MODELING FRACTURE IN FUNCTIONALLY GRADED MATERIALS WITH PHASE-FIELD METHOD

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Abstract

Phase field fracture predictions in functionally graded plates are carried out using exponential finite element shape functions. The rule of mixtures is employed to estimate the material properties according to the volume fractions of the constituent materials, which have been varied according to given grading profiles. Crack propagation paths and load deflection behaviors are investigated in paradigmatic examples of single-edge notched plate specimens to gain insight into the crack growth resistance of FGMs by conducting numerical experiments over a wide range of material gradation profiles and orientations.

1. Introduction

Fracture in engineering practice is often a direct cause of loss of products, services, or in more extreme cases, life. Its prediction and prevention as well as increasing component lifetime, are still a major concern and, as such, an area of great interest to many engineers and researchers. The development of computational methods to describe damage evolution, fracture, and fatigue in materials has been investigated extensively over the past decades. Of the methods that allow for interesting crack growth patterns like kinking and branching, the phase-field method has received a great deal of attention recently [1]. The phase-field method replaces discrete crack surfaces with a diffuse zone of damaged material by representing the crack with an additional continuous field variable called the phase-field order parameter. The unique advantage which makes the phase-field method stand out from other methods is that numerical tracking of discontinuities is no longer required [2], and complicated crack phenomena, including initiation, propagation, merging, branching, and fragmentation, are successfully predicted by this method [3]. Functionally graded materials (FGMs) are multifunctional composites with spatially varying volume fractions of constituent materials. The resulting graded macro properties enable designers to tailor the microstructure to specific operating conditions while minimizing problems associated with discrete material interfaces. This paper presents a phase field formulation for fracture in FGMs using exponential finite element (EFE) shape functions [4]. The model builds upon homogenization theory and accounts for the spatial variation of elastic and fracture properties.

2. Methodology

Exponential finite element shape functions offer higher computational efficiency in phase field computations of fracture due to their exponential nature. Therefore, finer meshes are not required in the regions adjoining possible crack propagation paths in the finite element mesh. Sharp gradients in the phase field variable are captured by these shape functions with a relatively coarser mesh. However, since exponential shape functions are unsymmetrical in nature [4], they need to be oriented beforehand to obtain a good approximation of the phase field variable. An approximate analysis using bi-linear shape functions is employed in this study to orient the EFE shape functions properly. The stiffness and fracture resistance dependence inherent to FGMs is inferred from the spatial variation of the volume fractions of constituent materials via homogenization scheme. ABAQUS is used as the finite element software to solve the coupled system of equations of the phase-field model. The variation of elastic and fracture properties is defined at each integration point, rendering a so-called graded finite element implementation.

3. Results

Fracture predictions are made for functionally graded alumina/zirconia functionally graded single-edge notched plate specimens under different loading conditions. For instance, the geometry and boundary conditions of the plate under tension are shown in figure 1(a). Graded material properties are realized in the implementation by directly varying the material properties at each integration point according to the homogenization scheme. The gradation is governed by the value of the volume fraction exponent used in the volume fraction law, and the value is seen to affect the fracture predictions. The effects of mode mixity are observed by assuming material gradation in different directions, and its impact on fracture predictions is observed. The material properties assumed to vary along the gradation are Young's modulus E, Poisson's ratio ν, and fracture toughness Gc. The variation of Young's modulus along the direction of property gradation in Y axis is shown in figure 1(b).

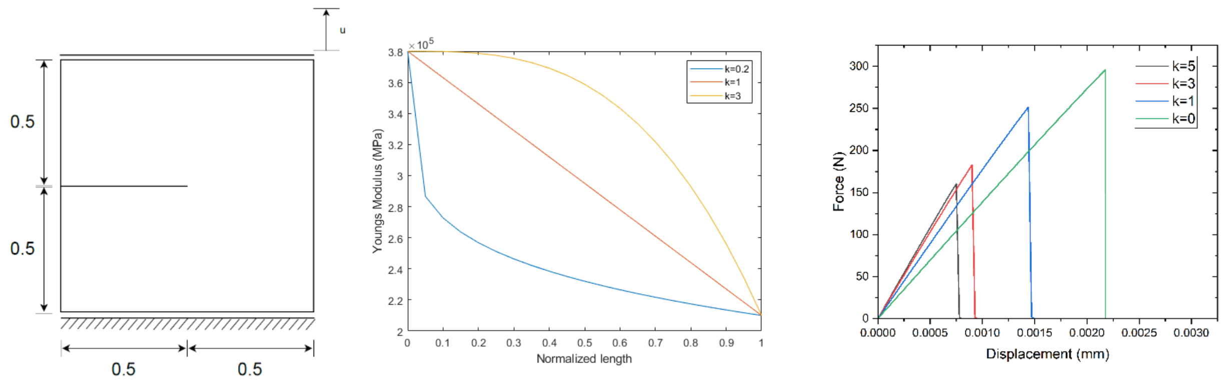

Fig.1 – (a) Geometry of single-edge notched plate under tension, (b) Variation of Young's modulus for material property gradation in the Y axis for three values of volume fraction exponent k, (c) Force displacement response of FGM plate with material gradation along the Y axis.

Figure 1(c) shows the force-displacement response of FGMs for material gradations of different volume fraction exponents. Homogenous responses corresponding to the constituent materials in the functionally graded mix are recovered for the bounding values of the volume fraction exponent in the material gradation law.

4. Conclusions

Fracture in functionally graded material plates is simulated numerically with the phase-field method by employing exponential finite element shape functions. The framework has the capability of naturally capturing the gradient in fracture resistance inherent to FGMs via a spatially varying critical energy release rate. Several paradigmatic examples are addressed to emphasize the method's potential in modeling the complex crack propagation paths that arise due to crack tip mode-mixity induced by the material property variation. Numerical predictions accurately reproduce experiments conducted in different types of functionally graded specimens and under a wide range of material gradient profiles. The results provide fundamental and quantitative insight into the role of the material property gradation on the crack propagation response.

References

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