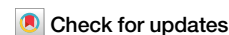


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Mechanical characterization of a 3D large strain zero Poisson's ratio helical metamaterial



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Mechanical metamaterials with zero Poisson's ratio (ZPR) offer unique advantages in applications requiring dimensional stability under large deformations. Here we present a three-dimensional, large strain ZPR metamaterial composed of shape-optimized helical ligaments arranged in a hierarchical lattice. The design reduces stress concentrations at the joints and supports substantial elastic deformation in tension, compression and shear, while maintaining orthotropic, decoupled stress-strain behaviour. Finite element analyses assess homogenized properties, buckling behaviour, and vibrational modes through the analysis of the phononic band gaps, showing low normalized Young's modulus and strain-invariant Poisson's ratios. We further examine the influence of ligament cross-sectional diameter and the effect of different base materials on stiffness and strain range. Experimental tests on 3D-printed specimens confirm the predicted ZPR behavior and deformation capacity. The metamaterial's elastic isotropy, fatigue resistance, and tailorable stiffness make it suitable for multifunctional applications including adaptive actuators, morphing structures, and energy-absorbing systems.

Metamaterials, a family of artificial materials possessing exotic properties uncommon in conventional materials¹, span diverse categories including mechanical, electromagnetic, and optical metamaterials. Mechanical metamaterials derive their macroscopic properties from microstructural design rather than material composition and often feature periodically arranged building blocks indicated as unit cells^{2–5}. Due to their geometric complexity and small dimensions, technologies such as additive manufacturing and 3D printing play an essential role in metamaterials development^{6–8}. Mechanical metamaterials encompass various types, including acoustic metamaterials⁹, metamaterials with negative compressibility transitions^{10,11}, pentamode metamaterials¹², and metatrimaterials¹³. Applications of mechanical metamaterials are widespread, ranging across several industries such as aerospace¹⁴, automotive¹⁵, defence¹⁶, medical biomaterials^{17,18}, seismic engineering¹⁹, robotics^{20,21}, and sports²².

Zero Poisson's ratio (ZPR) mechanical metamaterials are peculiar lattice structures that, when subjected to loading in one direction, exhibit no lateral expansion or contraction in the orthogonal directions, compared to positive (PPR) and negative (NPR) Poisson's ratio metamaterials^{3,23}. This unique characteristic, i.e. absence of stress and strain couplings, provides exceptional properties such as increased energy absorption and enhanced dimensional stability. ZPR metamaterials, being monoclastic, display a

single curvature under bending in comparison to PPR and NPR anticlastic and synclastic behaviours²⁴. Moreover, a high degree of precision in arranging unit cells, often characterized by intricate geometries, is essential to achieve ZPR behaviour. Applications of ZPR metamaterials extend across various fields: in vibration control applications, a reconfigurable 4D printed cylindrical design able to tune its mechanical properties was developed to provide vibration isolation²⁵; in tissue engineering, scaffolding metamaterial structures exhibiting ZPR behaviour simulated native tissue behaviour, facilitating force transmission during wound healing or tissue regrowth²⁶; for morphing wing applications in the aerospace industry, star-shaped honeycomb structures restrained Poisson's ratio effects, preventing an increase in effective stiffness during morphing actuation²⁷.

A common way to build ZPR metamaterials is by combining positive and negative Poisson's ratio unit cells, resulting in ZPR behaviour in one direction. For instance, AuxHex - a honeycomb-based metamaterial structure—combined PPR Honeycomb and NPR Re-entrant unit cell geometries to achieve ZPR behaviour through the neutralization of Poisson's ratios²⁸; similarly, a lattice structure with a double-U array of parallel fine cracks exhibited ZPR behaviour under tension, achieving strain levels of around 40%²⁹; 3D auxetic closed-cell structures achieved a combination of positive, negative, and zero Poisson's ratios by altering unit cell geometry⁶; a gardenia-shaped honeycomb design demonstrated the capability to achieve

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Poisson's ratio values close to zero by manipulating the angle between cell elements and connecting parts³⁰. Various cell geometries have been explored in constructing ZPR metamaterials: studies on pore metamaterials with star-shaped geometries have shown NPR or ZPR behaviour up to a tensile strain greater than 15%³¹; metamaterial structures with topologies resembling the 2D image of the DNA helix exhibited ZPR behaviour and superior energy absorption capability compared to traditional metamaterials³²; Fish Cells metamaterial, initially developed by Zadeh et al.^{33,34}, represents a 2D metamaterial exhibiting ZPR behaviour in two orthogonal directions, with potential applications in the morphing skin of aircraft wings³⁵. Extensive numerical analyses have been employed to elucidate the influence of joint geometry in Fish Cells, focusing on how stress concentration affects the tensile strain of the metamaterial, while equivalent elastic properties have been derived and scrutinized both analytically and numerically³⁴. The study encompassed a range of geometric parameters, variations in elastic properties and an exploration of the effective elastic modulus. Moreover, Jha et al.³⁵ introduced a multi-objective Genetic Algorithm (GA) shape optimization to enhance the ZPR characteristics of the Fish Cells metamaterial, considering quasistatic behaviour under large non-linear strains. Qin et al.³⁶ developed a 3D cylindrical Fish Cells zero Poisson's ratio metamaterial in two arrangements, revealing similar deformation mechanisms and stress concentration locations to the 2D Fish Cells metamaterial. However, the elastic tensile range was smaller than that of the 2D structure, and unit cell assembly direction significantly affected buckling, frequency behaviour, and mode shape.

In a recent investigation by Qin and Dayyani³⁷, a large strain ZPR spring-based metamaterial underwent a thorough examination, including variable stiffness and defects analyses, pure shear, modal and buckling analyses. Results highlighted the absence of stress concentration during deformation at the joints, a notable advantage over other metamaterial structures. The structure maintained ZPR behaviour even with 10% defects, exhibiting low shear modulus. Finally, Cimolai et al.³⁸ employed a multi-objective Genetic Algorithm for the shape optimization of a 3D helical structure, designed as basic unit cell ligament for potential 2D and 3D lattice metamaterials. The compliant helical structure demonstrated large tensile and compressive elastic strain deformation (39% and 33%, respectively).

The present article investigates the mechanical behaviour of a large strain 3D ZPR lattice helical metamaterial, based on optimized three-coils helical unit cells adapted from³⁸. The study demonstrates the structure's suitability for multifunctional mechanical applications where ZPR behaviour and large strain range are crucial. The article is organized as follows: the unit cell structure is first presented, with selected tessellation arrangements and validation of the ZPR behaviour; the homogenization study for Poisson's ratio and Young's modulus is then reported together with a parametric numerical study on the influence of cross-sectional diameter and the investigation on the influence of constitutive material properties; results from a set of linear perturbation analyses, including the analysis of phononic band gaps are then presented, followed by an experimental validation conducted on a 3D printed model to justify the proposed numerical results and modelling strategy; finally, a set of analytical considerations are performed, highlighting the peculiar orthotropic behaviour of the proposed metamaterial, and its suitability for multifunctional applications such as shape-morphing and smart actuators.

Results and discussion

Problem definition and ZPR validation

Research on 3D mechanical metamaterials for large elastic deformations is critical in modern engineering³⁸, with constraints of zero Poisson's ratio (ZPR) and lightweight adding a layer of complexity. Helical structures offer advantages over Fish Cells and Re-entrant structures due to their consistent behaviour under various loading conditions and reduced stress concentrations^{33–40}. Fish Cells in 2D lattices show limitations—including high joint stresses—which increase failure risks and fatigue effects, while also hindering their elastic strain capacity. A new metamaterial design is needed to combine Fish Cells' compliance and ZPR characteristics with improved

geometry: helical structures are promising candidates, offering evenly distributed stresses, enhanced deformation capacity, dimensional stability and fatigue resistance under extensive tensile and compressive strain³⁷. In previous work by Cimolai et al.³⁸, a methodology was developed for designing lightweight shape-optimized 3D helical structures, employing a Genetic Algorithm (GA) to optimize conventional coil spring designs for minimum mass and maximum tensile range. The multi-objective optimization problem was solved using a custom Finite Element (FE) routine written in MATLAB, which integrated Abaqus solver for fitness function evaluation.

Figure 1 details the strategy followed to assemble the metamaterial analysed in this study. Cubic unit cells are designed employing three-coils shape optimized helical structures (best-compromise result selected in ref. 38, reported in Fig. 1(a)) as unit cell ligaments, assembled in Fig. 1(b). To mitigate boundary effects at ligament ends, eliminating unrealistic stress concentrations at the joints and simplifying the 3D printing manufacturing process, 2 mm beam extensions were added to both ends of each ligament, as in Fig. 1(b). This modification not only enhanced the overall structural integrity but also facilitated a more practical manufacturing approach. Each cubic unit cell possesses a total of 12 optimized helical structures as basic ligaments. Moreover, as represented in Fig. 1(c) rotations of the base ligament are applied between orthogonal neighbouring elements to ensure absence of interpenetrations inside each unit cell in undeformed conditions, however introducing chirality in the structure.

Metamaterials are assembled as 3D lattices by tessellating with adjacent cubic unit cells along the three global orthogonal directions (X , Y , Z). Tessellation number is kept consistent across the three directions resulting in macroscopic cubic structures. Four distinct tessellation arrangements, characterized by varying numbers of unit cells ($3 \times 3 \times 3$, $5 \times 5 \times 5$, $10 \times 10 \times 10$ and $15 \times 15 \times 15$), are considered. For conciseness, in the following these will be indicated with the generic denomination l^3 with l being the number of unit cells in each direction (e.g., 10^3 for the $10 \times 10 \times 10$ arrangement). While computing the number of unit cells in a tessellation is straightforward, calculating the number of individual ligaments is complex due to shared ligaments between neighbouring unit cells, depending on their position inside the lattice (e.g., inner unit cells share all their ligaments with neighbouring unit cells). For a cubic tessellation with edge size l (number of unit cells along the edge), the total number of vertices V (joints between ligaments) and edges E (ligaments) can be calculated using the relations:

$$V = (l + 1)^3 \quad (1)$$

$$E = 3[l^3 + 2l^2 + l] \quad (2)$$

Figure 1(d) plots the number of vertices V and edges E vs tessellation number l for cubic tessellations, showing two exponential trends proportional to l^3 . From the analysis of such plot, it can be noticed how the considered tessellations belong to different orders of magnitude of simulated elements, with direct impact on computational performances. Figure 1(e) reports isometric and front views of the four considered tessellations. For easiness of visualization due to the largely different scales (the 15^3 model's volume is 125 times larger than the 3^3 model, with 80 times the number of helical structures), the models are represented as equal in size. Nonetheless, the helical ligaments maintain the same length and the models scale size accordingly with the increase in tessellation number: this does not affect numerical results as quasistatic simulations are employed in the homogenization study, and the models can therefore be thought as increasingly dense.

The examined metamaterials underwent different loading scenarios, with tensile and compressive loads being applied in the global Y direction. Given the designed ZPR nature of the metamaterial, it was anticipated that predominant displacement would occur alongside the direction of applied loads. Consequently, helical structures extending along this direction were expected to undergo substantial deformation, while ligaments perpendicular to the applied load (global directions X and Z) were anticipated to experience minimal to null deformation, providing evidence of ZPR

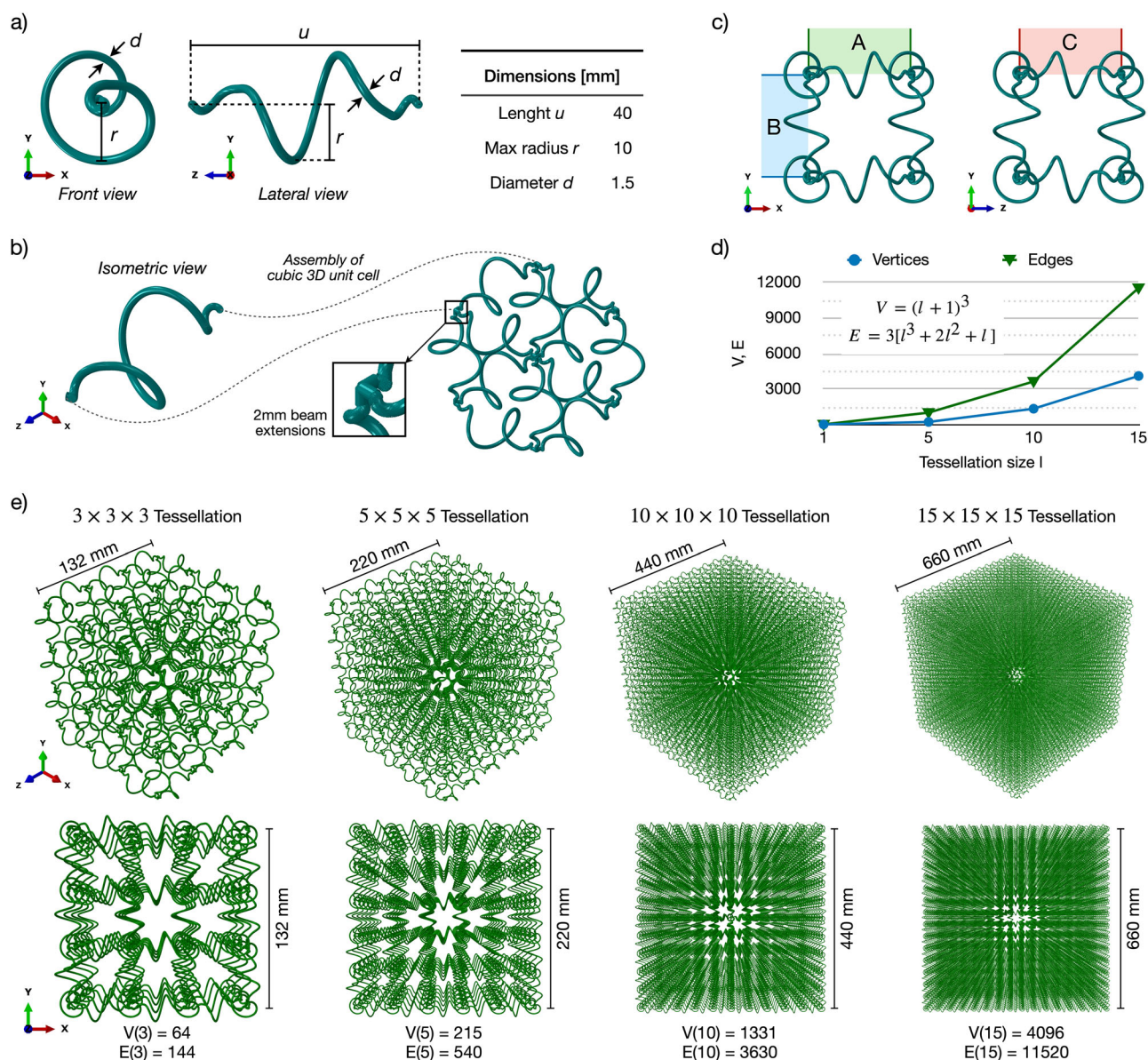


Fig. 1 | From helical structures to 3D metamaterials. **a** Front and lateral views of the three-coils optimized helical structure with selected dimensions (mm); **(b)** approach followed to build the cubic unit cell; **(c)** front and side views of the cubic unit cell: rotations are employed to overcome interpenetrations. Taking A as the base helical structure, B is the 90° clockwise rotated copy of A, around the global Z axis, and C is the 90° clockwise rotated copy of A, around the global Y axis; **(d)** plot of

