Auxetics and other systems of anomalous characteristics

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Preface - Auxetics and Other Systems of Anomalous Characteristics

The present volume on materials and models with negative Poisson's ratio (which are often referred to as *auxetics*) and other systems of anomalous characteristics is the thirteenth focus issue of physica status solidi (b) on this subject [Aux2017]. The volume contains twenty papers grouped into three sections: macroscopic auxetic materials and models, microscopic models of auxetics, and other systems of anomalous characteristics.

The section **macroscopic auxetic materials and models**, which contains eleven papers, starts with the work 'Shear stiffness and energy absorption of auxetic open cell foams as sandwich cores' by H. C. Cheng et al. [Che2018]. It provides, for the first time, the experimental measurement of the shear modulus of auxetic open cell foams used as cores in flexible sandwich panels. In this work sandwich beams with conventional and auxetic foam cores are produced both with equal thickness and equal weight configurations. The Authors use both three-point and four-point bending tests to measure the transverse shear modulus and stiffness of the foams and beams under linear and nonlinear loading. Cyclic tests are also performed to determine the loss factor due to hysteresis. The results not only provide a first in terms of shear modulus measurement of auxetic foams, but also show interesting quasi-zero and negative stiffness behaviours of sandwich beams with auxetic and conventional cores respectively, under large deformations. The paper also provides some discussions about the potential use of these unusual deformation mechanisms in engineering applications.

Duncan and co-workers [Dun2018] in 'Effects of heat exposure and volumetric compression on Poisson's ratios, Young's moduli and polymeric composition during thermo-mechanical conversion of auxetic open cell polyurethane foam' report a detailed study into the effect of processing parameters on the mechanical properties, dimensional stability and bonding in polyurethane foams converted using the thermo-mechanical process originally reported by Lakes. Compressive and tensile Poisson's ratios and Young's moduli are presented as a function of conversion time and temperature and imposed compression level. Combinations of processing parameters are also identified for dimensional recovery or stability, with or without a recovery phase (unconstrained re-heating), after conversion and these are presented in terms of measures of shape fixing and recovery employed in the shape memory polymer literature. Hydrogen bonding between urea groups is suggested to play a role in fixing the compression level in the converted foams.

A structure comprising tilted cubes connected by deformable alternating links at their corners is presented by Z. Rueger, C. S. Ha and R. S. Lakes [Rue2018] in their work 'Flexible cube tilt lattice with anisotropic Cosserat effects and negative Poisson's ratio'. A range of polyamide structures containing different numbers of cubes are made using 3D printing. The structures are found to display anisotropic negative Poisson's ratios, and torsion and bending tests demonstrate clear size effects. The responses are found to be consistent with Cosserat elasticity but not classical elasticity.

T. Strek, J. Michalski, and H. Jopek [Str2018] in their paper 'Computational Analysis of the Mechanical Impedance of the Sandwich Beam with Auxetic Metal Foam Core' perform a computational study about the effects of metal foams with Poisson's ratios varying between -1 and 0.5 and variable density over the vibroacoustic properties of cantilever sandwich structures. In this study the beams are subjected to harmonic uniform pressure distribution, and the metrics considered are essentially the mechanical impedance and the first six eigenvalues of the structure. Notable results here are represented by the dependency of the cut-off frequency of the impedance associated to the second eigenmode of the mode versus the Poisson's ratio, with the most auxetic configurations providing an increase of the antiresonance of the system. Similar frequency stiffening effects are also observed for the highest order modes.

A set of papers which study the response of structures to external mechanical loads, which may all be described as having a chiral motif, are presented by the Malta group. In their paper 'Different deformation mechanisms leading to auxetic behavior exhibited by missing rib square grid structures' Farrugia *et al*. [Far2018a] extend the current corpus of knowledge by showing how various auxetic structures can be obtained from a basic square lattice, which structures are then studied through finite element analysis (FEA). The predictions by Farrugia et al. are also confirmed though testing carried out on 3D printed prototypes. In the paper 'Analysis of the Deformation Behavior and Mechanical Properties of Slit-Perforated Auxetic Metamaterials', L. Mizzi *et al.* [Miz2018] use FEA to analyse the mechanical properties and deformation mechanism of systems that can be produced through I-shaped perforations. In particular, it is shown that by varying the orientation of the slits, the systems can be made to mimic deformation mechanisms associated with auxetic behaviour in anti-tetrachiral or re-entrant honeycombs. Most importantly this work also suggests that these systems with perforations can deform to large strain values while maintaining negative Poisson's ratio. In another paper by the same team, entitled 'A novel three dimensional lattice based on a generalisation of the anti-tetrachiral geometry', Farrugia *et al.* [Far2018b] present a discussion on properties afforded by a system built from three-dimensional chiral building blocks which can exhibit negative Poisson's ratio in multiple planes, the magnitude of which can be controlled though the choice of the relative lengths of the ligaments, their thickness and their width.

