# An adaptive hyper-reduced modeling framework for nonlinear failure analysis

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**ABSTRACT**

Fracture processes are often multiscale in nature. Macroscopic crack formation and propagation typically stems from the interaction between multiple nonlinear dissipative mechanisms taking place at a microscopic length scale. An increasingly popular approach is to resort to micromechanical and multiscale numerical analysis for predicting fracture. In such a micromodel, individual microscopic material components and their interfaces are modeled separately, allowing for specialized constitutive models to be used for each of them. The microscopic response can in turn be upscaled using multiscale techniques such as computational homogenization ($FE^2$).

However, this increase in analysis fidelity comes at the cost of reduced computational efficiency. A single $FE^2$ analysis, often with hundreds of embedded micromodels each featuring dense finite element meshes and complex material models, can easily have execution times in the order of weeks. Reduced-order modeling (ROM) techniques offer a potential approach to accelerate these micromodel computations. Constructing a reduced-order model consists in finding a surrogate solution space that is sufficiently accurate but has a significantly lower dimension than the original one. Finding this space is traditionally done through an *offline* training process in which the full model is executed for a set of representative load cases and the resulting solutions are compressed by machine learning algorithms.

Although these compressed models can be significantly faster than their full-order counterparts, correctly defining a training set can be a challenging task. For problems featuring strain localization or crack propagation, small changes in the loads applied to the micromodels lead to significant changes in failure behavior. Constructing a suitable reduced model would therefore require a very large training set, which in turn increases the dimension of the reduced solution space. Additionally, choosing the correct training cases often involves an arduous trial-and-error process that might lead to inaccurate compressed models.

In order to circumvent this issue, adaptive reduction techniques can be developed in order to eliminate the need for a training phase, perform the necessary reductions on the fly, and adaptively adjust the reduced solution space as the analysis progresses. In this work, the Proper Orthogonal Decomposition (POD) and Empirical Cubature Method (ECM) techniques are used to reduce the number of degrees of freedom of the problem and the number of integration point computations, respectively. The analysis starts with a fully-solved step and the two levels of model reduction are applied in steps: a POD-reduced model is first constructed and is followed by an ECM reduction phase. In order to improve the reduced solution, an equilibrium system partition is adopted in which mesh regions with highly nonlinear behavior are still solved in the full-order space. Solution accuracy is controlled by *online* error estimators and a domain-based reduced integration strategy. The framework is demonstrated with a number of numerical examples and its performance is assessed.