number of vertices V and edges E vs tessellation size l for a cubic tessellation. In the formulas in the inset, l represents the tessellation's edge size in number of unit cells; **(e)** from left to right, isometric and front views of the four considered tessellations. Edge dimensions (mm) and numbers of vertices and edges for each tessellation are also reported.

behaviour. Figure 2 details the setting for the ZPR validation study. Finite Element (FE) simulations are conducted using the popular FEA solver Abaqus. Nylon 12 is chosen as constitutive material for both numerical simulations and experimental testing, with properties extracted from ref. 41 and reported in Table 1. From the analysis of Fig. 2(a), it can be noticed how null macroscopic lateral displacement is recorded at large compressive and tensile strains $\epsilon^b = -30.7\%$, $\epsilon^t = 42.3\%$ (elastic buckling onset and yielding onset for the 10^3 tessellation, respectively), confirming ZPR behaviour. This is directly visible from the absence of stresses acting on helical ligaments orthogonal to the loading direction, implying decoupling of stresses and strains in the three global directions (X , Y , Z). In Fig. 2(b) tensile and compressive simulation results are also reported for the 3^3 , 5^3 and 15^3 tessellations. Front views are shown with the superposition of undeformed and deformed structures. It can be noticed how buckling strain diminishes for increasing tessellation size, with the 15^3 tessellation having a

compression range 27.2% lower than the 5^3 tessellation. All structures show dimensional stability in compression without lateral constraints. Additionally, buckling onsets happen in the elastic regime, with maximum stresses below Nylon 12's yielding stress of 19.17 MPa. As identical helical structures are used in all three orthogonal directions, results hold validity for tension and compression along the two other coordinate directions X and Z , resulting in independent deformations along each loading direction. In Fig. 2(a) the macroscopic effect of microstructural joint rotations is visible in the central region of the metamaterial by the slight displacements of horizontal columns of helical structures, as detailed and explained in Supplementary Fig. 1.

Homogenization study and compressive analysis

Before addressing the metamaterial's compressive behaviour through FE analyses, a homogenization study is performed to determine the minimum

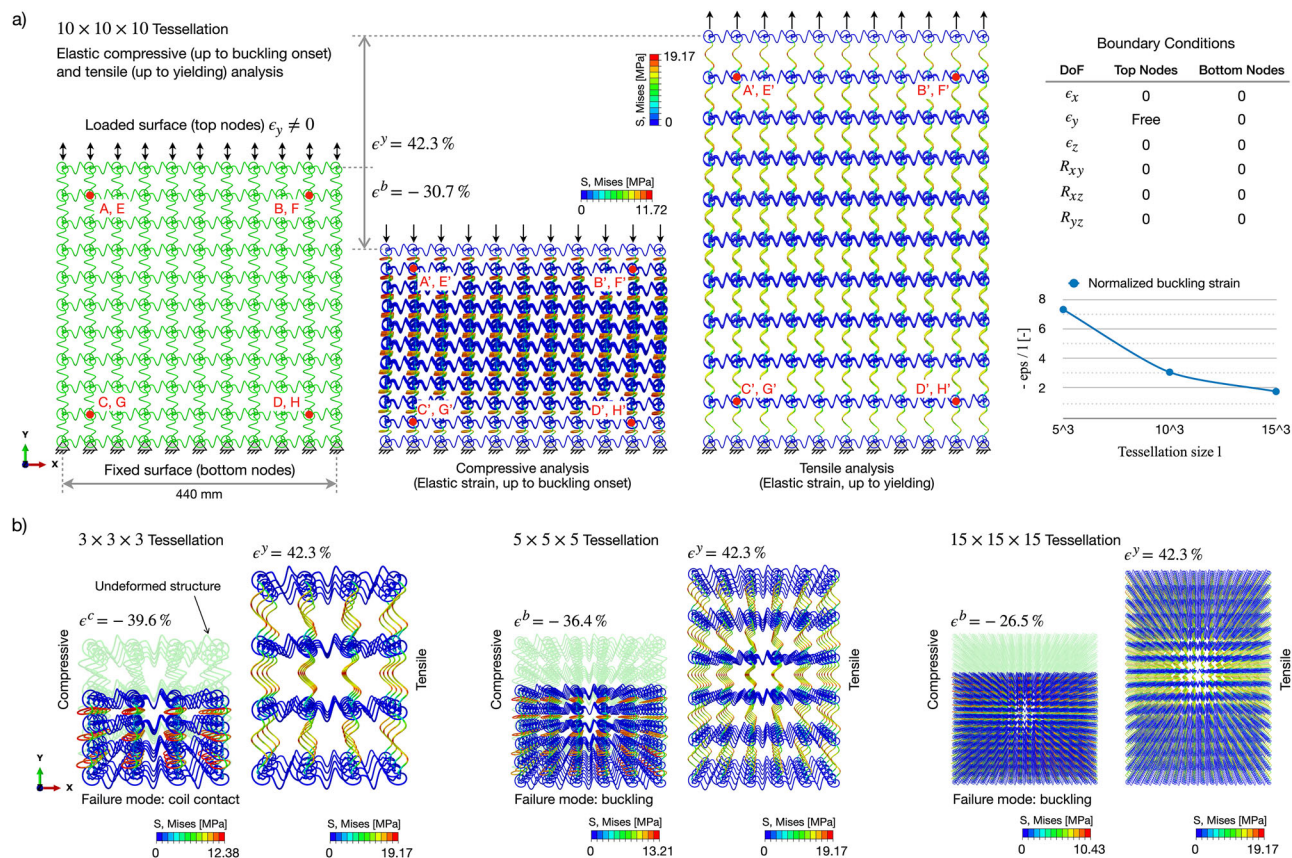


Fig. 2 | Methodology and results for ZPR validation. **a** Front view of the 10^3 tessellation selected for validation with stress contour plots shown for compression ($\epsilon = \epsilon^b$) and tension ($\epsilon = \epsilon^t$). Boundary conditions are indicated in the inset *Boundary Conditions*; variations in spatial coordinates of points A–H are recorded for computing Poisson's ratios; **(b)** views of stress contour plots for the three other

considered models in both compression and tension: in the compression case models are shown at contact onset ($\epsilon^c = -0.396$ for the 3^3 case) or elastic buckling onset ($\epsilon^b = -0.364$ for the 5^3 case, $\epsilon^b = -0.307$ for the 10^3 case, $\epsilon^b = -0.265$ for the 15^3 case), in the tension case models are shown at yielding ($\epsilon^t = 0.423$). All models utilize Nylon 12 as constitutive base material (yielding stress 19.17 MPa).

tessellation size for boundary effects-free results, highlighting the micro- and macro-structural deformation mechanisms.

The mechanical behaviour of any lattice structure is influenced by both boundary and loading conditions, and by the geometric arrangement and extension of the tessellation. Performing a homogenization study is essential to identify minimum tessellation sizes ensuring convergence in mechanical response of the metamaterial. The homogenization study allows to characterize the structure's behaviour under static loading, providing a clear overview of its response to axial deformation and sensitivity to buckling. Additionally, it allows to compute normalized Young's modulus and Poisson's ratios in both XY and ZY planes. Table 2 outlines the strategy followed to compute Poisson's ratio values $\nu_{xy} = -\epsilon_x/\epsilon_y$ and $\nu_{zy} = -\epsilon_z/\epsilon_y$. Strains are determined by averaging the distances between

pairs of fixed points inside the structure: ϵ_x is the average strain for the distance between the faces AECG and BFDH, ϵ_y for the distance between the faces AEBF and CGDH, and ϵ_z for the distance between ABCD and EFGH. Moreover, a simplified approach can be defined to compute the same values by using only the segments AB, AC, AE for ϵ_x , ϵ_y , ϵ_z respectively. Figure 3(a, b) reports the variation of Poisson's ratios ν_{xy} and ν_{zy} with increasing compressive elastic strain ϵ_e in the negative Y direction, for each tessellation arrangement until failure (self-contact or buckling onset). Dissimilarities in values between the two trends of Poisson's ratio are attributed to the differences in the metamaterial's internal structure resulting from rotated disposition of optimized helical structures inside each unit cell (highlighted in Fig. 1(c)). Specifically, the non-uniform rotational behavior of individual helical ligaments under axial loading drives asymmetric local deformations at the joints; these microscopic deformations influence the macroscopic Poisson's ratio values. Such microscopic behavior arises because helical ligaments exhibit differential wire shear stresses when subjected to tension or compression, causing joints to rotate asymmetrically in the YX and YZ planes. Consequently, these self-rotations affect the orthogonal helical structures differently in the YX and YZ planes due to their rotated disposition (structure's chirality), resulting in the differences between ν_{xy} and ν_{zy} . This phenomenon is visually illustrated in Supplementary Fig. 1, where the rotational response of individual helical ligaments under axial loading conditions is shown. Nevertheless, low values of Poisson's ratios in the order of $1E-3$ are a direct consequence of negligible stresses experienced by helical structures positioned orthogonally to the loading direction, aligned with global directions X and Z. Additionally, a noticeable decrease of Poisson's ratio values is highlighted for an increase in compressive strain, due to the densification of axial helical structures subjected to compression

Table 1 | Constitutive material properties of Nylon 12

Physical Properties	
Density ρ	843.68 kg · m ⁻³
Elastic Properties	
Elastic Modulus E_c	887.68 MPa
Yield Stress σ^y	19.17 MPa
Poisson's Ratio ν_c	0.39
Plastic Properties	
Plastic Stresses σ [MPa]	Plastic Strains ϵ [-]
19.174, 19.305, 23.711, 28.117, 32.523, 36.929	0, 0.0002, 0.0064, 0.0141, 0.0255, 0.0473

Table 2 | Strategy to compute Poisson's ratios $\nu_{xy} = -\varepsilon_x/\varepsilon_y$ and $\nu_{zy} = -\varepsilon_z/\varepsilon_y$ using control points ABCD-EFGH: comparison between complete and simplified calculation methods to calculate strains ε_x , ε_y and ε_z from individual segments deformations

Strain	Complete method	Simplified method	Representation
ε_x	$\varepsilon_x = \frac{1}{4} \sum_{e \in E^x_{\text{Parallel}}} \frac{ e' - e }{ e }$ $E^x_{\text{Parallel}} = \{\overrightarrow{AB}, \overrightarrow{CD}, \overrightarrow{EF}, \overrightarrow{GH}\}$	$\varepsilon_x = \frac{ A'B' - AB }{ AB }$	
ε_y	$\varepsilon_y = \frac{1}{4} \sum_{e \in E^y_{\text{Parallel}}} \frac{ e' - e }{ e }$ $E^y_{\text{Parallel}} = \{\overrightarrow{AC}, \overrightarrow{BD}, \overrightarrow{EG}, \overrightarrow{FH}\}$	$\varepsilon_y = \frac{ A'C' - AC }{ AC }$	
ε_z	$\varepsilon_z = \frac{1}{4} \sum_{e \in E^z_{\text{Parallel}}} \frac{ e' - e }{ e }$ $E^z_{\text{Parallel}} = \{\overrightarrow{AE}, \overrightarrow{BF}, \overrightarrow{CG}, \overrightarrow{DH}\}$	$\varepsilon_z = \frac{ A'E' - AE }{ AE }$	

loading which brings enhanced stability. Moreover, it is noticeable how the value of elastic strain at failure decreases with an increase in tessellation size, as noticed previously: this is an expected behaviour, as larger metamaterials are more susceptible to buckling phenomena due to longer columns of vertical ligaments, coupled with weak interactions between them, making them prone to early buckling onset.

