Discovery of damage tolerant quasi-disordered truss metamaterials inspired by natural cellular materials

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Natural cellular materials, such as marine mussels, honeycombs, woods, trabecular bones, plant parenchyma, sponges and protoreaster nodosus, have inspired the development of mechanical metamaterials with desired or extreme mechanical properties. These include various truss-like micro-lattices, i.e., truss mechanical metamaterials, at a scale ranging from nanometres to millimetres, manufactured using various additive manufacturing techniques. Truss metamaterials have provided unique opportunities to create lightweight structural components of high performance, such as lightweight sandwich structures [1,2]. In addition, truss metamaterials are highly tailorable and can be designed to meet various multifunctional requirements, such as simultaneous load bearing, active cooling, and noise reduction.

Up till now, the majority of the relevant research has focused on the truss mechanical metamaterials of highly ordered structures, i.e., the bulk metamaterial is formed by repeating a representative volume element (RVE) in the two-dimensional (2D) or the three-dimensional (3D) space. However, while nature-provided cellular materials resemble truss lattice structures of ordered, periodic arrangement, they are not perfectly periodic, and disorderliness has been observed in a wide range of natural cellular materials [3]. Natural cellular materials may benefit from the disorderliness within their internal microstructures to achieve damage tolerant behaviours. Inspired by this, we have created quasi-disordered truss metamaterials (QTMs) via introducing spatial coordinate perturbations or strut thickness variations to the perfect, periodic truss lattices. Numerical studies have suggested that the QTMs can exhibit either ductile, damage tolerant behaviours or sudden, catastrophic failure mode, depending on the distribution of the introduced disorderliness. A data-driven approach has been developed, combining deep-learning and global optimization algorithms, to tune the distribution of the disorderliness to achieve the damage tolerant QTM designs. A case study on the QTMs created from a periodic Face Centered Cubic (FCC) lattice has demonstrated that the optimized QTMs can achieve up to 100% increase in ductility at the expense of less than 5% stiffness and 8%–15% tensile strength. Our results suggest a novel design pathway for architected materials to improve damage tolerance.

References

[1] Liu, T., Deng, Z.C. and Lu, T.J., Design optimization of truss-cored sandwiches with homogenization. International Journal of Solids and Structures, 43(2006) 7891-7918.

[2] Liu, T., Deng, Z.C. and Lu, T.J., Bi-functional optimization of actively cooled, pressurized hollow sandwich cylinders with prismatic cores. Journal of the Mechanics and Physics of Solids, 55(2007) 2565-2602.

[3] van Egmond, D.A., Yu, B., Choukir, S., Fu, S., Singh, C.V., Hibbard, G. and Hatton, B.D., 2021. The benefits of structural disorder in natural cellular solids. arXiv preprint arXiv:2110.04607.