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Procedia IUTAM 10 (2014) 125 – 137

Procedia IUTAM

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23rd International Congress of Theoretical and Applied Mechanics

Evolving discontinuities and cohesive fracture

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Abstract

Multi-scale methods provide a new paradigm in many branches of sciences, including applied mechanics. However, at lower scales continuum mechanics can become less applicable, and more phenomena enter which involve discontinuities. The two main approaches to the modelling of discontinuities are briefly reviewed, followed by an in-depth discussion of cohesive models for fracture. In this discussion emphasis is put on a novel approach to incorporate triaxiality into cohesive-zone models, which enables for instance the modelling of crazing in polymers, or of splitting cracks in shear-critical concrete beams. This is followed by a discussion on the representation of cohesive crack models in a continuum format, where phase-field models seem promising.

Selection and/or peer-review under responsibility of the Organizing Committee of The 23rd International Congress of Theoretical and Applied Mechanics, ICTAM2012

Keywords: multi-scale methods, discontinuities, fracture, cohesive surfaces, phase-field models

1. Introduction

The demand for new or improved materials has been one of the driving forces behind the development of multiscale techniques. This class of methods aims at understanding the material behaviour at a lower level of observation, and can be a major tool for developing new materials.

When considering materials at a lower length scale, the classical concept of a continuum gradually fades away. At the macroscopic level we have to take into account evolving or moving discontinuities like cracks, shear bands, Lüders bands and Portevin-Le Chatelier bands, but at a lower level we also encounter grain boundaries in crystalline materials, solid-solid phase boundaries as in austenite-martensite transformations [1], and discrete dislocations [2]. Thus, the proper modelling of discontinuities has a growing importance in material science. Classical discretisation methods are not well amenable to capturing discontinuities. Accordingly, next to multiscale modelling, the proper capturing of discontinuities is a major challenge in contemporary computational mechanics of materials.

In this contribution we focus on the capturing of discontinuities. Basically, two methods exist to handle them. One either distributes them over a finite distance, or handles them as true discontinuities. The first method has been a subject of much research in the past two decades. It will be discussed briefly at the beginning of this paper, and we will come back to a continuum approach within the context of phase-field

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Selection and/or peer-review under responsibility of the Organizing Committee of The 23rd International Congress of Theoretical and Applied Mechanics, ICTAM2012
doi:10.1016/j.piutam.2014.01.014

methods at the end of this paper. A major part of this paper focuses on an enhancement of the cohesive-surface model for fracture to incorporate triaxiality effects.

2. Discrete vs. continuum representations of fracture

When scaling down, discontinuities arise which need to be modelled in an explicit manner. When the discontinuity has a stationary character, such as in grain boundaries, this is fairly straightforward, since it is possible to adapt the discretisation such that the discontinuity, either in displacements or in displacement gradients, is modelled explicitly. An evolving or moving discontinuity, however, is more difficult to handle. A possibility is to adapt the mesh upon every change in the topology, as was done by Ingraffea and co-workers in the context of linear elastic fracture mechanics [3], and later by Camacho and Ortiz [4] for cohesive fracture.

Another approach is to model fracture within the framework of continuum mechanics. A fundamental problem is then that standard continuum models do not furnish a length scale which is indispensible for describing fracture, or, more precisely, they result in a zero length scale. Since the energy dissipated in the failure process is given per unit area of material that has completely degraded, and since a vanishing internal length scale implies that the volume in which failure occurs goes to zero, the energy dissipated in the failure process also tends to zero. Two approaches have been followed to avoid this physically unrealistic situation, namely via discretisation and via regularisation of the continuum, see Fig. 1.

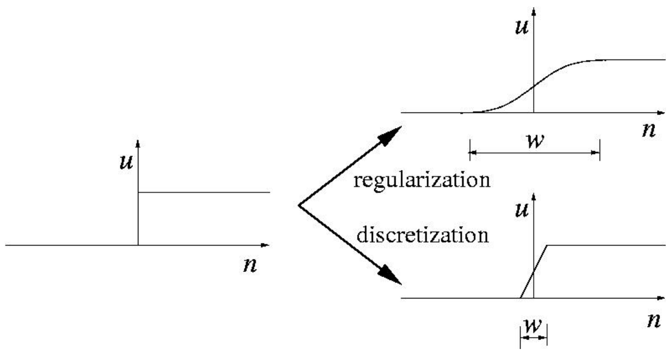

Fig. 1. Application of regularisation and discretisation methods to a discontinuity

In the first approach, researchers have let the spacing of the discretisation take over the role of the missing internal length scale, so that the discontinuity in the left part of Fig. 1 is replaced by a displacement distribution as in the right-lower part of this figure, where w is the spacing of the discretisation. The idea is then to choose the discretisation such that the spacing of the discretisation coincides with the internal length scale that derives from the physics of the process. Evidently, a good knowledge of the problem is required and solutions, including the proper choice for the discretisation, are problem-dependent. Nevertheless, this approach has been used successfully to obtain insight in various issues in materials science [5].

Yet, this approach can not be called a proper solution in the sense that the mathematical setting of the initial value problem remains unchanged. Indeed, the introduction of degradation of the material properties in a standard, rate-independent continuum model–and therefore, the introduction of a stress–strain curve with a descending slope–can locally cause the governing differential equations to change character. Without special provisions such as the application of special interface conditions between both domains at which different types of differential equations hold, the initial value problem becomes ill-posed. Numerically, this has the consequence that the solution becomes fully dependent upon the discretisation [6, 7]. An example is shown in Figs. 2 and 3. It concerns a bar composed of a porous, fluid-saturated material that is loaded by an impulse load at the left end. Upon reflection at the right boundary, the stress intensity doubles and the stress in the solid exceeds the yield strength and enters a linear descending branch, Fig. 2. The results are shown in Fig. 3 in terms of the strain profile along the bar at discrete time intervals. It is observed that