In the plots of Fig. 3(a, b) two trends of Poisson's ratio values are reported for each case, one represented through a continuous line and the other through a dashed line, computed employing the complete and simplified methods. Differences between the two trends are notably small, validating the simplifying methodology for the computation of Poisson's ratios (which will be used in the experimental analysis). Considering the cubic symmetry of the structure, it is concluded that negligible deformations of transversal helical structures for axial loadings in any coordinate direction—resulting in negligible values of Poisson's ratios consistent across the whole elastic deformation range—unequivocally substantiate the orthotropic ZPR behaviour of the examined structure. From the same set of simulation results, the calculation of the normalized Young's modulus E_n , defined as the ratio between the metamaterial's equivalent Young's modulus E and the Young's modulus of the base constituent material E_c ($E_c = 887.68$ MPa for Nylon 12), $E_n = E/E_c$, provides insights into the disparity between these quantities, as shown in Fig. 3(c). Normalized Young's modulus values are notably small (in the range of $1E - 6$), indicating that the metamaterial's equivalent Young's modulus is significantly lower than the base material's one, making it considerably more compliant and well-suited for applications where soft structures are appreciated. Moreover, the normalized Young's modulus values show a decreasing trend for an increase in tessellation arrangement at equal strain values, due to the increased number of stacked helical structures (Hooke's law for springs in series: sum of compliances), coupled with a decreasing trend for increasing strains for the same tessellation, notably due to the compression-induced increase in helical structure global diameter which results in changing spring stiffness³⁸.

The convergent trends of decreasing differences in ν_{xy} , ν_{zy} and E_n values for increasing tessellation sizes are reported in Table 3. The measured Poisson's ratio values difference decreases with increasing tessellation size, and by the 10^3 arrangement, the normalized differences (computed for each case by considering the % decrement from the previous tessellation model, divided by the current tessellation size l) fall below the 5% convergence threshold, indicating reliable homogenized behavior. ZPR trend reflects the metamaterial intrinsic joint-based deformations rather than computational artifacts: boundary effects were in fact minimized by positioning control points away from edges and averaging displacements, and both full and simplified measurement methods yielded consistent results. Thus, homogenization theory confirms that the 10^3 tessellation accurately represents the

metamaterial's mechanical response. Additionally Fig. 3(d, e) reports front, lateral and isometric views of displacement contour plots for the converged 10^3 tessellation, for two directions $U_1 = U_x$ and $U_3 = U_z$, and for three deformation phases (pre, during and post buckling onset), effectively showing the elastic buckling deformation behaviour of the laterally unconstrained structure. Buckling onset sparks from the lower half of the structure (close to the fixed surface). Curved edges in the post buckling phase are visible, with uneven lateral displacements which depends non-linearly on the compressive strain.

Influence of wire diameter and constitutive material properties

An exploration is conducted into the compressive behaviour of the metamaterial for varying ligament's wire diameter, with eight cases—spanning from 0.5 mm to 2 mm - systematically examined. These limits are chosen based on considerations of accuracy in the helix curvature's representation and limitations in the SLS 3D printing method for the successive experimental analysis, and although restricted in range they show sufficient expressivity to capture the changing response of the metamaterial. The thin beam elements approach previously implemented offers the advantage of low computational costs, beneficial for optimization convergence; however, this method may overlook certain aspects, such as stress concentration effects in joints areas due to narrow curvatures. On the other hand, high-fidelity 3D solid models, while time-consuming due to complex meshing algorithms provide a more comprehensive understanding of metamaterials deformation mechanisms, including stress concentration effects. To guarantee significant and accurate analyses, especially needed for capturing differences in cross-sectional diameter as small as 0.25 mm, C3D8 solid mesh elements have been employed. The 3^3 tessellation arrangement has been chosen for all simulations following computational considerations, as larger tessellations are built on an exponentially increasing number of simulated mesh elements. For easier application of compressive loads, and in accordance with the manufacturing strategy for experimental validation, the structure was incorporated with 12.60 mm straight beam elements extending from the joints on the top and bottom layers: the inclusion of these extensions facilitated the application of compressive loads on top joints, offering operational ease given the exceptionally fine mesh. Moreover, when building solid tessellations specific joint design has been employed to ensure accurate representation of the complex curvatures involved, as shown in Supplementary Fig. 2.

Figure 4(a) reports the plots of Poisson's ratios ν_{xy} and ν_{zy} vs elastic compressive strain ε_e for all cases analysed. An overall decreasing trend is recorded for increasing diameter values, although very limited in magnitude, realistically due to the increase in stability for thicker tessellations. Additionally, a decrease in compressive range is noticed due to inter-coil

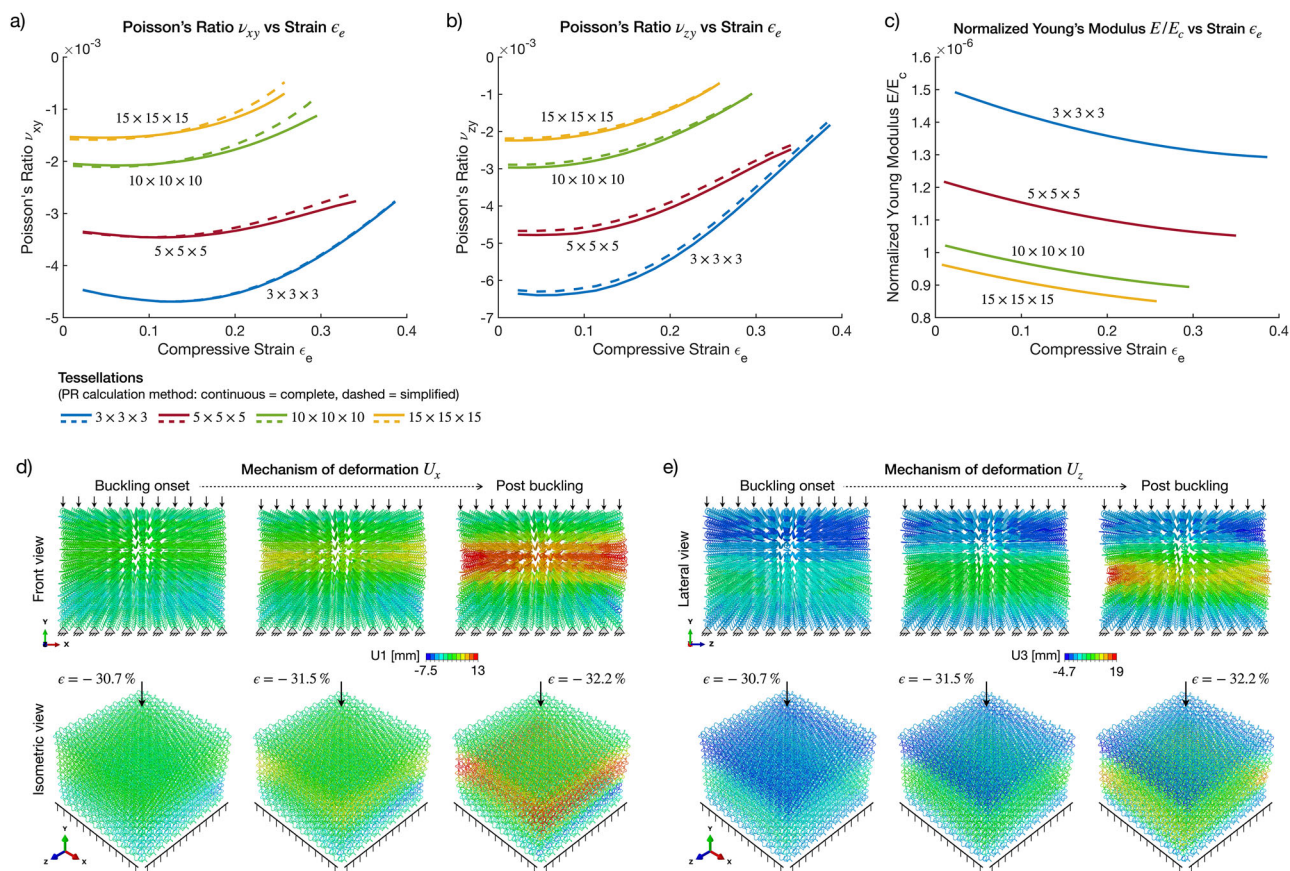


Fig. 3 | Metamaterial's behaviour under compression. **a, b** Plots of Poisson's ratios ν_{xy} and ν_{zy} vs elastic strain ϵ_e for each tessellation arrangement; **(c)** graph of normalized Young's modulus $E_n = E/E_c$ vs elastic strain for each tessellation arrangement (E_c being the base material's Young's modulus); **d, e** deformation mechanism in compression, including elastic buckling analysis and deformation

behaviour after buckling onset: **(d)** displacement contour plots (U_1 , mm) in direction X for pre- and post-buckling onset for the 10^3 model (front and isometric views), **(e)** displacement contour plots (U_3 , mm) in direction Z for pre- and post-buckling onset for the same model (lateral and isometric views).

contact happening sooner for thicker tessellations, as shown in Supplementary Fig. 2. The trends of Poisson's ratio values remain consistent with the ones obtained employing beam elements (Fig. 3(a, b)). Figure 4(a) includes a detailed view of the solid C3D8 mesh for the 1.25 mm diameter helical structure in front perspective, with a zoomed wire's cross section view revealing the detailed mesh. The plot in Fig. 4(b) reports the evolution of equivalent stress σ_{n-eq} , normalized by the Young's modulus E_c of the base material, vs elastic compressive strain ϵ_e . As expected, thicker structures are associated with stiffer behaviours, with the 2 mm model possessing a normalized stiffness 250 times higher than 0.5 mm model. Finally, the plot in Fig. 4(c) shows the evolution of the normalized Young's modulus $E_n = E/E_c$ vs elastic compressive strain ϵ_e . Again, an increasing trend of higher normalized Young's moduli is associated to an increase in wire diameter. Differences in stiffness and normalized Young's modulus between successive diameter cases is increasing for an increase in diameter, with the median equivalent Young's modulus for the 2 mm diameter case being approximately 3 times higher than for the 1.5 mm case. In the plots of Fig. 4(b, c) the decrease in compressive strain due to contact onset happening sooner is appreciated, while buckling onset is not recorded at this tessellation size.

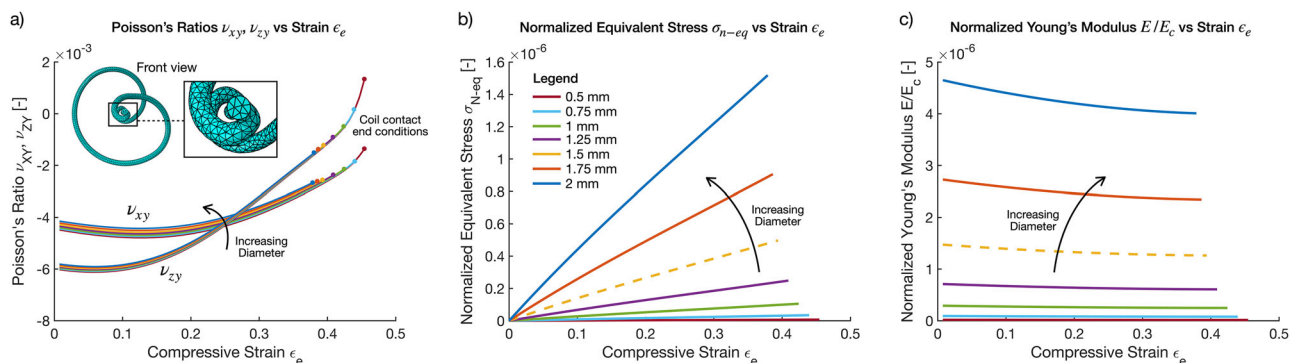
To clarify the influence of different base materials on the homogenized behaviour, further FE analyses have been performed on the 10^3 tessellation. Polylactic Acid PLA (modelled with linear elastic-plastic behaviour, as it was already the case for the preceding Nylon 12-based model), Aluminium 70-75 T6 (modelled with Johnson-Cook behaviour) and Ethylene-Propylene Diene Monomer EPDM (modelled with hyperplastic Ogden behaviour with $n = 3$) were selected as base materials, and compressive results compared with those obtained using Nylon 12.

