resemble stacked sheets akin to graphite, whilst 3D COFs such as COF-320 [6], feature an intricately interwoven diamond-like structure. Research on the mechanical properties of COFs has predominantly focused on 2D systems, revealing significant negative Poisson's ratios, reaching values of -1.5 [5]. On the other hand, the exploration of the mechanical properties of 3D COFs, particularly the Poisson's ratio and negative linear compressibility, are limited [7,8].

Molecular modelling of 3D COFs poses a number of challenges, particularly due to their relatively large pore sizes. In view of this, a methodology for simulating this class of materials by loading nitrogen molecules within the pores of these COFs was developed. From the results obtained, it was found that in all investigated cases geometry optimization yielded structures that closely resembled the experimental ones, when the structure was loaded with sufficient nitrogen molecules. Furthermore, the potential of such systems to exhibit a negative Poisson's ratio and/or negative linear compressibility was also investigated. This provides insight into the potential auxetic nature of existing molecular systems, paving the way for the design of other inherently auxetic materials at the molecular scale.

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Auxeticity in the face centered cubic crystals of hard spheres with 2D, 1D, and 0D inclusions

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Hard sphere potential, infinite when the spheres overlap and zero otherwise, is the simplest - purely geometric - interaction which distinguishes fluids and solids. It is known that the solid formed by identical hard spheres corresponds to a thermodynamically stable face centred cubic (f.c.c.) crystalline phase. Thus, the hard sphere system constitutes the simplest model of crystalline structures of cubic symmetry. This model is partially auxetic [1,2], i.e. in some directions it exhibits negative Poisson's ratio, whereas in other directions this ratio is positive or zero.

In this talk, the results of extensive research on the elastic properties of f.c.c. hard sphere crystals containing three different types of inclusions, that *preserve* the cubic symmetry of the phases, are summarized and compared. The studies concern periodic arrays of combinations of nanoslits, nanochannels or nanocavities filled by identical hard spheres that slightly differ in diameter from the ones forming the matrix crystal. Hence, the discussed inclusions can be seen as the arrays of nanolayers, nanorods, or pointwise nanoinclusions which will be referred to as (quasi-) two-dimensional (2D), one-dimensional (1D), and zero-dimensional (0D) inclusions, respectively.

It will be demonstrated that these inclusions typically increase the anisotropy of the resulting crystals when compared to the pristine, i.e. *inclusionless*, f.c.c. crystal. It is also shown that, at high pressures and when the diameters of inclusion spheres exceed those of the matrix spheres, the investigated inclusions imply an increase of the minimum Poisson's ratio (the latter is negative in the pristine crystal in some directions). Moreover, when the inclusion spheres are large enough, they eliminate the (partial) auxeticity of the studied structures. The presented comparison of various cubic systems reveals that, in order to modify qualitatively the elastic properties of the f.c.c. hard sphere crystal, instead of using (infinite) 2D and 1D inclusions one can use periodic arrays of very small 0D inclusions that, at least for Poisson's ratio, result in similar quantitative effects but require applying much lower concentration of the inclusion particles.

The comparison of elastic properties for model containing four and six nanochannels will be discussed [3, 4]. The studies were carried out for different inclusion sizes and thermodynamic conditions. It will be shown that, contrary to the previous model, the auxetic properties decrease but do not disappear, contrary to the case of the system containing four nanochannels. Moreover, the research showed that the hardness and stiffness of the model with six channels not only does not decrease, compared to the pure crystal of hard spheres, but also increases significantly with the increase in the size of the particles forming the inclusion [4]. This is a completely new result that has not been observed in previously tested models.

Acknowledgements

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Axisymmetric chiral auxetic structure

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Novel three-dimensional (3D) axisymmetric chiral structures with negative and zero Poisson's ratios will be presented based on the existing 3D conventional chiral unit cell [1]. The conventional tetra-chiral unit cell is mapped to the axisymmetric space to form the new 3D axisymmetric chiral structure (ACS). Two different structure designs were characterised depending on the period delay of the sine curve representing the horizontal struts of the structure. The structures are fabricated using additive manufacturing technology and experimentally tested under compression loading conditions. The digital image correlation methodology is used to determine the Poisson's ratio dependence on the axial strain. The computational model of axisymmetric chiral structures is developed and validated using the experimental data.

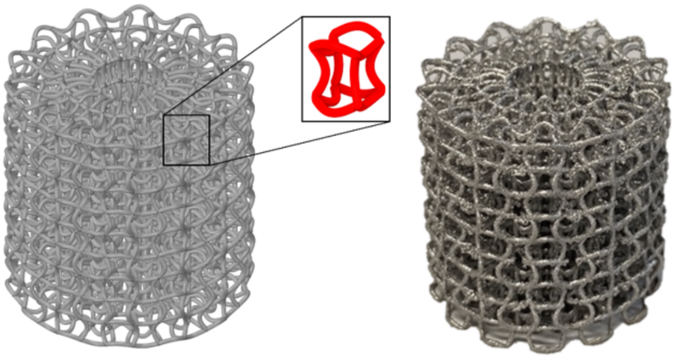

Figure 1. Designed and fabricated ACS structure.

