Investigation of a Finite Strain Phase Field Model for Ductile Fracture under Multi-Axial Stress States

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Introduction

Ductile fracture in elastoplastic solids starts at the micro-level where nucleation of small defects concentrated mostly in regions with large plastic deformations, initiates the crack. Micro-voids grow and coalesce into larger voids, and consequently realize their effects at the macro-scale by degrading the stiffness of the body. In addition to the plastic deformation, the mechanism of micro-void growth is influenced heavily by the multi-axis stress state experienced by the material. Many studies highlighted the influence of the hydrostatic stress on the ductile behavior of metals through either theoretical studies or experiments [2,3].

Phase field fracture modeling

The phase field approach to fracture, a smeared crack modeling technique, has gained significant attention in the past years. In this approach, the propagation of a crack surface is tracked implicitly through the evolution of an order parameter (the crack phase field $\phi$), which transitions smoothly between intact ($\phi = 0$) and fully cracked ($\phi = 1$) material points.

Fracture under multi-axis stress state

For brittle fracture, $G_c$ is commonly taken as a constant material parameter. On the other hand, in this work for ductile fracture, we assume that $G_c$ degrades depending on the loading condition and the state of stress and strain experienced by a material point. We propose a fracture toughness degradation function $F$, governing the evolution of $G_c$, of the form $G_c = F(\phi)G^0_c$ as a material parameter showing the initial crack resistance. We incorporate the Stress-Weighted Ductile Fracture Model (SWDFM) [1], and propose a fracture degradation function of the form

$$F = (1 - \alpha)(1 - D_{SWDFM})^\nu + F_{\alpha}$$

with $F_{\alpha}$ as a residual value of fracture toughness. In this equation, the damage quantity $D_{SWDFM}$ is defined as

$$D_{SWDFM} = C \int \left(1 - \alpha \right) \left(1 - \beta \right) \left(1 - \gamma \right) \left(1 - \zeta \right) \alpha \left(1 - \sigma \right) \text{d}V.$$  

Therein, parameters $C, \beta, \gamma$, and $\zeta$ are material constants calibrated based on experimental results, $\alpha$ is the internal plastic variable, $\beta$ is the stress triaxiality, and $\zeta$ is the Lode angle parameter.

This coupling with the SWDFM has the advantage that through degradation of the fracture toughness, damage concentrates in regions with high values of $D_{SWDFM}$ which takes into account plastic deformation, as well as stress triaxiality and the Lode angle parameter. With that, evolution of damage is related to stress-strain history of the material.

Results

We validate the proposed framework using a numerical study of experimental tests, considering various levels of stress triaxiality and the Lode angle parameter. Fig. 3 schematically presents the levels of stress triaxiality, and values of the Lode angle parameter at the location of crack initiation for different experimental tests. In particular, load-displacement curves for the Cylindrical Notched Tension (CNT) test and Blunt Notch (BN) test are shown in Fig. 4.

Conclusion

The proposed framework assumes a close connection between the stress-strain history of the material and the evolution of damage. To account for various multi-axis stress states, the degradation of the fracture toughness is coupled with the Stress-Weighted Ductile Fracture Model (SWDFM), which allows for accurate prediction of fracture initiation and advancement in elastoplastic solids. The capabilities of the proposed method were validated in a numerical study covering a wide range of stress and strain states.

References