Elastic and plastic stress-strain data for PLA, Johnson-Cook plasticity constants for Aluminium 70-75 T6, and material law parameters for EPDM are reported in Supplementary Tables 1–3. Results from the compressive analysis are presented in Fig. 5. All models use 1.5 mm wire diameter helical ligaments with beam-based mesh elements. Figure 5(a) shows the plots for equivalent stresses σ_{n-eq} , normalized by the Young's moduli E_c of the corresponding base materials, vs elastic compressive strain ϵ_e for the four considered models, highlighting similarities in mechanical responses: as expected, stronger materials are associated with stiffer behaviours (aluminium model reaching yielding at $\epsilon'_{Al} = 17\%$ with a reaction force RF_y above 2000N), while softer materials have corresponding softer behaviours (EPDM model still in elastic regime at $\epsilon = 30\%$ with a RF_y below 0.2 N). The plot for normalized Young's modulus E_n vs elastic strain ϵ_e , reported in Fig. 5(b) shows results closely aligned with those presented in Fig. 5(c), with normalized Young's modulus values in the range of $1E - 6$ for all four models. In particular, equivalent Young's moduli have been normalized by the Young's moduli of base constituent materials individually for each case, with $E_{c-Ny} = 887.7$ MPa for Nylon 12, $E_{c-Al} = 71.7$ GPa for Aluminum, $E_{c-PLA} = 1700$ MPa for PLA, and $E_{c-EPDM} = 3.2$ MPa for EPDM. All models show reliable ZPR behaviours, as highlighted from the plots of Poisson's ratios ν_{xy} and ν_{zy} vs strain ϵ_e in Fig. 5(c), along with consistent dimensional stability and independence of stresses and strains, confirming the independence of the metamaterial's macroscopic behaviour from its base constitutive material. From the results presented in this investigation, it is possible to compute values of mass-normalized stiffness equal to $k_{10c}^{Al} = 16.7 \text{ N} \cdot \text{kg}^{-1} \cdot \text{mm}^{-1}$ for the Aluminum 7075 T6 10^3 model in

Table 3 | Homogenization study results. Values of ν_{xy} , ν_{zy} and E_n for each tessellation arrangement at 10% strain, with normalized % difference from the previous tessellation size

Tessellation	Homogenization for ν_{xy}		Homogenization for ν_{zy}		Homogenization for E_n	
	ν_{xy} at $\epsilon_e = -10\%$	Normalized difference %	ν_{zy} at $\epsilon_e = -10\%$	Normalized difference %	E_n at $\epsilon_e = -10\%$	Normalized difference %
3^3	-4.72×10^{-3}	/	-6.24×10^{-3}	/	8.87×10^{-7}	/
5^3	-3.51×10^{-3}	5.13%	-4.59×10^{-3}	5.28%	9.41×10^{-7}	1.15%
10^3	-2.11×10^{-3}	3.99%	-2.75×10^{-3}	4.08%	11.1×10^{-7}	1.52%
15^3	-1.54×10^{-3}	1.80%	-2.04×10^{-3}	1.67%	13.6×10^{-7}	1.22%

Normalized difference is computed by considering the % decrement from previous tessellation, divided by current tessellation size. Homogenization is reached when normalized differences fall below 5% threshold.

**Fig. 4 | Wire diameter analysis. a** plots of Poisson's ratio values ν_{xy} and ν_{zy} vs elastic compressive strain ϵ_e , for different diameters, up to contact onset, with detailed view of the refined mesh for the single helical structure shown in front view; **(b)** plots of

normalized equivalent stresses σ_{n-eq} vs compressive strain ϵ_e ; **(c)** plots of normalized Young's moduli $E_n = E/E_c$ vs compressive strain ϵ_e .

compression ($m = 1.75$ kg), $k_{10}^{Ny} = 0.65 \text{ N} \cdot \text{kg}^{-1} \cdot \text{mm}^{-1}$ for the Nylon 12 model ($m = 0.525$ kg) and $k_{10c}^{PLA} = 0.84 \text{ N} \cdot \text{kg}^{-1} \cdot \text{mm}^{-1}$ for the PLA model ($m = 0.778$ kg). To conclude, an ad-hoc optimization of material properties could be potentially performed to tailor the metamaterial's response for specific applications (for example utilizing different base materials in the three orthogonal directions to achieve different mechanical responses) with certainty of maintaining large strain range capabilities, ZPR characteristics, dimensional stability and independence of stresses and strains among the three orthogonal directions.

Linear perturbation analysis

Linear perturbation analyses of complex structures are beneficial for their engineering applications, as they allow to clarify static and dynamic performances and evaluating operational limits. Eigenvalue buckling analyses are conducted to assess the behaviour of the metamaterial under compressive loads, determining potential instability points. Such analyses are crucial to quantify structural limits, avoiding catastrophic failures under compression when exceeding these limits³⁵. Additionally, modal analyses are performed to delineate the vibrational characteristics of the proposed structures, encompassing natural frequencies, mode shapes and phononic band gaps. They provide insights into the structural limits of the metamaterial concerning vibrational loads, with direct implications on its longevity (expressed by the fatigue life), in-service quality, and operational precision³⁸.

Table 4 collects first mode critical buckling loads and associated mode shapes representations, showcasing noticeable trends. As expected, critical buckling loads rise with increase in tessellation size ranging from 2.99 N for the 3^3 arrangement to 37.68 N for the 15^3 one, the latter being approximately 12.6 times larger than the former. Conversely, mass-normalized critical loads exhibit an opposite trend, ranging from 142.38 N/kg for the 3^3 tessellation to 22.58 N/kg for the 15^3 one, decreasing by approximately 6.3

times. The phenomenon of negatively correlated relationship between buckling strain and tessellation size (already evidenced in Fig. 2(b)) is a combined effect of both the increasing length of helical ligaments columns, according to Euler's theory, and weak interactions between adjacent vertical columns. Vertical columns formed by stacked helical structures act as slender beam elements under compression: according to Euler's buckling theory, the critical buckling load is dependent on the slenderness ratio. Additionally, the high compliance of transversal helical ligaments results in weak lateral interactions between adjacent columns, allowing such columns to buckle easily with increasing length, despite being connected, leading to earlier buckling onset in larger tessellations. Although the columns are linked by transverse ligaments, the weak interactions fail to provide sufficient lateral support to prevent buckling deformation, explaining the observed decrease in buckling strain with increasing tessellation size. From the analysis of mode shape representations relative to the first buckling mode, it can be noticed how buckling significantly influences helical elements aligned with the global Y axis (load axis). In each case, the overall metamaterial's deformation includes global bending towards both the positive X and Z directions.

Figure 6(a) illustrates trends of the first ten modal frequencies for each tessellation. An increase in tessellation size results in non-linear decreases in the values of frequencies, with the values for the 15^3 tessellation appearing exceptionally close, highlighting a change of behaviour from structures (lower tessellation arrangements, not homogenized) to homogenized metamaterials. Additionally, frequency values for the first and second modes, for the fifth and sixth modes, and for the seventh and eighth modes are exceptionally close for the 3^3 tessellation arrangement, then merging for higher arrangements. The frequency values range from 4.11 Hz (1st frequency, 15^3 tessellation) to 48.88 Hz (10th frequency, 3^3 tessellation), with the latter being approximately 11.9 times higher than the former. Notably, the tenth frequency of the 15^3 tessellation is lower than the first frequency of

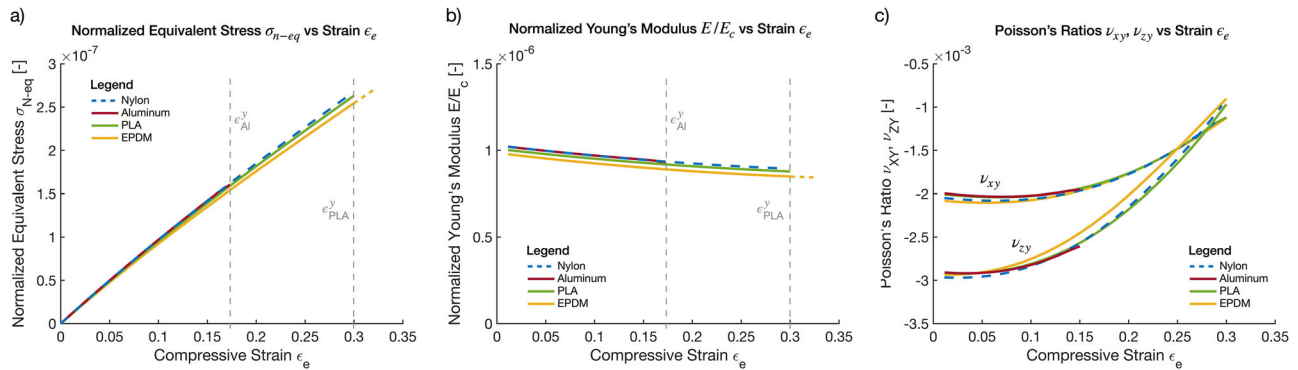


Fig. 5 | Influence of base material properties on the metamaterial's homogenized compressive behaviour. **a** Plots of normalized equivalent stress σ_{n-eq} vs elastic compressive strain ϵ_e , for the 10^3 tessellation for different base materials; **b**) plots of normalized Young's Modulus $E_n = E/E_c$ vs strain ϵ_e , for the 10^3 tessellation and for

the same material configurations; **c**) plots of Poisson's ratio values ν_{xy} and ν_{zy} vs strain ϵ_e , for the same configurations. The base Nylon 12×10^3 model is represented in dashed lines for comparison.

the 3^3 one, highlighting the impact of tessellation size on frequency range values. A phononic band gap analysis is included in Fig. 6(b). The analysis of the phononic band gap diagram for the first 100 modal frequencies reveal the presence of three band gaps in the proposed tessellation (the first ranging between 270.3 Hz and 285.1 Hz, the second between 470.2 Hz and 496.8 Hz, and the third between 803.2 Hz and 817.6 Hz). While the proposed metamaterial is not designed with vibration isolation as principal objective, optimizing the unit cell design, increasing stiffness, introducing material contrast, or incorporating tailored resonators may help the emergence of larger band gaps in such metamaterial if the application requires so. However, a tailored metamaterial design aimed at introducing desired band gaps is outside the scope of the present paper.

Table 5 details deformation modes for the first five distinct frequencies for the 10^3 tessellation. The first frequency shows a global bending towards the positive X axis, while the second frequency shows s-bending (second mode bending), characterized by opposite curvatures from left to right along the front face; the third mode displays hourglass (or four-lobe) deformation, with alternate bulges on the four vertical edges when viewed face-on, resembling an hourglass or four-lobed pattern; the fourth mode features breathing (or single-bulge) mode, where one edge bulges outward; finally, the fifth mode shows s-bending with opposite curvatures, giving it an s-shaped profile. Table 5 includes data from a mass and dimension-equivalent bulk continuum model, with boundary and loading conditions consistent with those applied to the analysed metamaterials. The bulk continuum model's first five frequencies range from 7189 Hz (first frequency) to 13211 Hz (fifth frequency), with values significantly higher than the ones of the 10^3 tessellation models. However, mode shapes loosely resemble those of the lattice tessellation: the first mode shows global bending towards the positive Z axis, while the second mode shows s-bending with the same orientation as the tessellation; the third mode displays hourglass deformation (however with bulges rotated 180° around the Y axis compared to the metamaterial); the fourth mode features breathing mode (rotated by 45° around the Y axis compared to the metamaterial); finally, the fifth mode shows double-bulge (or two-lobe) mode, with two distinct bulges appearing side-by-side, creating a two-lobe deformation (differing markedly from the corresponding fifth mode for the lattice tessellation).

Experimental validation

Quasistatic experimental compressive testing has been conducted on 3D printed models to validate the proposed numerical framework, by assessing ZPR characteristics in compression and comparing results with both beam and solid FE models⁴². Figure 7(a) illustrates the manufactured specimen with the selected dimensions highlighted, representing a 3^3 tessellation built employing helical structures of 1.5 mm wire diameter. The testing setup shown in Fig. 7(b) includes an Instron 4467 UTM equipped with a 5kN load cell and a position measurement

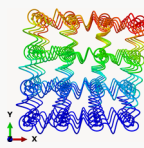
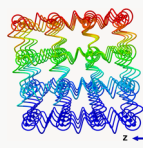
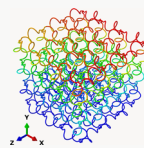
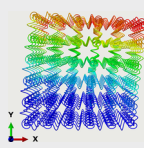
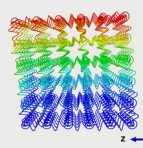
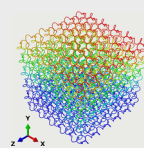
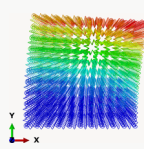
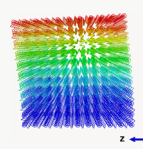
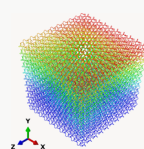
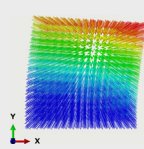
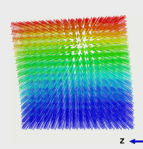
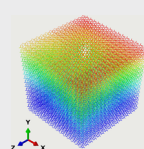
accuracy of 0.15%, a Nikon D700 DSLR camera positioned horizontally, aligned with the specimen's centre, to capture the compressive behaviour and joint deformations, and a computer. Figure 7(c) illustrates the diagram of Poisson's ratio ν_{xy} vs strain ϵ_e for both experimental specimen and numerical models built with both beam and solid elements. It can be noticed how results for beam and solid models are closely aligned, with solid model showing Poisson's ratio values slightly lower than the corresponding beam model, and how the experimental curve matches them with a maximum recorded error of 0.79% between the solid model and the experimental model, across the entire recorded strain range. The difference in alignment between solid and beam models was expected, as noted by Zadeh et al.³³, Qin et al.³⁷, and Chen et al.⁴², who made similar observations about deviations between the experimental procedures and numerical models. This alignment serves as validation for the numerical simulations conducted during this research, confirming the accuracy of the solid models as well as the approximation and reliability of the beam models. In Fig. 7(c), ν_{zy} is also presented for comparison, and it is noticeable how the range of its values is greater than that of ν_{xy} , although still in the order of $1E-3$ as previously noticed. This discrepancy is again attributed to differences in helical structures geometries, and positioning inside the unit cell, as shown in Fig. 1(c). In both cases, solid models result in slightly lower Poisson's ratio values. Experimentally derived values of ν_{xy} ranges from -0.00468 at 10% strain to -0.0025 at 40% strain, confirming the ZPR behaviour of the examined structure. Figure 7(d) illustrates characteristic stages of compression for the experimental specimen, with load [N] and displacement [mm] values coming from the UTM machine. Horizontal helical structures appear almost intact throughout the experimental testing, providing visual evidence of the ZPR behaviour of the metamaterial. Structural collapse occurred for the experimental model at a compressive strain of $\epsilon^f = -41.7\%$, in a post-contact stage ($\epsilon^c = -39.6\%$ from Fig. 2(b)), with the fracture happening at a joint in a boundary unit cell of the structure, accompanied by a distinct sound.