Additionally, the structural optimisation of one unit cell of the validated computational model was conducted to determine the optimal geometrical configuration of the unit cell, considering the target strain energy density as the optimisation objective function [2]. The results of the unit cell optimisation were then used to build the parametric computational model of the whole ACS structure, where the areas of the significantly different strut thicknesses were defined as a separate section to control the thickness of the struts discretely. The parametric computational model was then optimised. This resulted in a new, spatially graded ACS with a stiffer structure, providing 4.25 times higher energy absorption capability than regular ACS. With one of the highest Specific Energy Absorption (SEA) in the strut-based metamaterial class and thus ideal for future crash absorption applications.

Acknowledgements

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Enhanced Hybrid Materials: One-Pot Fabrication of Shear-Thickening Gel-Impregnated Auxetic Polyurethane Foam

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Introduction

Auxetic materials, distinguished by their ability to expand under tension due to their negative Poisson's ratio, have demonstrated considerable potential in applications requiring enhanced energy dissipation [1]. Notable advances have been achieved through the incorporation of innovative composites like graphene oxide and precisely engineered micropatterned surfaces, leading to significant improvements in impact resistance [2,3]. Despite these advancements, fully optimizing the energy dissipation capabilities of auxetic materials remains a formidable challenge.

The exploration of non-Newtonian shear thickening materials presents a promising strategy for boosting the impact resistance of auxetic foams [1]. These materials exhibit increased viscosity and stiffness under stress, thus offering enhanced protective qualities. However, their application in practical settings is often limited by issues such as leakage in fluid-based systems. Efforts to incorporate shear thickening gels have shown promising results [1,4], but achieving uniform distribution within the foams and refining the manufacturing processes for these hybrids continue to pose significant obstacles. Furthermore, integrating these non-Newtonian fluids can endow auxetic foams with self-healing properties, opening avenues for the development of more durable and long-lasting materials. Although the creation of self-healing foams has made progress, the application of these properties within auxetic structures is still in its early stages.

This abstract presents a research initiative aimed at developing hybrid auxetic foams through an innovative one-pot process that simultaneously converts foam into auxetic structures while polymerizing non-Newtonian fluids within the same mould. This method seeks to enhance energy dissipation and introduce self-healing properties, effectively addressing existing challenges and advancing material applications. The focus is particularly on sectors requiring robust impact protection, where such integrated manufacturing processes could significantly improve both efficiency and effectiveness.

Methods

Polyurethane foam samples measuring $7.8 \times 7.8 \times 4$ cm with densities between 18 and 25 kg/m^3 were cut out and injected with an ethanol solution containing precursors of the shear-thickening fluid polyborosiloxane (PBS): polydimethylsiloxane

(PDMS) and boric acid (BA) in a stoichiometric ratio of $r = 1.5$. After injection, the samples were oven-dried to evaporate the ethanol, then placed into a 6×6×2 cm closed mould and heated at 104°C for 3 hours. This process not only initiated the auxetic transformation of the foam but also triggered the polymerization of the PBS.

To evaluate the mechanical properties and auxetic behaviour, tensile tests were performed using an INSTRON 5966 dynamometer equipped with a Kinovea-based 2D motion analysis system to measure axial and longitudinal displacements and calculate the Poisson's ratio. Additional mechanical characterization included compression and indentation tests to further explore the behaviour of these hybrid systems under various stress conditions. The samples also underwent dynamic impact tests using a drop weight impact tester at varying energy levels to assess their energy absorption and dissipation capabilities. Morphological studies using optical microscopy and Scanning Electron Microscopy (SEM) were conducted to assess the structural integrity and distribution of PBS within the auxetic foam. These analyses were crucial for visualizing the microstructure and ensuring the uniform integration of PBS, which is essential for consistent mechanical properties throughout the material.

Results and Discussion

These materials have demonstrated interesting potential in terms of energy absorption, impact damping, and overall mechanical resistance. These qualities suggest they could be well-suited for environments that demand effective impact mitigation. Additionally, the incorporation of self-healing properties within these hybrids could improve their ability to sustain multiple impacts and mechanical stresses. This feature enhances the durability and functional longevity of the materials, supporting their performance across repeated uses.