In a more practical paper, '3D Printed Clamps to Study the Mechanical Properties of Tendons at Low Strains', M. Vella Wood *et al.* [Woo2018] present an innovative clamp design which makes use of 3D printing to produce made-to-measure sleeves that encloses the sample ends and also enables straightforward alignment within the testing equipment. The authors used these clamps on tendons and show that the Young's moduli obtained in the linear region are very similar to those obtained by other researchers for the same tendon using more complex clamps. The authors also re-confirm that tendons are capable of exhibiting a negative Poisson's ratio in the toe-region.

N. Novak *et al.* [Nov2018] in their paper 'Crushing behaviour of graded auxetic structures built from inverted tetrapods under impact' show an experimental and numerical work related to the crushing with a powder gun of additive layer manufactured tetrapod lattices with graded distribution of geometrical properties that lead to local variations of the Poisson's ratios. Here samples made using selective electron beam melting are subjected first to micro-CT and metallurgy characterisation to investigate the effective porosity generated by the manufacturing process. The samples are then subjected to high strain rate loading via a powder gun facility with impactor velocities up to 200 m/sec. An explicit Finite Element model has been developed in LS-DYNA to simulate the impact process. We can observe a remarkable agreement between numerical results and experiments, and clear evidence of the energy absorption increase and smoothing of the crushing behaviour because of the graded architecture adopted by the Authors.

N. Jiang and H. Hu [Jia2018] in 'Auxetic yarn made with circular braiding technology' use standard circular braiding technology and conventional yarns to produce braided auxetic yarns (BAYs). In addition to a compliant core yarn and stiff wrap yarn, as employed in the previously reported helical auxetic yarns (HAYs) originally developed by Evans and co-workers, the BAY also employs compliant wrap yarns, within which the stiff wrap yarns are helically interlaced. A range of yarn combinations and arrangements (e.g. number and position of stiff wrap yarns) are employed. In common with the HAY, the BAY displays strain-dependent Poisson's ratio, typically comprising a positive Poisson's ratio at low tensile strain before transitioning to auxetic behaviour at higher tensile strain. The activation (transition) strain and magnitude of Poisson's ratio can be carefully tailored by yarn selection and yarn arrangement, and the issue of stiff wrap yarn slippage evident in the original HAY is overcome in the BAY.

Staying within the auxetic textiles theme, but this time considering auxetic fabrics rather than auxetic yarns, A. Zulifqar and H. Hu [Zul2018] report in 'Development of bi-stretch auxetic woven fabrics based on re-entrant hexagonal geometry' the development of bi-stretch woven auxetic fabrics displaying auxetic response. The fabrics display the re-entrant hexagon motif for auxetic behaviour and are made using an established weaving machine and non-auxetic yarns. The trick to achieving the desired auxetic pattern for the fabric is to utilise a combination of elastic and non-elastic yarns and a combination of loose weave and tight weave sections. By sizing the warp yarns with water-soluble polyvinyl alcohol (PVA) and subsequent washing of the fabrics to remove the size, differential shrinkage between the elastic and non-elastic yarns causes the loose and tight weave sections to contract differentially to produce the desired fabric structure. Strain-dependent negative Poisson's ratios up to 100% tensile strain are reported when stretched in both the weft and warp directions.

The next five papers concern **microscopic models of auxetics**. The first work in this section 'Auxeticity in Metals and Periodic Metallic Porous Structures Induced by Elastic Instabilities' by D.C. Ho *et al.* [Ho2018] provides numerical and theoretical evidences that some elastic instabilities can be useful as they can cause auxeticity. The latter can be associated, *e.g.*, with phase transformations induced by the Born–Hill's elastic instability or with buckling of a micro-structure of some porous structures. The Authors hope that auxeticity of some metals and periodic metallic porous structures at nanoscale will be observed experimentally.

S. Czarnecki [Cza2018] in the paper 'An explicit construction of the underlying laminated microstructure of the least compliant elastic bodies' makes use of the Isotropic Material Design (IMD) method to investigate the degree of recovery of the microstructure of least compliant bodies when subjected to loading corresponding to Frank-Murat homogenization procedures. The paper considers in particular the development of laminates with auxetic properties made by sequences of two isotropic materials. The paper presents the general case of a cantilever beam with five lateral forces, with the method applied within a Finite Element framework. The work is interesting also because it clearly shows how the distributions of bulk and shear modulus is directional and different when considering third and sixth order rank tensors for the laminates.