Analytical derivation of mechanical properties

The Stiffness tensor of the proposed metamaterial takes the simplified form:

$$\vec{C}_{mm} = \begin{bmatrix} C_{11} & 0 & 0 & 0 & 0 & 0 \\ 0 & C_{11} & 0 & 0 & 0 & 0 \\ 0 & 0 & C_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{44} \end{bmatrix} = \begin{bmatrix} E & 0 & 0 & 0 & 0 & 0 \\ 0 & E & 0 & 0 & 0 & 0 \\ 0 & 0 & E & 0 & 0 & 0 \\ 0 & 0 & 0 & G & 0 & 0 \\ 0 & 0 & 0 & 0 & G & 0 \\ 0 & 0 & 0 & 0 & 0 & G \end{bmatrix} \quad (3)$$

Table 4 | Buckling analysis. Front, side and isometric views of each tessellation are reported with the corresponding displacement contour plots

Tessellation	Critical load [N]	Structure mass [kg]	Mass-normalized critical load [$N \cdot kg^{-1}$]	First buckling mode shape		
				Front view	Side view	Isometric view
3^3	2.99	0.021	142.38			
5^3	5.97	0.078	76.54			
10^3	18.37	0.525	34.99			
15^3	37.68	1.669	22.58			

All critical loads and mode shapes are relative to the first buckling mode of each structure.

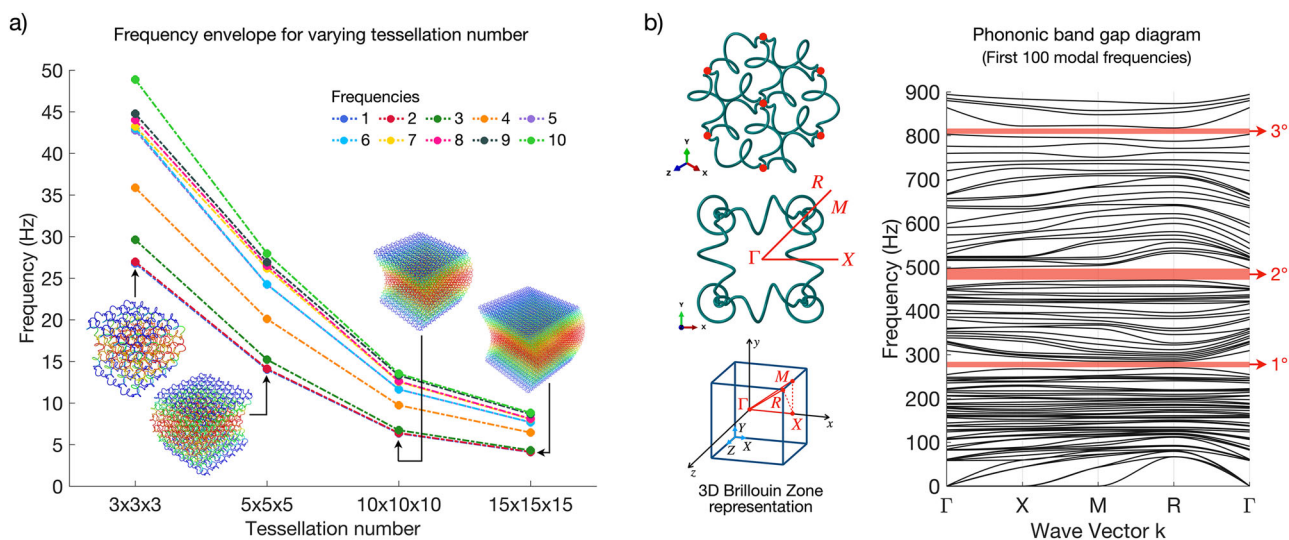


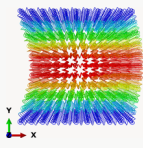
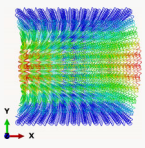
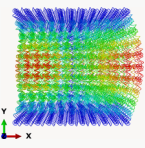
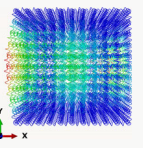
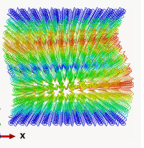
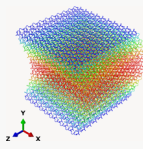
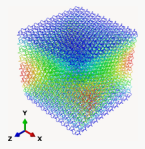
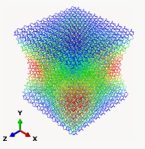
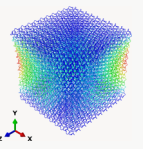
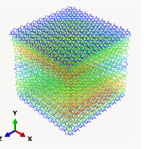
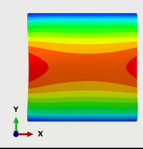
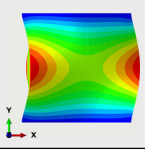
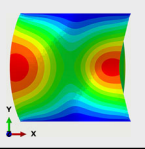
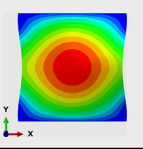
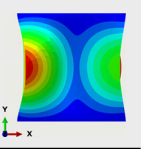
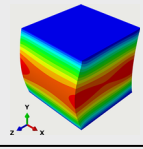
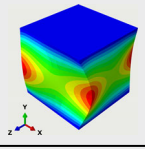
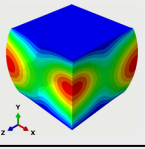
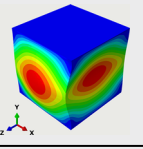
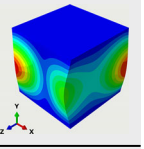
Fig. 6 | Modal and phononic band gap analyses. **a** First 10 frequencies envelope for different tessellations, highlighting peculiar convergent behaviour; **(b)** phononic band gap analysis. The 8 points selected for periodic boundary condition

applications are highlighted, together with the representation of the 3D Brillouin zone for the helical unit cell.

Where $C_{11} = E$ is the equivalent Young's modulus of the metamaterial, which is directly related to the helical structures' elastic constant, and here assumed to be equal in all three orthogonal directions, while $C_{44} = G$ represents its shear stiffness, and all off-diagonal

terms are zero due to ZPR behaviour. The equivalent Young's modulus E of the lattice can be mathematically derived from the stiffness of an individual helical structure by considering the application of Hooke's Law. For a given loading direction

Table 5 | Modal analysis

Tessellation		1st frequency	2nd frequency	3rd frequency	4th frequency	5th frequency
10^3	Front view					
	Isometric view					
	Frequency (Hz)	6.40	6.74	9.74	11.66	12.62
	Global deformation mode	Global bending	S-bending	Hourglass	Breathing	S-bending
Equivalent bulk continuum model	Front view					
	Isometric view					
	Frequency (Hz)	7189	7379	12093	12662	13211
	Global deformation mode	Global bending	S-bending	Hourglass	Breathing	Double bulge

Front and isometric views are reported for the 10^3 tessellation arrangement for the first five frequencies, with frequency values. An equivalent bulk continuum model is reported for comparison, with mass and size identical to the 10^3 model.

$i = X, Y, Z$, the metamaterial Young's modulus E_i can be obtained as:

$$E_i = \frac{\sigma_i}{\varepsilon_i} = \frac{F_{mm-i}/A_{r-i}}{\delta_i/L_{mm-i}} \quad (4)$$

where F_{mm-i} is the reaction force exerted by the metamaterial, A_{r-i} is the cross-sectional area (equal to one cubic tessellation's face), δ_i is the imposed displacement, and L_{mm-i} is the undeformed side length of the metamaterial in the loading direction, proportional to the unit cell's size and tessellation number l . The total reaction force F_{mm-i} can be expressed as $F_{mm-i} = k_{mm-i} \cdot \delta_i$ where k_{mm-i} is the stiffness of the metamaterial in the loading direction, function of the stiffness of a single helical structure k_{hs} as:

$$k_{mm-i} = (l+1)^2 \cdot (l/k_{hs})^{-1} \quad (5)$$

By substituting (5) into the previous expression (4) for E_i , we obtain the following expression:

$$E_i = \frac{[(l+1)^2 \cdot (l/k_{hs})^{-1}] \cdot L_{mm-i}}{A_{r-i}} \quad (6)$$

The analytical expression for k_{hs} is not trivial, as shape-optimized helical structures possess convoluted geometries with complex curvatures compared to conventional coil springs. However, it can be computed numerically through FE analysis. Figure 8 shows tensile and compressive analyses conducted on the homogenized tessellation, highlighting large strain capabilities and the equality of stiffnesses among the three coordinate

directions X, Y, Z . The analyses are performed to extract reaction force values in the three loading directions, as shown in the reaction force RF vs elastic strain ε_e plots. An approximate value for the stiffness of a single helical structure k_{hs} is computed from FE analysis, resembling values of $k_{hs}^T = 0.047 \text{ N} \cdot \text{mm}^{-1}$ and $k_{hs}^C = 0.035 \text{ N} \cdot \text{mm}^{-1}$ (which represents median stiffness value; the actual stiffness for an individual helical structure is variable with strain $k_{hs} = k_{hs}(\varepsilon)$. See ref. 38 for more details). By applying (5), the theoretical stiffness values for the metamaterial are calculated and plotted against the numerical analyses, validating the proposed analytical model and the first quadrant of the Stiffness tensor in (3). It is possible to reduce the computational complexity of designing the mechanical properties of the metamaterial by designing a single helical structure, guaranteeing that large strain capabilities, dimensional stability and ZPR behaviour are maintained at every scale of application. While buckling onset is due to the structural topology of the metamaterial and can be controlled with external constraints, the specific yielding strain in Fig. 8 is due to the base material used (Nylon 12) and can be drastically improved choosing the right constituent material properties.

Shear analysis is conducted on the homogenized tessellation to characterize its deformation modes and quantify its resistance to tangential loads, highlighting peculiar deformation mechanisms. Two cases are analysed, corresponding to pure and simple shear loading respectively. In the pure shear case, displacements have been applied in tangential directions to the top and lateral surfaces (positive X and Y displacements for the surfaces normal to the $+Y$ and $+X$ directions, respectively), while the opposing edge has been fully constrained to avoid rigid body motion. In the simple shear case, displacement has been applied on the upper

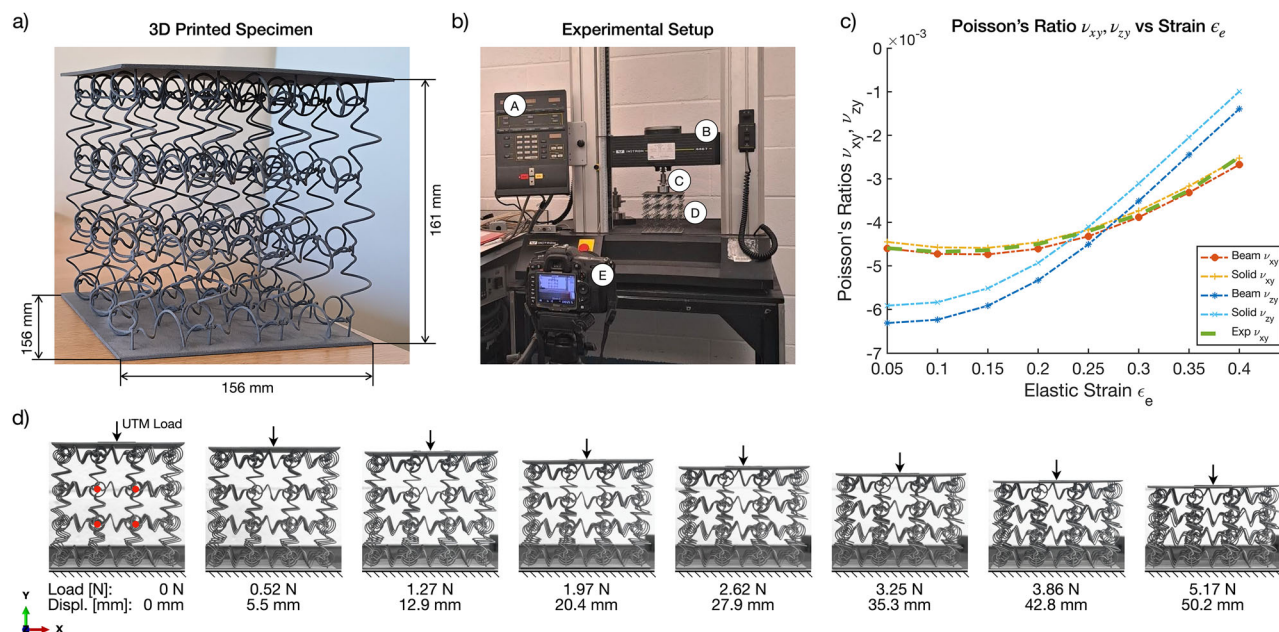


Fig. 7 | Experimental validation setup and results. **a** 3D printed specimen for experimental testing, with dimensions highlighted. Beam extension elements are used to connect the specimen to the added upper and lower plates; **b**) experimental setup for compressive quasistatic testing (A = UTM controller, B = Instron 4467 UTM, C = 5Kn Load Cell, D = Specimen, E = DSLR camera); **c**) Poisson's ratios vs

strain diagram: the Poisson's ratios in the XY directions for the experimental model, the beam model and the solid model are illustrated; moreover, the Poisson's ratios in the ZY directions for beam and solid models are presented for comparison; **d**) characteristic views of the compression testing on the 3^3 test specimen: (1) is undeformed, (2-8) show the compression evolution up to contact onset.

surface nodes of the model, while the bottom surface has been fully constrained.