The preliminary observations indicate potential for these hybrid auxetic foams in environments that require both impact resistance and durability. The integration of energy dissipation and self-healing properties could prove beneficial across a range of applications, such as protective gear and sports equipment, where resilience is key. These initial findings support further exploration and research into the capabilities and applications of these advanced materials.Inizio modulo

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Smooth bimaterial structures realising negative thermal expansion

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Structures with negative thermal expansion can be important as elements of hybrid materials and composites with controllable thermal expansion. Such materials will develop reduced thermal stresses under temperature change, which will increase the material and structural longevity. A number of structures were proposed that emulate negative coefficients thermal expansion. However, these structures (as well as many auxetic structures) suffer from stress concentrations created at sharp connections.

Here we propose circular and spiral negative thermal expansion structures which are free from the stress concentrators. The basic structure we propose is an incomplete biomaterial ring made from conventional positive thermal expansion materials: the external part of the ring is made of a material with the positive coefficient of thermal expansion which is higher than that of the internal part of the ring. As the ring is incomplete, the presence of free ends leads to reduction of the curvature radius with temperature increase and thus produces shrinkage of the ring.

Negative viscosity component of the hard-sphere crystal

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The hard-sphere system (in which the particles cannot overlap with each other) is a useful reference system in many fields, in particular, it is a fundamental model in the statistical mechanical theory of fluids and solids. One of the lesser explored phenomena related to the hard-sphere system is the behavior of its transport coefficients in the solid phase.

In this presentation the transport coefficients, mainly the viscosity tensor components, of the hard-sphere system in the solid phase will be discussed. The transport coefficients have been determined by extensive molecular dynamic simulations to an extent and accuracy not previously reported in the literature, which will be presented [1]. It will be demonstrated that the viscosities (shear, cross, longitudinal, and bulk) of the hard-sphere crystal display, unlike in the fluid, a surprisingly simple behavior in that they can be represented well by a simple function of the density-scaled compressibility factor. It will also be shown that among the viscosity tensor components, the cross viscosity exhibits a completely different and surprising behavior compared to the other viscosities, in being positive in the dense fluid and negative over the entire solid range.

This behavior of the transport coefficients was analyzed in detail using the revised Enskog theory [1]. This theory is an extension of the Enskog kinetic theory approach which is expected to be applicable to moderately dense systems. The revised Enskog theory expressions, in which three parts are considered (an instantaneous (I), kinetic (K), and so-called α-part), facilitate our understanding of the existence of simple scaling of the transport coefficients in the hard-sphere crystal. In the presentation all three parts will be discussed in detail. The knowledge of these different parts allows an assessment of the degree of agreement between the ("exact") molecular dynamic simulation results and the predictions of the theory. It also allows for more in-depth speculation on the possible origins of the different behavior of the individual viscosity coefficients.

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Exploring Dynamic Variability in Poisson's Ratio: Modelling Damping of Auxetic Viscoelastic Materials

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This study evaluates the intricate relationship between the damping characteristics and Poisson's ratio of viscoelastic materials. Focusing on their impact on structural behaviour and implications for engineering design practices. By examining the dynamic response of multi-layered laminate cantilevered beams, we aim to shed light on how variations in Poisson's ratio influence the viscoelastic damping behaviour of such beams.

We explore the suitability of regular rheological models for auxetics and investigate how changes in Poisson's ratio affect the extreme limits of indentation, bulk, and shear modulus of viscoelastic materials (figure 1) [1]. Examining how these changes relate to viscoelastic energy response, loss, and damping mechanisms [2], with the goal of determining whether changes in Poisson's ratio can influence the layer size required for specific engineering applications.

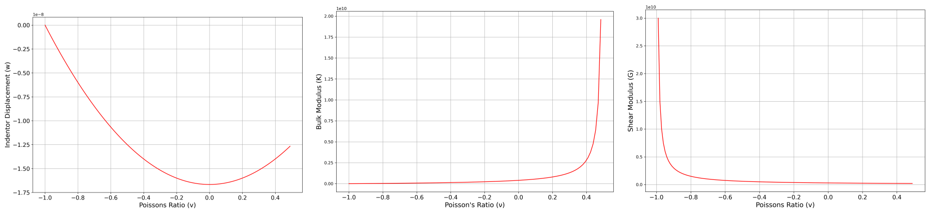

Figure 1. Poisson's ratio effect on Left: Indentation, Centre: Bulk modulus, and Right: Shear modulus.

Our geometric analysis focuses on the cantilevered beam configuration (figure 2). Comprising an elastic core, viscoelastic damping, and constraining layers [3]. By varying Poisson's ratio within the viscoelastic layers (ranging from -1 to $+0.5$) while considering the elastic behaviour of the core material, we gain insights into the complex interplay between material properties and structural response. Our findings reveal dynamic patterns regarding the influence of Poisson's ratio on the damping of viscoelastic materials. These insights contribute to understanding how auxetics can be leveraged to achieve weight reduction, damping optimisation, or better suited material choices.

