A phase-field approach for modeling three-dimensional crack interactions in layered materials

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1. INTRODUCTION & OBJECTIVE

Detection and tracking of cracks are important in engineering analysis and design. High-fidelity finite element models can effectively predict the conditions under which fractures initiate and propagate and guide engineering decisions. Although several such models have been developed over the years, a reliable fracture simulator for three-dimensional applications remains elusive. Several existing models are two-dimensional and are, therefore, unable to simulate non-planar failure surfaces. Additionally, simulating crack interactions like coalescence and branching is challenging, even in two-dimensional models. However, in heterogeneous material systems, complex crack interactions and non-planar failure surfaces are frequently observed[1-4]. As such, it is necessary to develop a method that can capture the behavior of closely interacting cracks in three dimensions (3D) to predict the failure behavior of such materials accurately.

Recently, the phase-field method has gained popularity for modeling brittle fractures, as it can seamlessly handle complex crack interactions. The phase-field method considers damage as a smeared zone in the continuum with degraded mechanical stiffness. In addition to displacements, damage is solved as a nodal field, and the damaged regions are directly identified based on the nodal values of damage. Therefore, explicit tracking of cracks is no longer necessary in these methods. Furthermore, fracture propagation is recast as an energy minimization problem such that no additional crack propagation criteria are required. However, accurate resolution of the smeared zone of damage is necessary, which makes these methods computationally intensive. Although some attempts are made to incorporate mesh-adaptivity and reduce their computational burden, applications of the phase-field approach to fully three-dimensional problems are limited due to their high computational cost.

This study aims to develop a three-dimensional phase-field framework for simulating fracture propagation under purely mechanical loading. We implement the phase-field method in 3D using a C++ finite element library, deal.ii[5]. The deal.ii library allows better performance in computational cost and memory management, making it suitable for large-scale problems. We conduct various parametric studies in 3D to investigate the influence of relative fracture orientations (interactions), mismatch in mechanical properties, and in-situ stress contrast on fracture propagation in heterogeneous material systems.

2. EFFECT OF NOTCH INCLINATION ON THE INTERACTION BETWEEN MULTIPLE FRACTURES

This section investigates the influence of notch inclination on fracture propagation in a 3D specimen under a biaxial loading state. The specimen comprises four notches, with two of them horizontally placed and the other two inclined at various angles ($\boldsymbol{\theta}$) with respect to the vertical axis (Figure 1).

The simulation results (Figure 2) demonstrate that although the fracture propagation from the notches begins at approximately the same loading in all cases, the vertical fractures experience a greater resistance as the inclination of the notches increases. This behavior can be explained by considering the relationship between the principal loading direction and the normal to the fracture plane. With increasing notch inclination, the angle between the principal loading direction and the normal to the fracture plane also increases. Consequently, the cracks require more twisting to align their normals with the principal loading direction, leading to enhanced ductility of the specimen.

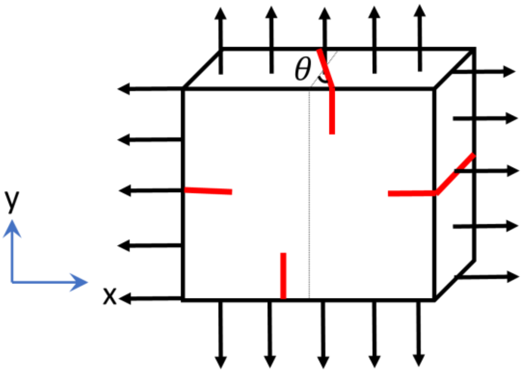

Figure 1. Problem setup.

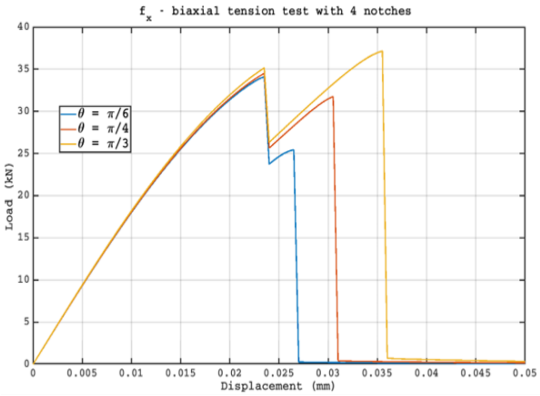

Figure 2. Load-displacement curve.

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