Figure 9(a) shows the evolution of the equivalent shear stresses τ_{n-eq} , normalized by the shear modulus G_c of the constituent material, vs the elastic shear strains γ_{x-e} , together with the plot of the normalized shear modulus $G_n = G/G_c$ (G_c being the shear modulus of Nylon 12, $G_c = 319.3$ MPa according to the relation $G_c = \frac{E_c}{2(1+\nu_c)}$, with $E_c = 887.68$ MPa and $\nu_c = 0.39$ as reported in Table 1), up to yielding ($\gamma_{x-Y} = 0.482$ in the case of pure shear) or up to coil contact ($\gamma_{x-C} = 0.6$ in the case of simple shear). It can be noticed how trends of simple and pure shears are different, due to differences in deformation mechanics and boundary constraints (pure shear involves uniform, symmetric loading with minimal rigid-body motion, while simple shear introduces rigid-body rotation, localized stress concentrations, and additional constraints that amplify axial and bending stresses, altering the load paths and increasing overall stiffness response). From pure shear, the median value among the considered strain range for the normalized shear modulus is $G_n = 3.79 \cdot 10^{-7}$, which brings to a median shear modulus value of $G = 1.21 \cdot 10^{-4}$ MPa, lower than the value $G = E/2$ expected from orthotropic material theory. Figure 9(b) shows front view stress contour plot at yielding for the homogenized tessellation under pure shear loading. Higher stresses are recorded on the unit cell ligaments linked to the constrained edge of the tessellation, while the upper left and lower right edges are less affected by shear stresses. In the case of simple shear, Fig. 9(c), it can be noticed how the most stressed ligaments belong to the four corners of the structure, with upper left and lower right corners subjected to compression, and the lower left and upper right corners subjected to tension. In the case of simple shear, inter-coil contact is recorded for the helical ligaments belonging to the lower right edge of the tessellation, where the maximum stress concentration is also recorded (maximum stress below yielding stress). Moreover, in both cases of pure and simple shear loadings, stress concentrations are recorded on the joints between unit cells, due to the reaction moments acting on them and coming from the deflection of helical ligaments outside their working axis (longitudinal axis), highlighting a novel deformation mechanism. Finally, a peculiar S-shaped bending is visible from the deformed shape of vertical helical columns in the case of simple shear, which globally affects the

deformed shape of the metamaterial and is due to the change in stiffness of the helical ligaments subjected to differential tension/compression due to the linearization/densification of the ligaments, as shown in Supplementary Fig. 1.

Overall, the discrepancy between the shear modulus observed in pure shear and the value expected from orthotropic theory ($G = E/2$) arises from the discrete mechanics and geometry of the metamaterial: when subjected to shear, individual helical ligaments experience complex deformation modes, including stretching, compression, and bending, which are less efficient at transmitting shear stresses compared to axial loading; additionally, stress redistribution and the diagonal orientation of some ligaments relative to the principal shear directions reduce the effective stiffness. These factors cause the global shear response to deviate from the idealized orthotropic continuum assumption, making the material generally anisotropic in nature, although described in a linear approximation by the diagonal Stiffness tensor in (3).

The proposed metamaterial shows capability to undergo uniform volumetric compression when subjected to hydrostatic pressure. In particular, the bulk modulus K , which measures its resistance to uniform compression, can be expressed as:

$$K = -V_0 \frac{P}{\Delta V} \quad (7)$$

Where V_0 is the undeformed volume, ΔV is the volume change under pressure, and P is the hydrostatic pressure. Figure 10(a) shows uniform volumetric compression simulation on the homogenized tessellation. The boundary conditions used to simulate this behaviour include three pinned surfaces (surfaces with normal vectors $-X$, $-Y$ and $+Z$) and three surfaces with imposed displacements on their normal directions, with the other degrees of freedom unrestrained. Compression is performed up to inter-coil contact, happening at an elastic compressive strain of $\epsilon^c = -35.4\%$ (the compressed model at ϵ^c has volume $V_c = 0.023\text{m}^3$, while the undeformed volume is $V_0 = 0.085\text{m}^3$). It is noticeable how the increased external constraints prevented the structure to undergo any buckling deformation (buckling onset was previously recorded at $\epsilon^b = -30.7\%$ for the

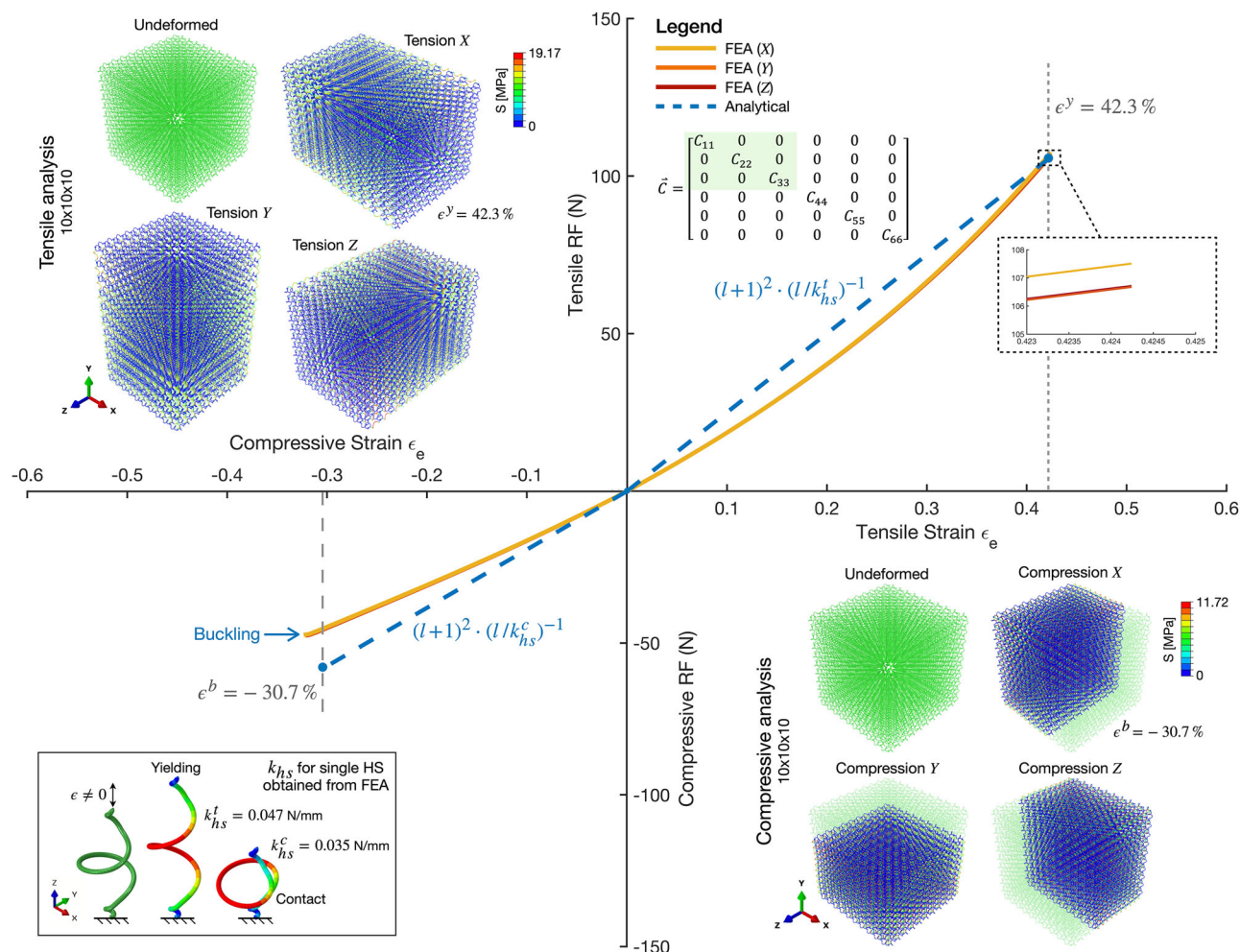


Fig. 8 | Stiffness analysis on the 10^3 tessellation, highlighting large strain capabilities. Plots for tensile and compressive reaction forces RF vs elastic strain ϵ_e are shown, compared to the analytical derivation from (5). Nonlinearity in the mechanical response is due to the linearization (in tension) / densification (in compression) of the helical structure, which brings to a changing stiffness due to the

diminishing / increasing coil radius (j-shape curve highlighted in ref. 38). The median stiffness value for the individual helical structure is computed as the slope between the points $(0, 0)$ and $(\epsilon^j, RF_{\phi^j})$ in the tensile case, and $(0, 0)$ and $(\epsilon^c, RF_{\phi^c})$ in the compressive case, with ϵ^c being the strain at self-contact of the individual helical structure (inset on the bottom left corner of the image).

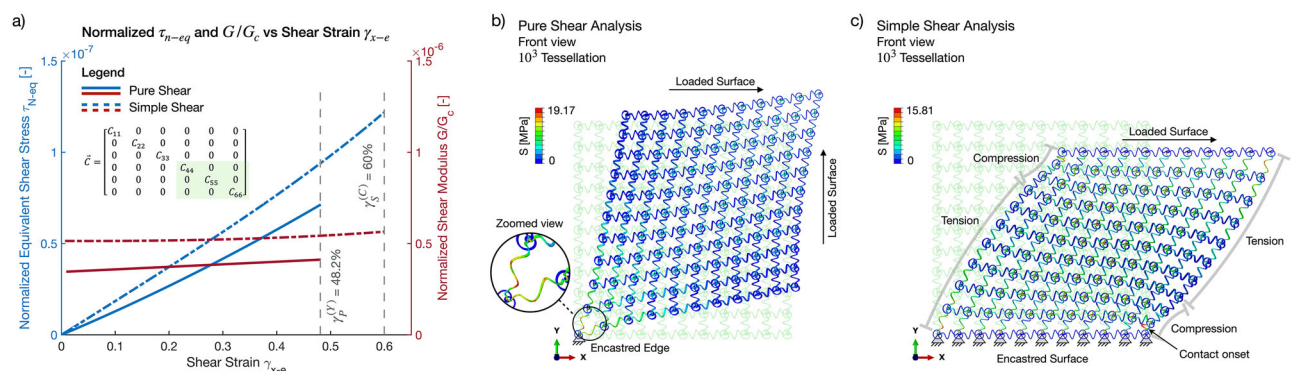


Fig. 9 | Shear analysis on the 10^3 tessellation. **a** Plots of normalized equivalent shear stresses τ_{n-eq} and normalized shear modulus $G_n = G/G_c$ vs elastic shear strain γ_{x-e} for the 10^3 tessellation subjected to shear loading, up to yielding ($\gamma_{x-Y} = 48.2\%$ in the case of pure shear) or up to coil contact ($\gamma_{x-C} = 60\%$ in the case of simple shear);

(b) stress contour plot (front view) highlighting the stress distribution and peculiar deformation mechanism, in the case of pure shear loading; (c) stress contour plot (front view) highlighting the stress distribution and peculiar deformation mechanism, with critical corners highlighted, in the case of simple shear loading.

unrestrained 10^3 tessellation). The value of hydrostatic pressure acting on the metamaterial is given by the reaction force exerted on one surface, which depends on the deformation state as highlighted in Fig. 8, $P(\epsilon) = RF(\epsilon)/A_r$. It is possible to plot the relationship $-V_0 \frac{P}{\Delta V}$, as represented in the plot of Fig. 10(a), to show the value of bulk modulus expressed by Eq. (7). Moreover, the point of first contact in compression is located among helical structures close to the external edges of the tessellation (in particular, in the lower left and lower right corners of the front face), while most helical structures inside the tessellation are not yet in self-contact, as shown in Fig. 10(b). This behaviour is due to an overall internal rotation of the structure, which happens around the $+X$, $+Y$ and $+Z$ directions at the same time, and is noticeable from slight misalignments of longitudinal columns of helical structures aligned with the three global axes. This is another effect of the second-order couplings due to structure's chirality which is further explained in Supplementary Note 1.

Stress concentration is a critical factor influencing structural failure, especially in complex geometries such as the helical metamaterial presented in the proposed study. In this context, stress concentration refers to the localized increase in stress around geometrical discontinuities such as joints or transitions between different structural elements. Regions with geometrical discontinuities are prone to higher stress levels compared to the surrounding material, potentially leading to premature failure. The stress concentration factor K_t , which is the ratio of the highest stress to the nominal far field stress, is usually expressed as $K_t = \frac{\sigma_{\max}}{\sigma_{\text{nominal}}}$, where $\sigma_{\max}$ is the maximum stress at the discontinuity and σ_{nominal} is the nominal far field stress. For the helical metamaterial presented in this study, stress concentration predominantly occurs at the joints between helical ligaments in the case of shear loading (as visible in Fig. 9(b, c)) or at points of maximum helical radius within the helical structure in the case of axial loading (due to the shear stresses acting on the helical wire, which are maximum in the large central coil of each helical ligament, as visible for example in Fig. 2). Table 6 reports values of maximum and minimum stress acting on selected helical ligaments for the different loading cases analyzed (including compression, tension and shear loadings). In each case, the single helical ligament reporting the maximum Mises stress value is selected from the whole tessellation, and its specific highest and lowest stresses are extracted to show-case the differences in stress distribution under different loading conditions. The stress concentration factor is then calculated according to the ratio $K_t = \frac{\sigma_{\max}}{\sigma_{\min}}$. Potential solutions to reduce stress concentrations and improve the structural integrity of the helical metamaterial include geometric optimization, material distribution and structural topology modification. Geometric optimization includes ensuring gradual curvature transitions within the helical coils to minimize bending-induced stress concentrations; however, this would alter the helical ligament design, potentially

compromising the balance between minimum mass and maximum tensile range³⁸. Material distribution include varying the diameter of helical wires and joint connections across different regions to improve stress distribution; the use of functionally graded materials, with stiffness varying along the helical structure, could also enhance load-bearing capacity at critical points. Finally, structural topology modification includes redesigning joint connections for smoother load transfer, reducing stress concentrations at intersections under shear loading. Implementing these solutions is however time consuming and outside the scopes of the current presentation.