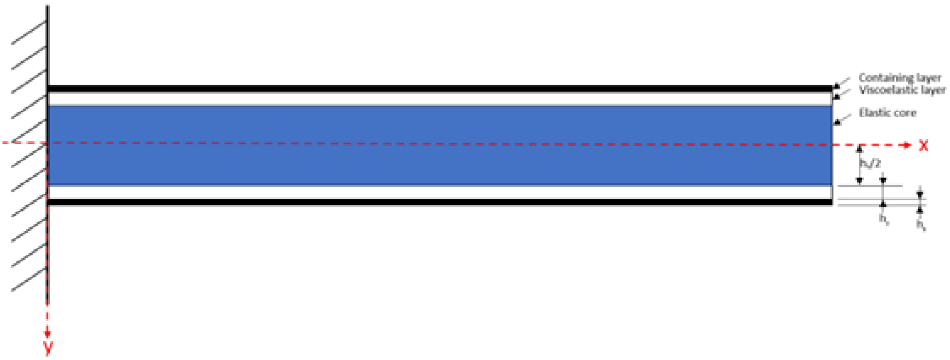

Figure 2. Five-layer-laminate composite cantilever beam

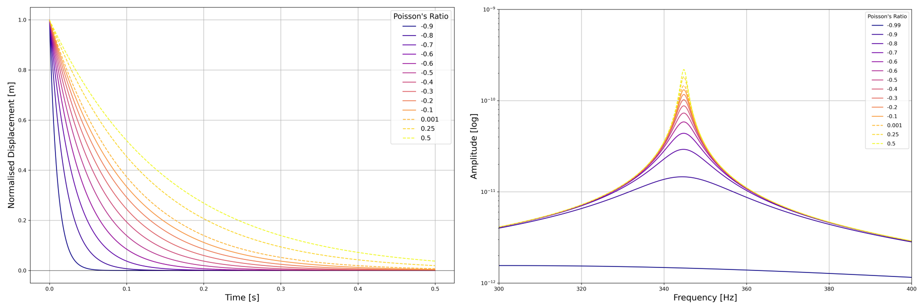

Figure 3. Left: End of beam decay response to viscoelastic damping over a range of Poisson's ratios ($-1 > \nu > 0.5$) and Right: Resonance response over varying Poisson's ratio ($-1.0 > \nu > 0.5$) on the viscoelastic-elastic cantilever beam.

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Emerging auxeticity in porous and wood composite materials under relative humidity conditions

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Concerns about sustainability and environmental aging are driving recent developments in materials, particularly metamaterials. Additionally, variations in temperature and relative humidity can be used as tools to trigger unusual deformation mechanisms and multifunctionality. In this talk, we will discuss how the concept of hygromorphism has been recently applied to develop classes of metamaterials and meta-composites, and how relative humidity and different types of loading affect the quasi-static mechanical and vibrational behavior of auxetic foams. We will also demonstrate how variations in relative humidity can trigger the emergence of auxeticity in new types of bamboo composites.

Thermal stresses in periodic cellular auxetic structures with rotating units

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Materials with a negative Poisson's ratio (auxetics) have been known for over 130 years [1]. In the early 1900s, physicist Voigt was the first who reported this property [2] and his work suggested that the crystals can become thicker laterally when stretched longitudinally. Unfortunately, this discovery was ignored for a few decades until 1980s [3-6].

Based on the deformation mechanism, the auxetic cellular structures have been classified by Saxena et al. [7] and Lim [8] into three main types: 1) re-entrant type; 2) chiral type; and 3) rotating units. In particular, Saxena et al. [7] summarized different types of auxetic structures and models as:

1. re-entrant type (2D re-entrant, 2D re-entrant triangular, 3D re-entrant, double arrowhead);
2. rotating polygons (squares, rectangles, rhombi, parallelograms, triangles, tetrahedral);
3. chiral type (chiral circular, rotachiral, 3D chiral, anti-chiral);
4. perforated sheets (perpendicularly oriented cuts, randomly oriented cuts, diamond perforations, star perforations, 2D sheet containing holes);
5. crumpled sheets (aluminium thin foils, graphene sheet);
6. other (nodule fibril model, hexa-truss, egg rack structure, missing rib, generalized tethered nodule, entangled single wire auxetic, grooved block of metal, hard discs).

These types of structures have been investigated by many researchers, eg. [9-20].

Compared to materials with negative thermal expansion (NTE), the thermal properties of materials with negative Poisson's ratio (NPR) (auxetics) are not often investigated [16]. In this research, the thermal properties of periodic cellular auxetic structure with a rotating units mechanism [17-20] are investigated and simulated using the finite element method (Fig. 1). The influence of Poisson's ratio of auxetic structure on their thermal properties (thermal stresses) is analyzed and observed for the unit cell of structure (Fig. 2).

