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Re-entrant inclusions in cellular solids: From defects to reinforcements

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ABSTRACT

A contrast in Poisson ratio is a possible strategy to enhance the stiffness of composite structures. In solid materials Poisson ratio is hardly tailorable unless cellular architectures are considered. Here, we first investigated the effect of a single re-entrant inclusion acting as a defect into a regular (non-re-entrant) honeycomb lattice. Building on this, we generated regular patterns of re-entrant inclusions into a regular hexagonal cellular matrix and we characterized the apparent stiffness and Poisson ratio of the obtained structures. We also explored the role of the intrinsic material properties of the inclusion as well as of its closest environment on the interplay between the deformations of different phases in the lattice. Our main finding is that a small fraction of re-entrant inclusions (around 12%) is sufficient to generate a substantial augmentation in stiffness (300%) at constant overall relative density and without inducing strong anisotropy. Eventually, we fabricated by 3D polyjet printing bi-material composite architectures to demonstrate the superior mechanical behavior obtained exploiting the Poisson effect.

1. Introduction

The combination of basic building blocks with contrasting properties is a promising route to obtain composites far exceeding their individual constituents [1]. This strategy is frequent in biological materials where the spatial arrangement of different components with opposed behavior is tightly controlled at several length scales, resulting into intricate hierarchical structures with outstanding mechanical performance [2]. Biological composites have often cellular (or highly porous) architectures, which efficiently combine the conflicting requirements of light weight with high stiffness, strength and buckling resistance [3]. Numerous studies investigated how simple cellular architectures can be modified to increase mechanical performance by incorporating construction principles typically found in biological structures [4]. Designing cellular solid with a hierarchical architecture is one powerful strategy to enhance stiffness, energy absorption, damage tolerance and auxetic behavior typically at constant mass [5–11]. Functional grading is another feature widespread in biological architectures which is assumed to mitigate stress incompatibilities when going from highly dense to highly porous regions, one example being the gradual change in porosity between cortical and trabecular bone [12]. Grading has been incorporated into 2-dimensional man-made cellular structures [13,14] and the mechanical quantity mainly profiting from functional grading is most likely energy absorption [15]; less clear is the effect of grading on the elastic properties, particularly if the overall mass is kept constant. The interplay between hierarchical structuring and functional grading for the elastic behavior of honeycombs has also been analyzed: a synergistic effect of both hierarchy and grading on apparent stiffness has been shown to occur only for highly slender cell walls [16].

In general, adding architecture to a material allows expanding the so-called material space, i.e., the range of properties that a structure can reach without modifying material chemistry [17,18]. One physical quantity which can be highly tailored in cellular materials is the Poisson ratio, which essentially defines the transverse deformation of an object loaded longitudinally. Most bulk materials without an underlying architecture have Poisson ratio varying within a very narrow range, typically between 0 and 0.35 [19], whereas the Poisson ratio of cellular solids can change substantially, depending on the deformation mechanisms [20]. Some cellular architectures (called auxetic) even show negative Poisson ratio, indicating the tendency to contract perpendicular to the compression direction [21]. Interestingly, the combination of positive and negative Poisson ratio materials may produce a contrast in the local deformation mechanism which can lead to a global stiffening effect. Indeed, this phenomenon has been demonstrated through micromechanical modeling and computer simulations in different virtual composites of auxetic and non-auxetic phases. Depending on the geometry of the com-

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posite (e.g., auxetic fibers embedded into a non-auxetic matrix [22], alternating layers of auxetic and non-auxetic laminates [23–25], auxetic inclusions of different shapes within a non-auxetic matrix [26,27]) different degrees of stiffness enhancement have been calculated, with the maximum stiffness increase being usually linked to the highest anisotropic behavior. Although the proposed structures have remarkable properties, even far beyond classical rule of mixture, their fabrication is to date extremely challenging, mainly due to difficulties in tailoring Poisson ratio in solid materials. Conversely, cellular solids have been extensively used to design and fabricate very diverse re-entrant architectures at different length scales [28–30]. Some studies also investigated the combination of auxetic and non-auxetic geometries either organized into several alternating layers of limited thickness (typically one unit cell) [31,32] or grouped into distinct large regions with limited transitions between auxetic and non-auxetic architectures [33,34].

Here we employed cellular solids to design and fabricate architectured composites with re-entrant inclusions embedded into a regular matrix. Inclusions and matrix are based on unit cells of regular and re-entrant hexagonal honeycombs, respectively (Fig. 1A). In a previous study on a honeycomb lattice, we reported a complex interaction between a minimal structural defect and the local environment around it. Specifically, a defect generated by reducing the thickness of just one joint (i.e., three beams meeting at a junction of the honeycomb) did not cause an increase in the local strain energy in the defect but rather in its closest environment [35]. The same phenomenon has been observed in three-dimensional regular and disordered cubic architectures [36]. Motivated by these findings, we firstly analyzed the local effect of a single re-entrant inclusion into an otherwise regular honeycomb (Fig. 1B). We characterized the interplay between the strains in the inclusion and in the surrounding joints; we also explored the role of the local Young's modulus of the inclusion as well as of its closest environment (which we referred to as "interface" joints) on influencing the deformation behavior and hence the possible stiffening effect of the inclusion (Fig. 1C). A single inclusion can be considered as a punctual "defect" in the regular lattice: the mechanical characterization of the single "defect" was then used to guide the design of patterned structures, consisting of regular arrangements of re-entrant inclusions into a hexagonal honeycomb matrix (Fig. 1D). These architectured materials were then mechanically characterized by finite element simulations. Finally, we used multi-