Multifunctional integration and significance

The unique properties evidenced in this study make the proposed metamaterial a promising candidate for various applications, including precision actuators (where the ability to independently and finely control deformations in each direction enables the creation of high-precision positioning devices), smart structures (where the material's predictable and controllable response to multi-axial loading could be useful in adaptive or responsive structural systems), tailored compressibility applications, where the uniform volume change under hydrostatic pressure could be exploited in applications requiring specific compressibility characteristics), energy absorption devices (where the linearly independent spring-like behaviour in each direction could potentially be utilized in energy-absorbing structures or materials), sensor technologies (where the direct relationship between applied forces and dimensional changes could be leveraged for force or pressure sensing applications).

While the ZPR characteristics of the proposed metamaterial offer significant advantages, further analysis reveals additional capabilities that enhance its potential for advanced applications, which emerge from its behaviour under multi-axial loading conditions and its potential for programmable deformation. While the initial model considered identical helical structures in all directions, the concept can be extended to incorporate direction-dependent stiffnesses: by using helical structures with different elastic constants in each direction (k_x , k_y and k_z for helical structures in global directions X , Y and Z respectively), a metamaterial can be defined with anisotropic mechanical properties while maintaining perfect ZPR behaviour among large deformations. By rewriting (3) in the direction-dependent stiffnesses case, the Stiffness tensor takes the more general form:

$$\vec{c}_{\text{mm}} = \begin{bmatrix} C_{11} & 0 & 0 & 0 & 0 & 0 \\ 0 & C_{22} & 0 & 0 & 0 & 0 \\ 0 & 0 & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix} = \begin{bmatrix} E_x & 0 & 0 & 0 & 0 & 0 \\ 0 & E_y & 0 & 0 & 0 & 0 \\ 0 & 0 & E_z & 0 & 0 & 0 \\ 0 & 0 & 0 & G_{xy} & 0 & 0 \\ 0 & 0 & 0 & 0 & G_{xz} & 0 \\ 0 & 0 & 0 & 0 & 0 & G_{yz} \end{bmatrix} \quad (8)$$

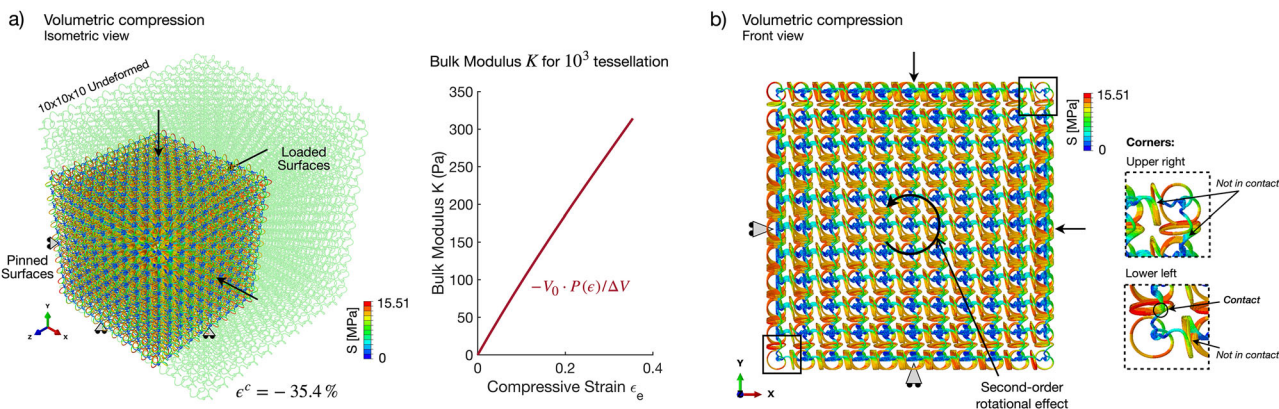


Fig. 10 | Volumetric compression on the 10^3 tessellation. a) 10^3 tessellation in undeformed stage and in volumetric compression up to first coil contact. Notably, the increased constraints on all surfaces (compared to the previous compressive analyses with free lateral surfaces) eliminate buckling effects, increasing dimensional

stability and allowing the tessellation to reach coil contact in compression. Also shown plot of Eq. (7) from numerical results; (b) Front view of the compressed model, with analysis of the self-contact failure in individual helical ligaments as well as the second order, rotational effect impacting the overall tessellation.

Table 6 | Stress distribution on the 10^3 tessellation for different loading conditions

Loading condition (failure mode)	Stress distribution in the critical helical ligament at failure [MPa]		Stress concentration factor in the critical ligament at failure $K_t = \frac{\sigma_{\max}}{\sigma_{\min}}$ [-]
	Maximum Stress	Minimum Stress	
Compression (buckling onset)	11.72	0.98	11.96
Tension (yielding onset)	19.17	1.61	11.91
Pure Shear (yielding onset)	19.17	3.20	5.99
Simple Shear (self-contact)	15.81	3.95	4.00

For each loading condition, the unit cell showing maximum stress value is selected and its maximum and minimum stress values are collected.

Where $C_{11} = E_X$, $C_{22} = E_Y$ and $C_{33} = E_Z$ are now independent and related to the three constants k_X , k_Y and k_Z , as per (6). Building upon the concept of selective dimensional control, the metamaterial exhibits remarkable shape-morphing capabilities: by applying varying stress magnitudes along different axes, complex three-dimensional transformations can be achieved. This property can be described by the specific form took by the decoupled deformation gradient tensor, which highlights how independent strains in each direction contribute to overall shape change:

$$\begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} = \begin{bmatrix} 1 + \varepsilon_X & 0 & 0 \\ 0 & 1 + \varepsilon_Y & 0 \\ 0 & 0 & 1 + \varepsilon_Z \end{bmatrix} \begin{bmatrix} \hat{x} \\ \hat{y} \\ \hat{z} \end{bmatrix} \quad (9)$$

where $[\hat{x}, \hat{y}, \hat{z}]^T$ are the original coordinates of a given point and $[x', y', z']^T$ are the transformed coordinates and ε_X , ε_Y , ε_Z are the strains in the three coordinate directions.

The ZPR behaviour and independently controllable directional responses of the metamaterial analysed in this paper offer a promising platform for developing multifunctional systems: based on the decoupled stress-strain relationships in different directions, diverse functionalities such as sensing, actuation, and load-bearing capabilities can be integrated within a single metamaterial structure. This multifunctionality can be schematically represented by a function vector $F^- = [f_X^{\text{sensing}}(\sigma_x, \varepsilon_x), f_Y^{\text{load}}(\sigma_y, \varepsilon_y), f_Z^{\text{actuation}}(\sigma_z, \varepsilon_z)]$, where f_i represents the specific function (sensing, actuation, load-bearing, etc.) in the i^{th} direction, dependent only on stresses and strains in that direction. Figure 11 depicts a potential multifunctional design of the proposed metamaterial: while the load bearing capacity can be designed using thicker helical structures or a suitable rigid base material for the specific ligaments in Y direction, sensing and actuation capabilities may be obtained employing conductive/piezoelectric covering materials or Shape Memory Alloys (SMA) for ligaments in the X and Z directions. As individual helical structures in the metamaterial are independent components, different regions of the material system body may be designed with different sensing, actuation and load bearing capabilities, effectively responding to the designer expectations in various application profiles. However, while a comprehensive experimental investigation into specific applications is in principle possible, it is outside the scope of the present paper, as it would require extensive simulation, prototyping, testing, and optimization, leading to an independent publication.

Conclusion

In this paper, the mechanical behaviour of a zero Poisson's ratio 3D helical metamaterial subjected to large elastic strains was addressed. A notable feature of the proposed metamaterial was the absence of stress concentrations at the joints between unit cells in axial loading, which provided advantages over existing ZPR metamaterials—such as Fish Cells—, that suffer from stress concentrations greatly impacting their large strain potential. Different loading cases were considered, with analyses conducted on four different tessellations. The investigation on the magnitudes of the Poisson's ratio and the normalized Young's

modulus confirmed the ZPR and compliant characteristics, making the helical metamaterial a candidate for applications in tissue engineering or soft robotics, where compliance is required.

First, the proposed helical metamaterial was modelled in Abaqus and underwent a homogenization study, with convergence of mechanical properties achieved for the 10^3 tessellation arrangement. When subjected to axial loading, it was observed that helical structures perpendicular to the global loading direction did not deform, confirming the decoupling of mechanical loads between orthogonal unit cell members, and therefore a consistent ZPR behaviour of the structure. This is a significant improvement compared to traditional ZPR structures, which typically display only “approximately zero” PRs and suffer from a progressive deviation from the ZPR behaviour as the deformation increases, due to intricate and macroscopic load interdependencies between unit cell's ligaments that also hinder their large strain capabilities. In contrast, the helical structure-based metamaterial achieves a significant ZPR over large strain ranges, without the inherent limitations observed in traditional designs, as the load interdependencies are significantly contained and only appear as second-order effects. A wire diameter study was conducted by considering different cross-section values ranging from 0.5 mm to 2 mm. The impact of varying wire diameter on the compressive behaviour, as well as on Poisson's ratios and normalized Young's modulus, was investigated. It was observed that, while the compressive behaviour was not significantly affected by the diameter variation, the normalized Young's modulus showed substantial sensitivity to it. This is interesting from an applicative point of view, especially for soft robotics and medical applications where tailored Young's modulus values in each spatial direction can be achieved by tailoring the wire diameter of individual unit cell ligaments inside the metamaterial with a highly granular level of control, while maintaining ZPR characteristics. Furthermore, buckling and modal analyses were conducted for all tessellation arrangements and for an equivalent bulk continuum cube of identical size and mass to the 10^3 tessellation. Additionally, the presence and extension of phononic band gaps were investigated to provide a complete picture of the metamaterial's behaviour. Finally, experimental analysis was conducted through compressive testing to validate the proposed numerical methodology. The experimentally recorded values of Poisson's ratios exhibited a strong agreement with the numerical values, with an overall 0.79% error for ν_{xy} in comparison to the numerical model with refined solid mesh. Analytical modelling was performed to investigate the linear elastic behaviour of the structure. It was recognized that, although based on an anisotropic micro-structure, the homogenized metamaterial shows a peculiar orthotropic-like behaviour with a simplified, diagonal stiffness tensor dependent only on its Young's and Shear moduli. Finally, a set of analytical derivations further demonstrated the dependence of its Young's modulus from the elastic constant of the individual helical structures. The proposed advanced capabilities, derived from the linear independence of stresses and strains, the precise ZPR characteristics and the granular control of the material stiffness, underline the potential applications of the proposed metamaterial, with the ability to create tailored anisotropic responses opening possibilities in the development of direction-dependent multifunctional mechanical metamaterials. In fields such as soft robotics, the programmable shape-morphing and selective dimensional control could enable the creation of

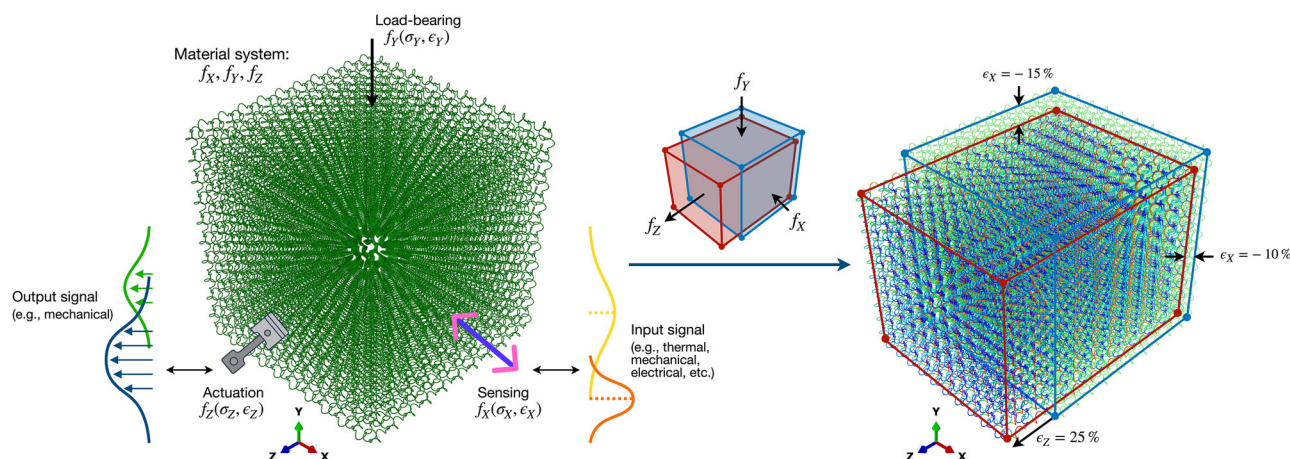


Fig. 11 | Example of multifunctional design of a material system. Three properties of sensing (in direction X), load bearing (direction Y) and actuation (direction Z) are characterized by the function vector $F(f_X, f_Y, f_Z)$. On the left, potential

interlinkages between multifunctional capabilities are evidenced; on the right an example of smart actuation devices with integrated capabilities of load-bearing, sensing and actuation.

highly adaptable structures, while the possible implementation of sensing and actuation capabilities based on conductive/piezoelectric or thermal materials (4D printing) could enable the creation of intelligent material systems, able to respond and adapt effectively to the surrounding environment.