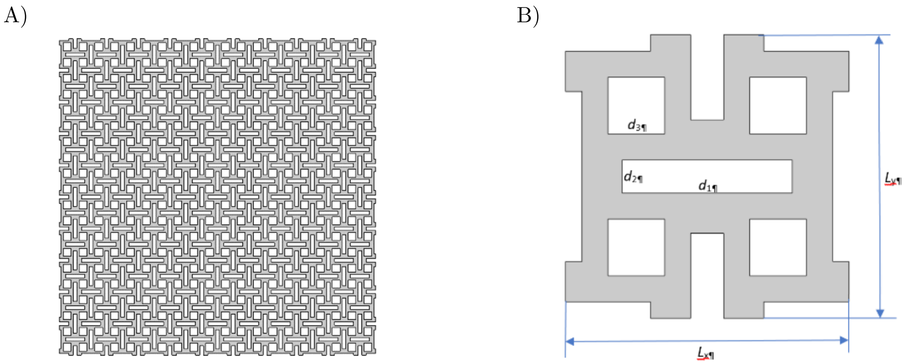

Figure 1. View of: A) periodic auxetic structure, B) unit cell.

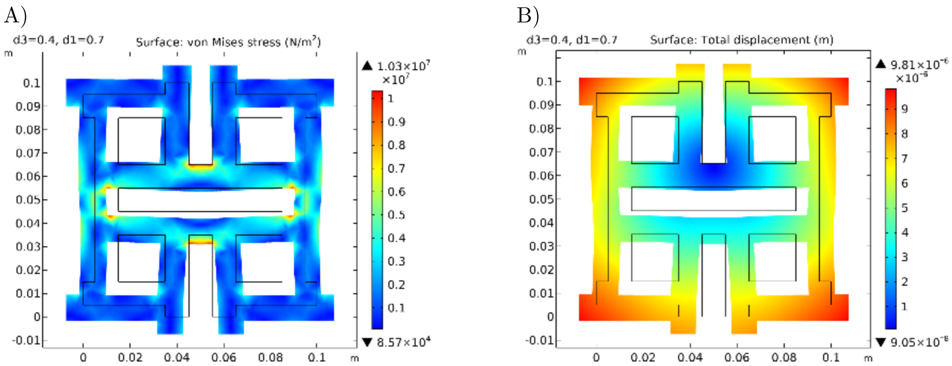

Figure 2. Numerical results for unit cell: A) Huber von Mises - Hencky stresses and B) total displacement.

Acknowledgements

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Sandwich panels made of veneer with a "negative" honeycomb core

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A circular economy requires the design of biodegradable and easily reused composites. So far, many works have concerned layered structures made of metal or synthetic materials [1,2]. However, in the literature, the number of research devoted to the design of layered honeycomb wood panels is very limited [3,4]. Among them, few works concern structures with auxetic properties [5,6]. For this reason, the research aimed to design wooden composites with a wavy auxetic core and to determine the impact of the core's geometric imperfections on honeycomb panels' mechanical properties.

The sandwich panels' cores were made of birch veneer and cardboard, and the claddings were made of birch plywood. Poisson's ratios of cores with geometric imperfections were experimentally determined and then compared with the calculation results of several numerical models presenting simplified structures (Fig.1). For the numerical calculations, all the elastic properties of orthotropic materials were measured (Fig.2). The influence of core arrangement on selected mechanical properties of panels during three-point bending was experimentally investigated.

Based on the test results, geometric imperfections do not eliminate the auxetic properties of the core but affect the negative values of Poisson's ratios (Fig.1). The obtained composites are distinguished by high moduli of linear elasticity and specific fracture modes (Fig.3). Compared to particleboards and MDF boards, new sandwich panels are characterized by a higher modulus of elasticity, greater energy absorption capacity, and similar values to plywood, but they have a significantly lower density. It has also been shown that the numerical simplification of core geometric imperfections is effective and can be applied to other computational models.

