
Mechanical characterization of architected materials with tunable disorder

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Abstract

Because of the relative simplicity of their design, ordered and periodic arrangements have been widely used for years to generate architected materials. However, the design space of metamaterials is virtually infinite and can go well beyond the standard non-stochastic arrangement. To allow designers to explore such a design space, its complexity must be mastered, and relations concerning how to correlate the material arrangement with its properties must be identified. Structures based on the periodic repetition of a single unit cell constitute the maximum level of complexity reduction, as the architected material's overall properties depend on the features of the single building block used to generate it (1). Throughout the years, the possibilities offered by a plethora of different unit cells have been explored, generating many design possibilities, all characterized by different parametrizations of the building blocks they are based on. Each has then been correlated with the set of properties that could be obtained by tuning their design parameters (2).

Despite the many possibilities offered by such an approach, in recent years, interest has been witnessed in developing architected materials whose design could go beyond the conventional repetition of a unit cell. Recent advances in generative Machine Learning (ML) technologies and computational design have provided powerful tools that can be coupled with designers' intuitions for obtaining unprecedented levels of accuracy in the correlation between geometrically complex design spaces and their relative properties (3). ML algorithms can manage structures whose intricacy goes well beyond that of ordered ones, which in nature only constitute a set of limited cases. ML algorithms can then be used to generate and study the properties of architected materials whose geometry is closer to those available in nature (4).

Recent studies in the field of irregular disordered geometries have highlighted the superior behavior exhibited by structures characterized by heterogeneous topologies. Similarly to naturally formed structures (such as trabecular bones, bird beaks, or turtle shells), irregularly architected materials exhibit isotropic behaviors and especially high resistance to the presence of local defects. These two properties are rarely witnessed with conventionally ordered metamaterials because of the strong correlation between the unit cell (and the direction of its periodic repetition) and the overall properties of the structures. It is then deemed fundamental that newer properties, closer or surpassing that of natural materials, are added to the repertoire of behaviors that can be obtained with metamaterials (5,6).

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Among the many design solutions for disordered architected materials developed throughout the years, one of the most used approaches is based on the employment of the Voronoi tessellations to generate truss-based structures. Studies on irregular Voronoi-based structures have shown that they can exhibit isotropic behaviors and that the impact of local defects on their mechanical responses is hindered by the irregularity of their geometry. This is why Voronoi tessellations were used to build an architected materials generation framework that could include both ordered and disordered designs to push the boundaries of the set of obtainable properties to include the largest amount of behaviors possible (5,7,8).

To obtain such a defined design space, the parametrization was based on controlling the degree of disorder of the structures. Starting from a perfectly ordered periodic distribution of the Voronoi tessellation seeds, a controlled and parametrized perturbation to the seeds' positions can be applied to generate irregular structures. Consequently, the perturbation level applied to the structures could be used as a parameter to allow continuous shifting from ordered to disordered designs. Other parameters are included in such a design framework. Control over other geometric features of the structures was also included to extend the number of tunable properties. Specifically, the possibility of replacing trusses with nonlinear beams was added to the framework. The pre-perturbation seeds' distribution was tuned with a geometric parameter. This way, the presence of non-convex cells was ensured, and the variability of generated geometries was broadened.

To assess the properties of the generated design space, the compressive behavior of a set of structures created using this approach was explored through finite element simulations and experimental tests performed first on 2.5 D structures. A direct correlation between the degree of disorder and the mechanical properties, such as stiffness and Poisson ratio, was obtained. As could be expected because of their similarity with natural structures, disordered ones also exhibit enhanced failure resistance under compression, mainly because of the deformation mechanism on irregular and non-convex cells. The shape and the connectivity of the cells proved to be highly relevant aspects that influence the failure of the structure.

The presentation will start by introducing the proposed design framework and will continue detailing the numerical and experimental results obtained on the 2.5 D structures. Finally, it will discuss the preliminary considerations performed on how this framework could be extended to allow the generation of 3D disordered structures.

Keywords Disordered structures, Mechanical metamaterials, 2.5D structures, Poisson's ratio

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