There is significant potential for further research on the examined metamaterial. Different arrangements of the unit cell ligaments could be explored, and the comparison of various shapes for both the unit cell and the tessellation could be undertaken. Considering the metamaterial's outstanding performance under compressive loading, exploring additional loading scenarios, including fatigue and dynamic impact would be valuable to define its behaviour comprehensively and its suitability for diverse applications. Furthermore, future work may involve defect modelling and an effect of defects study. Exploring defect parameters and understanding the effects of defect's concentration in specific areas of the structure, as well as their impact on different tessellation numbers, could help addressing the manufacturability and reliability of the proposed metamaterial. Finally, the potential for multifunctional integration based on different helical structures shapes suggests applications in smart structures and adaptive systems where multiple capabilities are required within a single material framework. In this frame, a comprehensive and granular analytical theory could enhance the design of multifunctional application reducing the need for numerical and experimental analyses.

Methods

Finite element analysis

Finite Element (FE) simulations are conducted using the popular FEA solver Abaqus. Nylon 12 is chosen as constitutive material for both numerical simulations and experimental testing, with properties reported in Table 1. Except for cross-sectional diameter analysis, all simulations utilize beam-based helical structures; the cross-sectional diameter of the ligaments is set at 1.5 mm, and a mesh size of 0.75 mm for the B32 beam elements is employed after a mesh sensitivity analysis, ensuring a detailed representation of the metamaterial's behaviour. The bottom joints of the lattice structures are spatially constrained, preventing rigid body motions or rotations, while unidirectional loads are applied to the top joints constraining other degrees of freedom (simulating an end plate applying loads to the structures). Simulations are conducted until failure, which can be either yielding (in tension or compression), overall buckling onset, or self-contact of individual ligaments inside the tessellation. The number of finite elements (beam elements) for each tessellation arrangement is equal to 19,440 for the 3^3 tessellation, 72,900 for the 5^3 tessellation, 490,050 for the 10^3 tessellation and 1,555,200 for the 15^3 tessellation.

Poisson's ratio, equivalent Young's modulus and shear modulus calculation

The study of ZPR behaviour in compression focuses on the trend of two Poisson's ratio values, ν_{xy} and ν_{zy} , computed dividing strains in global X and Z directions, ϵ_x and ϵ_z respectively, by the strain in the global Y direction (loading direction) ϵ_y : $\nu_{xy} = -\epsilon_x/\epsilon_y$ and $\nu_{zy} = -\epsilon_z/\epsilon_y$, with a minus sign to account for the compressive effect. Strains are determined by averaging the distances between pairs of fixed points inside the structure: as highlighted in Fig. 2(a) for the case of the 10^3 tessellation, ϵ_x is the average strain for the distance between the faces AECG and BFDH (originally parallel when the metamaterial is undeformed), ϵ_y for the distance between the faces AEBF and CGDH, and ϵ_z for the distance between ABCD and EFGH. To eliminate boundary effects, the selected points are positioned within a unit cell distance from the external edges, points A, B, C, D being on the front facing surface and points E, F, G, H being on the rear surface in the representation of Fig. 2(a).

The metamaterial's equivalent Young's modulus E is computed at any strain value as $E = \frac{\sigma}{\epsilon}$, where $\sigma = \frac{RF}{A_r}$ is the equivalent stress from the reaction force $RF = RF(\epsilon)$, obtained from FE results and acting on the resisting area A_r (square face of side length $u \times l$, where $u = 44$ mm is the helical ligament length and l is the number of unit cells along the edge), and ϵ is the corresponding elastic strain. From the definition of normalized Young's modulus E_n , defined as the ratio between the metamaterial's equivalent Young's modulus E and the Young's modulus of the base constituent material E_c : $E_n = \frac{E}{E_c} = \frac{1}{E_c} \cdot \frac{RF/A_r}{\epsilon_c}$.

For shear analysis, the equivalent shear stress has been obtained by dividing the total reaction force (shear force F_i) acting on the loaded surface(s) by the corresponding resisting area A_r : $\tau = \tau_{yx} = \tau_{xy} = F_x/A_r = F_y/A_r$. Global shear strain can be computed, in pure shear loading, as $\gamma_x = \delta X/L_{mm-y} + \frac{\delta Y}{L_{mm-x}}$, where δX and δY are the global displacements of the loaded surfaces in the positive X and Y directions, and $L_{mm-x} = L_{mm-y}$ are the undeformed lengths of the metamaterial in the X and Y directions. In the case of simple shear, the global shear strain can be computed as $\gamma_x = \delta X/L_{mm-y}$. Finally, the shear modulus can be calculated as $G = \tau/\gamma$.

Linear perturbation analysis

FE simulations are employed for buckling response evaluation, encompassing all considered tessellation arrangements (ranging from 3^3 to 15^3). In all models, the bottom surface has been given fixity conditions while the applied load is set at 1 N on the top surface, and helical ligaments are modelled using beam elements to minimize computational complexity. FE simulations are employed for modal evaluation as well, comparing

tessellation arrangements and a bulk continuum cube with equivalent mass and dimensions of the 10^3 case. For modal response evaluations, both top and bottom surfaces of each tessellation have been given fixity conditions. The continuum model, built using the same material properties of Nylon 12, possesses a modified density of $6.17 \text{ kg} \cdot \text{m}^{-3}$, with dimensions resembling those of the 10^3 arrangement—each side measuring 440 mm. Such density value has been artificially selected to guarantee the bulk continuum to have the same mass of the 10^3 tessellation, according to the relation $\rho = m/V$, where ρ is the density of the constitutive material, m is the mass of the structure and V its undeformed volume (in the case of the lattice tessellation, the mass value m is extracted from FE results and is equal to 0.525 kg for the Nylon 12 based 10^3 model).

Phononic band gap analysis is conducted to identify frequency ranges where elastic wave propagation is prohibited within the metamaterial. This phenomenon arises due to periodic variations in the material's geometry or properties, leading to destructive interference of wave modes. The phononic band gap diagram in Fig. 6(b) has been obtained by applying Bloch boundary conditions to the cubic unit cell (effectively simulating an infinite tessellation), sweeping the wave vector $\mathbf{k}$ through the 3D irreducible Brillouin zone $\Gamma \rightarrow X \rightarrow M \rightarrow R \rightarrow \Gamma$, performing an eigenfrequency extraction at each wave vector value and plotting the resulting dispersion curves to locate any gaps (frequency ranges with no real modes).

Experimental analysis

Figure 7(a) illustrates the manufactured specimen, representing a 3^3 tessellation built employing helical structures of 1.5 mm wire diameter. Given the high precision required to manufacture the specimens—due to their complex three-dimensional geometry, curvatures, and small thicknesses, Selective Laser Sintering (SLS) 3D printing technique was chosen for its capability to produce complex geometric components, making it ideal for prototyping. Flat plates were added to the top and bottom surfaces of the specimen to facilitate the application of boundary conditions, with the bottom plate acting as a base to sustain the specimen, and the upper plate distributing the loads coming from a Universal Testing Machine (UTM). Straight beam elements were added to enable the contact between the metamaterial and the plates, extending from top and bottom joints of the structure. Nylon 12 was selected as base material for the 3D printing process, with material properties listed in Table 1. The testing setup shown in Fig. 7(b) includes an Instron 4467 UTM equipped with a 5kN load cell and a position measurement accuracy of 0.15%, a Nikon D700 DSLR camera positioned horizontally, aligned with the specimen's centre, to capture the compressive behaviour and joint deformations, and a computer. Static tests were conducted at a speed of 2 mm/min until collapse of the structure. UTM data in the form of load-displacement values were collected, and pictures analysed using Plot Digitizer to accurately determine joints' centre movements. Poisson's ratio values were then calculated using the obtained data in conjunction with the UTM data, employing the simplified Poisson's ratio calculation method.

Analytical derivation of stiffness tensor

In continuum mechanics the Stiffness tensor $\mathbf{C}^{\leftarrow}$ establishes the linear relationship between stresses and elastic strains in a material and takes the general form C_{ij} , with i, j ranging from 1 to 6. Its components are directly related to the material's mechanical properties (in particular, Young's moduli in the principal directions, Poisson's ratios, Shear moduli). The unique design of the metamaterial presented in this study, based on a hierarchical structure of cubic unit cells, results in several distinctive properties: in particular, the homogenized metamaterial shows behaviours common to orthotropic materials (although being generally anisotropic under different loading conditions), with cubic symmetry when identical helical structures are employed in all directions; additionally, the material possesses ZPR characteristics in all three orthogonal directions, resulting in individual independent deformations along each loading direction without affecting the two orthogonal dimensions. For a generic orthotropic material,

the Stiffness tensor takes the general form:

$$\overset{\leftarrow}{C}_0 = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix}$$

where relationships between components C_{ij} and engineering constants E, G, ν are given by the following equations:

$$\begin{aligned} C_{11} &= \frac{1 - \nu_{23}\nu_{32}}{E_2 E_3 \Delta}, C_{22} = \frac{1 - \nu_{13}\nu_{31}}{E_1 E_3 \Delta}, C_{33} = \frac{1 - \nu_{12}\nu_{21}}{E_1 E_2 \Delta}, \\ C_{12} &= \frac{\nu_{21} - \nu_{31}\nu_{23}}{E_2 E_3 \Delta}, C_{13} = \frac{\nu_{31} - \nu_{21}\nu_{32}}{E_2 E_3 \Delta}, \\ C_{23} &= \frac{\nu_{32} - \nu_{31}\nu_{12}}{E_1 E_3 \Delta}, \Delta = \frac{1 - 2\nu_{13}\nu_{21}\nu_{32} - \nu_{13}\nu_{31} - \nu_{23}\nu_{32} - \nu_{12}\nu_{21}}{E_1 E_2 E_3}, \\ C_{44} &= G_{12}, C_{55} = G_{13}, C_{66} = G_{23} \end{aligned}$$

For the homogenized metamaterial investigated in this study, we can consider a first-order linearized behaviour and explicitly assume $\nu_{ij} = 0$ for $i, j = 1, 2, 3, i \neq j$, in the elastic range. Therefore, based on the previous relationships, the Stiffness tensor takes the simplified form already presented in (3):

$$\overset{\leftarrow}{C}_{\text{mm}} = \begin{bmatrix} C_{11} & 0 & 0 & 0 & 0 & 0 \\ 0 & C_{11} & 0 & 0 & 0 & 0 \\ 0 & 0 & C_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{44} \end{bmatrix} = \begin{bmatrix} E & 0 & 0 & 0 & 0 & 0 \\ 0 & E & 0 & 0 & 0 & 0 \\ 0 & 0 & E & 0 & 0 & 0 \\ 0 & 0 & 0 & G & 0 & 0 \\ 0 & 0 & 0 & 0 & G & 0 \\ 0 & 0 & 0 & 0 & 0 & G \end{bmatrix}$$

Where $C_{11} = E$ is the Young's modulus of the metamaterial, which is directly related to the helical structures' elastic constant, and here assumed to be equal in all three orthogonal directions, while $C_{44} = G$ represents its shear stiffness, and all off-diagonal terms are zero due to ZPR behaviour. The simplification to a diagonal matrix with two unique non-zero components (C_{11} and C_{44}) in the Stiffness tensor in (3) arises from the metamaterial's unique properties:

1. *ZPR characteristics leading to the absence of cross-coupling terms:* as the imposed strain in any direction does not induce normal strains in perpendicular directions, all Poisson's ratio-related terms appearing in off-diagonal elements C_{12}, C_{13}, C_{23} become zero and the main lattice axis (global directions X, Y and Z) coincide with the three principal directions for both stresses and strains. A mathematical derivation of this statement can be proved using Castigliano's theory assuming a first-order approximation of the unit cell's behaviour and is illustrated in Supplementary Fig. 3. Additionally, the absence of non-negligible couplings between normal stresses and shear strains leads to all other off-diagonal terms ($C_{14}, C_{15}, \dots$) to be zero;
2. *Cubic symmetry leading to equal diagonal terms for the three orthogonal directions:* when identical helical structures are employed in all three orthogonal directions the metamaterial exhibits cubic symmetry, requiring that $C_{11} = C_{22} = C_{33}$ (normal stiffnesses are equal in all directions) and $C_{44} = C_{55} = C_{66}$ (shear stiffnesses are equal in all planes);
3. *Independence of normal and shear deformations leading to only two independent components:* in the proposed metamaterial, normal stresses only produce normal strains, and pure shear stresses only produce shear strains. This decoupling is reflected in the stiffness tensor having only C_{11} and C_{44} (for normal and shear stiffnesses, respectively) as non-zero elements. A precise analysis of second-order, cross-coupling behaviours is contained in Supplementary Note 1.

Data availability

All data generated or analysed during this study are included in this published article (and its supplementary information files).

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Author contributions

G.C.—Conceptualization, Methodology, Investigation, Validation, Visualization, Writing—Original draft. Q.Q.—Validation. P.M.—Methodology. I.D.—Supervision, Resources, Writing—Review and editing.

Competing interests

The authors declare no competing interests.

Additional information

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