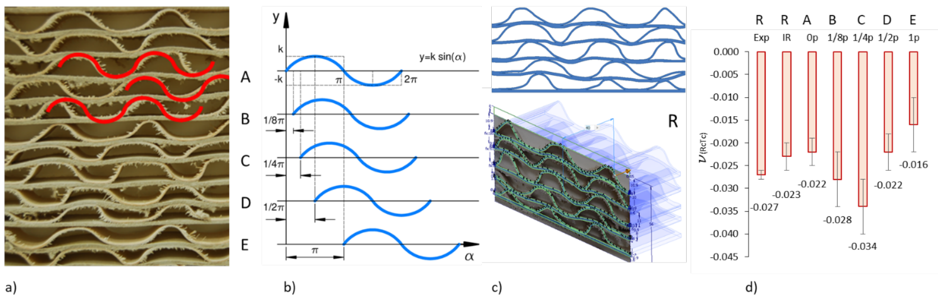
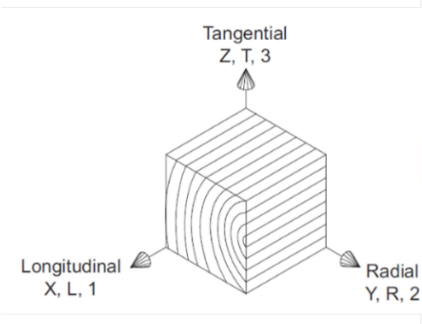


Figure 1. Properties of auxetic core a) imperfections, b) simplification model, c) real model, d) Poisson's ratios.



$$\begin{pmatrix} \varepsilon_{LL} \\ \varepsilon_{RR} \\ \varepsilon_{TT} \\ \gamma_{RT} \\ \gamma_{LT} \\ \gamma_{LR} \end{pmatrix} = \begin{pmatrix} \frac{1}{E_L} & \frac{-\nu_{LR}}{E_R} & \frac{-\nu_{LT}}{E_T} & & & \\ \frac{-\nu_{RL}}{E_L} & \frac{1}{E_R} & \frac{-\nu_{RT}}{E_T} & & 0 & \\ \frac{-\nu_{TL}}{E_L} & \frac{-\nu_{TR}}{E_R} & \frac{1}{E_T} & & & \\ & & & \frac{1}{G_{RT}} & 0 & 0 \\ & 0 & & 0 & \frac{1}{G_{LT}} & 0 \\ & & & 0 & 0 & \frac{1}{G_{LR}} \end{pmatrix} \begin{pmatrix} \sigma_{LL} \\ \sigma_{RR} \\ \sigma_{TT} \\ \tau_{RT} \\ \tau_{LT} \\ \tau_{LR} \end{pmatrix}$$

Figure 2. Orthotropic model for all materials.

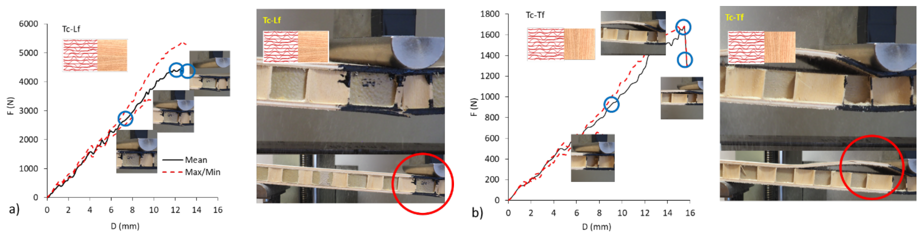


Figure 3. Results of bending test for models a) Tc-Tf, b) Tc-Tf.

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New Developments in Odd Viscoelasticity and Chiral Active Matter

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This talk explores recent advancements in elasticity, focusing on the effects of chirality and the interplay with active matter systems. Defined by their non-equilibrium nature, active matter systems comprise elements that either utilize energy or execute work, thereby presenting a significant deviation from traditional equilibrium-centric theories. This deviation has spurred the emergence of models termed odd (visco)elasticity, odd thermoelasticity and odd Cosserat elasticity, which reevaluate how materials react to external stimuli. Unlike conventional elasticity, which perceives materials as continuous media that undergo deformation under external forces, odd elasticity introduces a scenario where active odd materials can engage in both deformation and rotational actions in response to such forces, offering a new perspective on material behavior at the microscopic scale. Transitioning to odd viscoelasticity, we discuss the details of the framework, the unconventional material responses it predicts, and implications across various active matter scenarios in condensed matter physics.

Models of auxetics at the atomic and molecular level

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Three research directions for auxetic models at the atomic-molecular level are presented. The first direction of research in the search for new auxetic molecular models concerns the influence of particle geometry on Poisson's ratio in two-dimensional systems, using the example of hard cyclic tetramers [1-3]. The second research direction refers to models with different intermolecular interaction potentials [4-8]. The third approach combines the possibility of reducing the value of the Poisson's ratio by appropriately changing the intermolecular interaction with simultaneous modification of the structure as in the case of composite material but at the atomic or molecular level [9-13]. The results of computer simulations of the models are discussed in detail. Taking into account the enormous possibilities of modern nanotechnology in the synthesis of nanoparticles and nanostructures with various geometries, these results may help indicate the direction of the search and synthesis of auxetic materials and auxetic nanocomposites.

