The Fully-nonlocal Quasicontinuum Method: A Concurrent Multiscale Approach to Predict Fracture in Periodic 3D Metamaterials

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Given the ongoing up-scaling of manufacturing processes, the prediction of the robustness of the macroscale response of a fabricated structure in the presence of imperfections, e.g., pre-cracks, is crucial. While fracture of linear elastic continua is well-characterized by the toughness K_{IC}, recent studies suggest that this is not necessarily the case for 3D mechanical metamaterials, even in the linear regime [1]. It was shown that the fracture toughness is affected by not only the crack size but also the load triaxiality. They further showed that the effect of the triaxiality and the number of unit cells (UCs) over the crack flank can be captured via a single parameter, which is related to the T-stresses. These observations suggest that the commonly reported metamaterial scaling laws are insufficient to characterize fracture in 3D truss-based metamaterials. To investigate fracture in large manufacturable specimens that contain millions of periodically arranged UCs, continuum finite element simulations are too costly. Therefore, homogenization becomes the method of choice. However, classical hierarchical homogenization techniques rely on the assumption of a separation of scales. When the separation of scales brakes down, e.g., in the case of fracture mechanics, such techniques fail. Therefore, we present a concurrent multiscale technique, viz. a fully-nonlocal quasicontinuum (QC) multi-lattice formulation based on a conforming mesh. Our QC formulation is applied to trusses, whose struts are represented by linear elastic, geometrically nonlinear corotational beams. This setup captures significant nonlinearity and localization effects in fully-resolved regions, while efficiently approximating the remaining simulation domain through a coarse-graining technique. Coarse-graining is achieved by selecting representative UCs (RepUCs) and introducing geometric constraints based on interpolation, here exploiting finite-element interpolation. Previous studies showed that within coarse-grained regions the strain energy of bending-dominated lattices undergoing non-uniform deformation is overpredicted when using affine interpolation. The overprediction was shown to occur due to overconstraining the lattice by preventing bending without stretching of individual truss members [2]. Therefore, we extend the existing framework by introducing higher-order interpolation in the coarse-grained region, while using the simplicity of affine interpolation in the discrete, fully-resolved domain. In conclusion, we present an efficient multiscale framework to investigate fracture in periodic truss-based metamaterials. The method is equivalent to a fully-discrete calculation in certain regions, e.g., near the crack flank, where every UC is also a RepUC, but is significantly more efficient in coarse-grained regions. Results include the fracture toughness of a variety of stretching- and bending-dominated truss lattices.

References

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