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Generalized finite element method for bridging fine-scale heterogeneity to the structural scale

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ABSTRACT

Phenomena spanning multiple spatial scales and encompassing multiple physics disciplines of interest are prevalent in many modern engineering applications; structural or global failure is often caused by the onset of very local damage like cracks or shear bands. In the case of heterogeneous materials, damage evolution is governed by microstructural details that can be several orders of magnitude smaller than structural dimensions. The mathematical homogenization theory has been used extensively as a tool for analyzing multiscale response of heterogeneous materials. Available multiscale or homogenization-based schemes achieve coupling between scales of interest by the numerical solution of a macroscale boundary value problem using homogenized or upscaled properties from microscale problem solutions. However, a persistent limitation in these approaches is that the solution of the homogenized macroscale problem may misrepresent complex solution behavior in the vicinity of localized gradients or singularities due to structural loads or geometry. Understanding the true behavior of solution fields in these regions is necessary to quantify failure initiation and evolution, so the intrinsic coupling of material- and structural-level phenomena must be addressed. However, the fidelity required to capture physics at each scale is extraordinarily expensive under traditional analysis techniques. This study presents a Generalized Finite Element Method for the computational modeling of structures subjected to extremely localized thermo-structural loadings in the presence of material heterogeneity, a class of problems where homogenization-based approaches may be invalid. This method is based on the use of custom enrichment functions generated from the solution of fine-scale boundary value problems which can capture localized behavior due to material-scale effects on the coarse, structural scale via a partition of unity approach. This method experiences no restrictions on inter-compatibility and continuity among micro or local solutions, an issue which plagues many existing multiscale techniques. Furthermore, fine-scale problems are shown to be intrinsically and rapidly parallelizable. The method is demonstrated on several representative thermo-structural problems in order to examine its accuracy, efficiency, and flexibility.