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Effective elastic properties of three-dimensional auxetic unit cells with periodic boundary conditions

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We numerically study the effective elastic properties of complete and partial auxetic composite materials via the homogenization of their unit cells with or without periodic boundary conditions. The partial auxetic composite materials consist of a star-shape or chiral cylindrical inclusion embedded in a cylindrical matrix. The complete auxetic composite materials consist of three-dimensional star-shape inclusion embedded in a matrix cube. By using the finite element numerical method, all components of the elastic tensors of the composite materials are calculated. It is found that when the modulus ratio of matrix to inclusion is extremely small or large, the composite materials may exhibit effective negative Poisson's ratio. In addition to the effects of constituents' elastic properties on overall properties, the effects of microstructural geometries and periodic boundary conditions on the effective elastic properties are examined. Furthermore, the negative stiffness effects on the composite materials are also studied for their exceptional points, leading to unbounded effective elastic properties, in the context of non-Hermitian physics.

Anomalous frozen evanescent phonons

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Propagating phonons are the eigensolutions of the elastic-wave problem in periodic media. In addition, generally, also evanescent phonon modes exist that oscillate in space and time and that exponentially decay in space, corresponding to a complex valued wavevector. We discuss frozen evanescent phonons as the eigensolutions of periodic elastic problems in the static regime (zero frequency). Such solutions always exist, but they are usually uninteresting because their decay length is very short. We show that the decay length or characteristic length in periodic metamaterials can become anomalously long under certain conditions. We connect these conditions to the usual real-valued phonon band structure via the Cauchy-Riemann equations. Experiments and theory on 3D printed nonlocal metamaterials are in excellent agreement. The connection to nonlocal electrically conducting metamaterials will be made.

Preparation and properties of helium containing hybrid fluoroperovskites, and how the helium modifies their negative thermal expansion

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In 2017, we reported, based on high pressure neutron powder diffraction, that compression of $CaZrF_6$ in helium at room temperature, and pressures of less than 0.5 GPa, led to the formation of the defect perovskite $[He_{2-x}][CaZr]F_6$, which could be recovered to ambient pressure at low temperature. The incorporation of helium modified the material's negative thermal expansion. Our subsequent work showed that stoichiometric $[He_2][CaZr]F_6$ likely forms at pressures ~ 1 GPa and that this material is stable to high pressures, unlike $CaZrF_6$. Remarkably, this perovskite still shows negative thermal expansion and, on compression at low temperature, it shows a tilting transition typical of perovskites. This prompted an exploration of other frameworks that could incorporate helium to form new perovskites.

We will present results from neutron, X-ray and gas uptake and release measurements for $CaNbF_6$ and ScF_3 in high pressure helium. The insertion of helium into these materials modifies their thermal expansion, elastic stiffness and phase behavior. Similar to the situation with clathrates, gas uptake by $CaNbF_6$ can be modeled using a Langmuir isotherm, but only once the nonideality of helium at high pressures and low temperatures is accounted for. Initial experimental estimates of the enthalpy change for helium uptake suggest an important role for entropy in the insertion of helium to form perovskites with helium on the A-site, as the enthalpy change is likely small and positive.

Modeling of auxetics using systems interacting *via* hard potential

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Starting from Lakes' pioneering work [1] materials and models exhibiting negative Poisson's ratio (PR) have gained increasing interest. Evans coined them auxetics [2]. Obviously, isotropic systems can be either auxetic or not. This is because their PR does not depend on direction. The planar system of hard cyclic hexamers [3], is a good example of a model in which all solid phases are elastically isotropic and which highest density (chiral) phase shows negative Poisson's ratio [4,5]. It is worth noting that all the solid phases of hard cyclic hexamers are elastically isotropic by symmetry. This is a consequence of the fact that each of them shows a 6-fold symmetry axis [3]. The latter implies elastic isotropy in two dimensions (2D) [6]. Strictly speaking, even a 3-fold axis would suffice for elastic isotropy in 2D [7,8]. However, in the case of anisotropic systems, the situation is not that easy. Namely, PR in 2D anisotropic systems depends on the direction of the applied stress [9,10]. Moreover, in three dimensional (3D) anisotropic materials and models PR depends both on the direction of the applied stress and on the (transverse to stress) direction in which the strain is measured. Thus, to distinguish materials with negative PR in all directions from materials for which PR is negative for some directions and non-negative in others, the notion of partial auxeticity was introduced [11,12]. It is important to note here that unlike to 2D, there is no periodic crystal in three dimensions (3D) that is elastically isotropic by symmetry. This is a simple consequence of the fact that cubic crystals, which show the highest elastic symmetry in 3D, are described by three (not two, as in isotropic media) elastic constants [6]. Lower symmetry crystals are described by even larger numbers of elastic constants [6]. However, by modifying interatomic or intermolecular interactions one can increase the elastic symmetry of crystals under certain thermodynamic conditions (pressure and/or temperature) when some relations between elastic constants are fulfilled, such as $C_{44} = (C_{11} - C_{12})/2$ which implies isotropy of cubic crystals under zero pressure; C_{ij} are the elastic moduli in Voigt's notation. One can say that in the latter case the isotropy is not achieved through symmetry but through the modification of interactions. In other words, through energy [13].

