Hierarchical Microstructure Controls Interface Failure Patterns

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Hierarchical materials are complex, multi-scale systems where structural patterns are repeated across scales in a self-similar fashion. Hierarchical microstructural patterns are often credited as determinant factors in the high fault tolerance of biological and bio-inspired materials. In problems of interface failure an example is the Geckos paw, where hierarchically structured fibers are believed to play a role in its strong adhesion behavior, which is maintained over many cycles of attachment and detachment [1]. In the broader context of fracture mechanics, the fact that hierarchical organization is integral to enhanced fracture toughness is now widely accepted [2].

Modeling hierarchical structures is naturally a multiscale problem, where stress redistribution and crack propagation must be accounted for at the different microstructural levels. To address this problem, discrete hierarchical lattice/network models have been used in recent years, where the network constituents are elastic load-carrying elements, subject to a failure criterion. Models of this type have helped show the mechanisms by which hierarchical materials induce localized patterns of stress redistribution, which result in the arrest of crack propagation, the emergence of diffuse damage, and the increase of fault tolerance. This behavior has been recently confirmed in experiments with hierarchically patterned semibrittle materials [3].

While most of the above results deal with bulk fracture, here we address the problem of interface adhesion and failure/detachment of hierarchical materials in contact with heterogeneous substrates. To this end, we introduce a three-dimensional hierarchical network model, where discrete links/elements fail based on a maximum distortion energy (von Mises) criterion with Weibull distributed thresholds, modeling inhomogeneities in local cohesive and adhesive strengths. Element elasticity is modeled both in terms of the scalar Random Fuse Model and of the tensorial Timoschenko beam theory.

We find that the hierarchical structure induces scale invariant detachment patterns, which in the limit of low interface disorder prevent interface failure by crack propagation ("detachment fronts") [4]. In the opposite limit of high interface disorder, hierarchical patterns ensure enhanced work of failure as compared to reference non-hierarchical structures.

Our statistical analysis of fracture surfaces indicates that the hierarchical organization is responsible for a substantial enhancement in the localization of damage near the interface, confirming the hypothesis that similar multi-layer fibrous or porous patterns are essential in the performance of bio-inspired reusable and reversible adhesives. We discuss the origin of this localization phenomenon using concepts of spectral graph theory and multiscaling analysis techniques. While our study of hierarchical fracture and failure is motivated by examples of fibrous materials of biological interest, our results indicate that hierarchical patterns can be useful in engineering scenarios where the focus is on tuning and optimizing adhesion properties.

References

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