Fracture of microarchitected solids and their anomalous toughness

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There has been an explosion in the development of light and strong mechanical metamaterials in the past decade [1-3] reporting extreme effective properties. As rapid progress in additive manufacturing and design methodology continues to proliferate these metamaterials, their application as structural materials is ultimately limited by their tolerance to damage and defects. While significant advances have been made in reporting extreme properties such as stiffness and strength, material properties that enable us to define the tolerance of metamaterials to defects as yet remain unclear. All work to-date has a-priori assumed (and without a-posteriori experimental validation) that a material property known as fracture toughness exists for these materials akin to usual continuum structural materials. In fact, all existing experimental measurements are based on metamaterial specimens comprising only dozens to at most a few hundred unit cells where the so called “K-field” required to define an effective toughness is not established. The material properties that govern the defect sensitivity of metamaterials thus remain largely unknown.

Via a combination of additive manufactured metamaterial samples with millions of unit cells printed by a large area high resolution additive manufacturing technique, a range of loading conditions and detailed in-situ X-ray tomography all combined with very large-scale numerical simulations (in excess of 100 billion degrees of freedom) we have uncovered [4] the elusive failure mechanics of mechanical metamaterials. We have demonstrated that (i) the property known as fracture toughness is insufficient to characterise fracture and (ii) standard fracture testing protocols, established over the last 50 years, are inappropriate for such materials. The outcome is succinctly summarised in a fracture mechanism map that fully characterises the fracture of three-dimensional metamaterials under arbitrary loading conditions.

Even more intriguingly, again using a combination of dynamic X-ray tomography coupled to finite element calculations we show that metamaterials made from a purely elastic parent material display rising R-curves. These rising R-curves are not a consequence of the usual crack ductility mechanisms such as crack tip plasticity or crack bridging but rather due to an inverse elastic strain gradient effect that seems to be unique to such metamaterials. We shall discuss these inverse elastic strain gradients effects and the consequent specimen size effects wherein continuum fracture properties are not realised in metamaterials until they exceed 10s of million-unit cells. Such specimens are not only unrealistic in terms of current testing/manufacturing capabilities but also in terms of most applications. We shall end with a discussion on the analogy between the anomalous toughening of the biological metamaterial, viz. trabecular bone and these artificial metamaterials.

References

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