Hard potential, infinite when interacting molecules overlap and constant (usually taken to be zero) elsewhere, is the simplest (purely geometric) interaction potential that characterizes the size and shape of a molecule. Its main advantage, apart from the simplicity, is the ability to reproduce excluded volume effects and to mimic short-range intermolecular correlations which are crucial for most of the physical properties of the condensed matter systems.

The lecture will present a short review of theoretical research and computer simulations of the simplest 2D and 3D hard body models exhibiting auxeticity or partial auxeticity [14].

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Optimization of auxetic geometries in multiphase materials with increased stiffness and near-zero lateral strain

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Auxetic materials and structures exhibit negative values of Poisson's ratio, which makes their deformation pattern unusual compared to conventional materials. The auxetic effect stems mostly from the geometry of auxetic's internal structures and is mostly independent on the properties of the bulk material [1]. Material properties of auxetic structures can be changed and tailored to meet the demands by making changes in the geometry of their unit cells.

Multiphase materials combine two or more phases in the structure of a single composite material, often with increased properties, which differ from the simple sum or mean of its components. Auxetic materials can be utilized in development of multiphase materials with increased Young's modulus. This effect can be obtained by properly distributing the different phases in the volume of the composite material and utilizing the auxetic effect [2]. Combining structures with different values of the Poisson's ratio allows to obtain structures with near-zero lateral strain, or near-zero effective Poisson's ratio [3].

This work presents the results of development of multiphase materials with increased stiffness and near-zero lateral strain obtained with known auxetic unit cells subjected to optimization to obtain the desired values of effective material properties via multiscale modelling. Values of material properties of all considered phases were obtained via multiscale modelling of representative volume elements of their respective auxetic and conventional unit cells.

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Self-similarity of ferroelastic textures and acoustic signals. A way to auxeticity?

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When a crystal undergoes a phase transition with rotational symmetry breaking the low-symmetry phase, if not cracked or pulverised, shows a number of ferroic domains separated by coherent domain walls [1]. The number is equal to the index of the low-symmetry point group in the high-symmetry one. If the order parameter involves a strain, the low-symmetry phase is called ferroelastic and the domain pattern ferroelastic texture [2]. A rare example of ferroelastic texture is so called star pattern [3]. Recently this kind of pattern has been revealed in an organometallic complex [4]. The known star patterns occur in systems where a three-fold axis exists in the high-symmetry phase and is lost in the low-symmetry one, see Figure 1(a). The star pattern is self-similar, i.e. invariant with respect to spatial scaling. Are similar patterns possible with higher order axes lost? Figure 1(b) shows a four-arm star. When the domains are removed, the domain walls show a structure which, when treated within a Keating model shows auxetic properties in some directions of applied stress. Is this observed in nature? Are there auxetic ferroelastic textures? Another open question is whether a self-similarity can be attained in magnetic systems of an appropriate shape [5].

Whereas it is not straightforward to quantify planar and three dimensional self -similar objects, apart from direct microscopic observations, we can easily detect the self-similarity and its disappearance in acoustic signals synthesized according to the Weierstraß-Mandelbrot function [6]. An example will be presented.

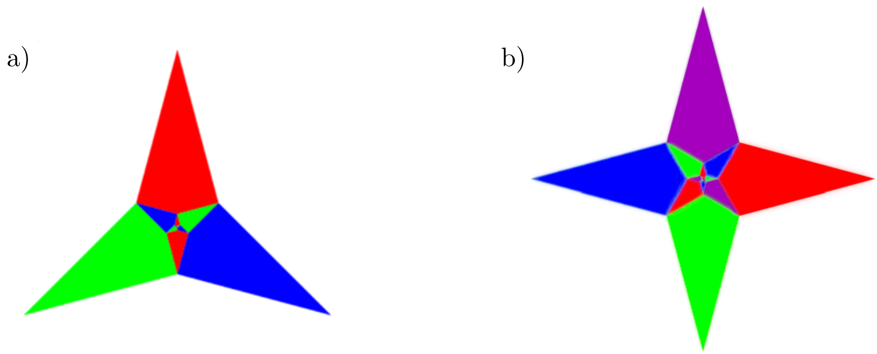

Figure 1. Schematic of three-arm star pattern (a). Hypothetic four-arm star (b).

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