The theoretical paper presented by the Malta group, 'On the compressibility properties of the wine-rack-like carbon allotropes and related poly(phenylacetylene) systems' [Deg2018] looks at a number of carbon-based two-dimensional nano networks, some of which are shown to exhibit more than one negative mechanical property. This work, which extends earlier studies of the same authors [doi: 10.1002/pssb.201700380 and 10.1002/pssb.201700190], shows how some of the networks can be both auxetic and exhibit negative linear compressibility.

Another paper on carbon-based materials, entitled 'Elastic Properties of Fullerites and Diamond-Like Phases' is presented by Rysaeva et al. [Rys2018] where various nanoscale auxetic structures are studied though a combined analytical modelling and molecular dynamics (MD) approach. Based on the classification proposed by Branka *et al.* [Phys. Status Solidi B 248, No. 1, 96–104 (2011) / DOI 10.1002/pssb.201083981], these novel forms of carbon were shown to be partially auxetic. Some of these systems also benefit from very high Young's modulus which exceeds 1.8TPa.

Periodically distributed cylindrical nanoinclusions are studied by Monte Carlo simulations in 'Auxetic Properties of a f.c.c. Crystal of Hard Spheres with an Array of [001]-Nanochannels Filled by Hard Spheres of Another Diameter' by J. Narojczyk et al. [Nar2018]. The simulations show that symmetry of such crystals changes from the cubic to tetragonal one. When spheres inside the inclusions are smaller than spheres forming the crystalline matrix, the changes of Poisson's ratio are qualitatively similar to the changes observed earlier in the Yukawa sphere crystal, that is, the introduction of nanochannels causes simultaneous decrease of the Poisson's ratio for [110][1-10]-directions, and its increase for [110][001]-directions. Filling the nanochannels with spheres having diameters greater than that of the spheres in the crystalline matrix, causes a strong decrease of the minimum Poisson's ratio value. The most negative value of the Poisson's ratio found amongst all systems studied was as low as -0.873.

The following four papers discuss **other systems of anomalous characteristics**. The first of them is a modelling paper 'Negative Environmental Expansion for Interconnected Array of Rings and Sliding Rods' presented by T.C. Lim [Lim2018] who develops a model for the response to changes in pressure, temperature and/or moisture. He shows how a structure made from an interconnected array of rings and sliding rods, all made from conventional materials, can exhibit negative compressibility (NC), negative thermal expansion (NTE) or negative moisture expansion (NME).

Negative stiffness associated with rolling of non-spherical particles is considered theoretically by I. Karachevtseva, E. Pasternak and A.V. Dyskin [Kar2018] in 'Negative Stiffness Produced by Rotation of Non-Spherical Particles and Its Effect on Frictional Sliding'. By modelling the rolling particle as an inverted pendulum, equivalent to a mass on a negative stiffness spring connected in series with a positive stiffness spring, it is shown that when the negative stiffness (determined by the mass) matches that of the conventional spring the frequency reaches zero and the system becomes unstable. It is then shown that fluctuations in the friction force develop in the frictional sliding of a set of randomly sized rolling non-spherical particles between sliding surfaces, consistent with observations in, for example, debris in machining of material, or fragments of rock in sliding faults.

In 'Effects of Cracks on Anomalous Mechanical Behavior and Energy Dissipation of Negative-Stiffness Plates' Y.C. Wang, Lai and Shen [Wan2018] use the phase fields model to study the behaviour of plates with cracks and having negative stiffness (NS) characteristics. Here the NS behaviour is triggered by the presence in multi-domain plates of finite ferroelastic phase transitions that interact with surrounding positive stiffness regions. The paper provides evidence for various interesting physical aspects. The first is that the presence of cracks does not affect the overall elastic modulus, which is in opposition to what normally witnessed in 'classical' positive stiffness materials. On the contrary, damping properties could also be increased. The stress concentration of crack tips leads to an early trigger of the phase transitions. A remarkable observation is the presence of an equivalent negative damping due to energy produced during different phase transitions, and it can explained by the fact that the NS material in those conditions is not anymore passive.

The paper 'Delocalized Nonlinear Vibrational Modes in Graphene: Second Harmonic Generation and Negative Pressure' by E. A. Korznikova *et al.* [Kor2018] closes this thematic issue. In this work its Authors study delocalized nonlinear vibrational modes in graphene by applying molecular dynamics computer simulations. By proper selection of the amplitudes of the modes, second harmonic generation takes place in the system. For particular modes, the higher harmonics can have frequency nearly two times larger than the maximal frequency of the phonon spectrum of graphene. These and other results presented in the paper contribute to better understanding of nonlinear dynamics of the graphene lattice.

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