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Doctoral Thesis Outline

Title: Smoothing Gradient Damage Modeling in Brittle/Quasi-brittle Fracture: Algorithms and Applications
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The thesis, entitled "Smoothing Gradient Damage Modeling in Brittle/Quasi-brittle Fracture: Algorithms and Applications”, consists of nine chapters, written in English. Analysis of fracture behavior of brittle and quasi-brittle materials such as concrete, ceramics, and rock is important for the design and maintenance of civil engineering structures. Among the many fracture analysis methods, the smoothed gradient damage method (SGDM) has attracted much attention as an element-independent analysis method that can appropriately represent damage bandwidths by incorporating anisotropy and nonlocality of strain. In this study, SGDM has been further improved and extended to analyze various failure problems.

In Chapter 1, existing damage approaches for the simulation of localized failure problems in quasi-brittle/ brittle materials are presented. The objectives of the doctoral research and the goals of the dissertation are introduced. From Chapter 3 to Chapter 8, six fracture problems are presented and resolved by developing efficient damage models based on the smoothing gradient-enhanced damage model. In these chapters, the results of several numerical tests are shown and evaluated to prove the efficiency of the proposed technique and analyze the interested fracture phenomena.

In Chapter 2, the fundamental formulations of the local, gradient-enhanced damage model and SGDM are presented. In particular, the smoothing technique is detailed. From the basic concept of SGDM, which can give mesh-independent solutions and enable the usage of the same low-order elements for approximation of displacements and nonlocal equivalent strain, significant developments can be made to capture various fracture problems, which are described in the following chapters.

Chapter 3 addresses the extension of the SGDM to the mixed-mode fracture issue, which is commonly included in both mode-I and -II of failure. The feasible method to tackle this combination of damage is utilizing an equivalent strain definition that accounts for the tension and the shear characteristics of the strain tensor. Generally, the intention is not to replace any existing techniques for estimating the equivalent strain but offering another possible choice based on Ottosen's failure criterion, which is integrated into SGDM in the form of four-parameter equivalent strain formulation, and thus reasonable results of mixed-mode fracture in quasi-brittle materials are obtained. The novel aspect of this work is to present a simple computational scalar damage approach for studying the complicated mixed-mode problem. Applications show that the new evaluation technique of the equivalent strain helps improve the capability of the smoothing gradient damage model in modeling mixed-mode fracture.

Chapter 4 focuses on a dynamic description of the smoothing gradient-enhanced damage model. The dynamic behaviors of structures at low and high loading rates are explained in this chapter. To capture well dynamic structural response, two effective rate-dependent damage laws are introduced to consider the inertia effects of the dynamic regime and enhance the capability of the adopted approach in modeling dynamic fracture and crack branching. More specifically, the two rate-dependent damage laws are utilized to specify the dynamic tensile strength, and then the dynamic initial damage threshold can be calculated. The most suitable rate law for dynamic analysis at low and high loading rates is selected through numerical investigations. Equivalent strains, which can deal with the mixed-mode problem, are also evaluated so that the developed damage model can be utilized to analyze the complex stress state at high loading rates. Static and dynamic numerical tests are conducted to verify the precision of proposed approaches.

Chapter 5 presents a novel gradient-enhanced damage model named ASGDM, which accounts for directional-dependent damage evolution in two-dimensional brittle materials. In particular, unidirectional fiber-reinforced composites and polycrystalline materials are considered. As inspired by the anisotropic phase-field models using a second-order structural, this chapter also presents a simple computational damage scheme based on the SGDM, in which the isotropic damage evolution law is redefined by introducing the second-order structural tensor, aiming at driving the directional-dependent fracture properties. This structural tensor restrains the crack growth in the direction of the predefined fracture plane. In other words, this improvement results in the ability to dictate the crack orientation with fiber plane directions defined in advance. The cleavage fracture and transgranular fracture of anisotropic materials, e.g., polycrystalline, can be captured. It is highlighted that the new definition utilizes solely a scalar damage variable, in contrast to most other existing gradient damage models that usually employ damage tensors or higher-order gradient terms. Furthermore, as inspired by the elegant features of the staggered scheme in phase-field models, a simple staggered method is thus presented to solve a coupled system of equations in the context of the developed ASGDM for directional-dependent fracture analysis. In contrast to the usual monolithic solver scheme for coupled problems, the staggered calculation scheme solves the governing equations in a decoupled manner. In this sense, the staggered approach demands a large number of calculation steps but reduces the derivative terms and simplifies the coupled matrix.

Chapter 6 presents two additional relations associated with the tensile strength of grain boundary and bulk material into ASGDM to account for the interface fracture. These two relations are regarded as the fracture energy distribution and misorientation functions. The main idea is that the tensile strengths at interface regions and within grains are different and can be distributed smoothly through suitable relations. When tensile strength at each material point is specified, the threshold of strain softening is also determined, and the material deterioration at calculated points can be described precisely.

Chapter 7 analyzes the failure process in pre-cracked rock specimens. To enhance the ability to capture the mixed-mode rock fracture, a novel equivalent strain is developed. In general, the four-parameter equivalent strain and the bi-energy norm equivalent strain are combined to exploit all the good features of both equivalent strains. Moreover, the staggered scheme in Chapter 5 is also applied to simplify the algorithm and the specification of complicated parameters in four-parameter equivalent strain formulation.

In Chapter 8, The smoothing gradient-enhanced damage model is extended to thermo-mechanical fracture problems by coupling the governing equation, i.e., the equilibrium and evolution equations, with the heat conduction equation for steady state and transient heat transfer cases. In particular, the damage variable is embedded into the heat balance equation to capture the adiabatic characteristic of the fracture process zone. Many numerical benchmark tests from experimental and numerical contributions are numerically performed to evaluate the accuracy and efficiency of the developed gradient-enhanced damage model. The main target is to capture the failure process with all the considered thermal fracture phenomena.

The final chapter 9 summarizes achievements and future works.