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Aperiodic Monotile Lattices: A Potential Pathway to Ductile, Tough, and Lightweight Metamaterials

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Abstract

The rapid evolution of additive manufacturing of lattice materials has opened new directions for tailoring mechanical properties through architectural design. In this work, we investigate aperiodic monotile lattices, which are single-shaped unit cells that tile a plane without periodicity. Aperiodic monotiles have been recently identified in the mathematical literature. We are exploring two features of aperiodic monotile lattices: (i) the variable node connectivity, determined as the number of struts emanating from a node, which concentrates material at critical locations and (ii) the global, rather than local, deformation characteristic which may distribute the deformation throughout the lattice, delaying crack nucleation and propagation. We designed a series of specimens as extruded 2-dimensional lattices with a constant relative density of 15% and identical strut thicknesses. We generated four geometries with varied unit cell geometry: a conventional hexagonal honeycomb, a Voronoi foam, and two aperiodic monotile lattice geometries with the 'arrow' and 'hat' unit cell geometries. All lattice specimens were 3D-printed via stereo-lithography (SLA). Quasi-static and cyclic loading compression tests were performed on a mechanical testing machine to capture their stress–strain behaviours and fatigue performance. High-resolution optical imagery was applied to capture the mechanical tests, tracking strut deformation, strut failure, and nodal rotation. We found that aperiodic monotile lattices exhibit a lower Young's modulus (by approx. 15 % relative to hexagonal honeycombs).

However, compared to a constant plateau stress which correlates to collapse band formation in hexagonal lattice, aperiodic monotile lattices show a distinct hardening, which is due to their more global deformation. Furthermore, we found that these lattices also exhibit stress-strain curves that are continuous without sharp stress drops which typically correlate with local strut failures. Strut failure was observed only at high macroscopic strains of approx. 50%. Node failure, which is typically the initiation site in conventional lattices, was largely suppressed in the aperiodic monotile geometries, probably due to redundant load paths that mitigate crack propagation. Cyclic tests reveal a reduction in hysteresis loss for aperiodic monotile specimens, suggesting enhanced resilience under cyclic mechanical loading. In conclusion, aperiodic monotile lattices may show a favourable trade-off between stiffness and ductility with a potentially increase of fracture toughness. Future work will explore a wider spectrum of monotile geometries, systematically varying relative density to map its effect on mechanical performance. Integrating aperiodic monotile architectures into composite systems could enable the next generation of more damage-tolerant components, for example, crash-resistant battery packs for electric vehicles.

Keywords:

lattices aperiodic monotiles rapid-prototyping compressive strength