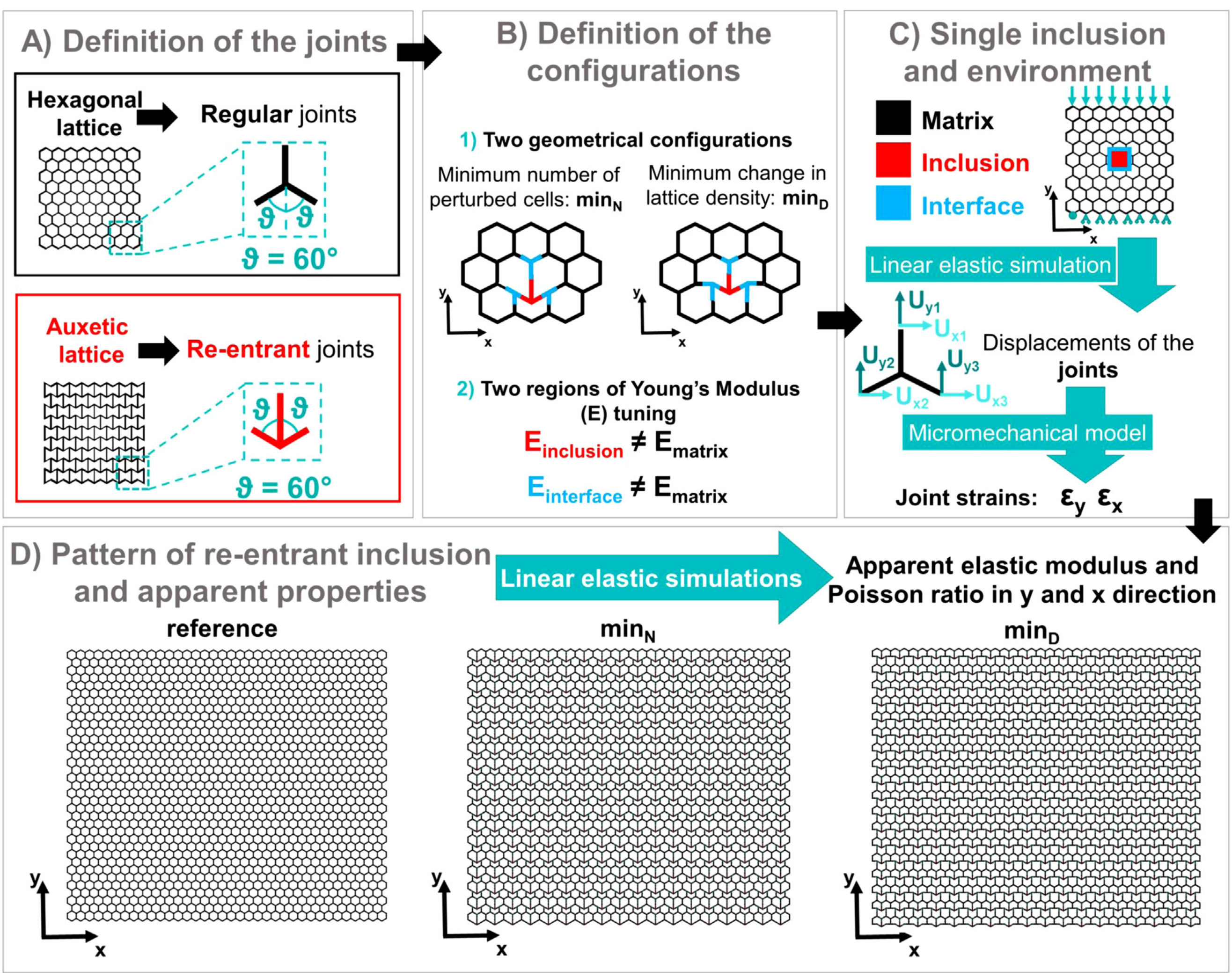

Fig. 1. Summary of the simulation workflow followed to design and to characterize cellular solids with re-entrant inclusions. (A) Starting from the definition of re-entrant and regular (hexagonal) joints, (B) a single re-entrant inclusion in a matrix with positive Poisson ratio was introduced according to two different geometrical configurations. The Young's modulus of the inclusion or of the first neighbor joints (named "interface") was tuned with respect to the Young's modulus of the remaining regular joints (named "matrix"). (C) The mechanical response of the lattice with a single inclusion acting as a defect was assessed simulating a vertical compression and then applying a micromechanical model to estimate inclusion strains. (D) The last step consisted in generating a regular pattern of inclusions and testing the enhancement in the mechanical behavior of the lattice.