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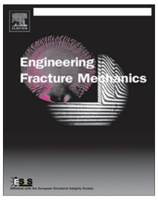

On the use of finite elements with a high aspect ratio for modeling cracks in quasi-brittle materials

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ABSTRACT

A new technique for modeling cracks in quasi-brittle materials based on the use of interface solid finite elements is presented. This strategy named *mesh fragmentation technique* consists in introducing sets of standard low-order solid finite elements with a high aspect ratio in between regular (or bulk) elements of the mesh to fill the very thin gaps left by the mesh fragmentation procedure. The conception of this strategy is supported by the fact that, as the aspect ratio of a standard low-order solid finite element increases, the element strains also increase, approaching the same kinematics as the Continuum Strong Discontinuity Approach. As a consequence, the analyses can be performed integrally in the context of the continuum mechanics, and complex crack patterns can be simulated without the need of tracking algorithms. A tension damage constitutive relation between stresses and strains is proposed to describe crack formation and propagation. This constitutive model is integrated using an implicit–explicit integration scheme to avoid convergence drawbacks, commonly found in problems involving discontinuities. 2D and 3D numerical analyses are performed to show the applicability of the presented technique. Relevant aspects such as the influence of the thickness of the interface elements and mesh objectivity are investigated. The results show that the technique is able to predict satisfactorily the behavior of structural members involving different crack patterns, including multiple cracks, without significant mesh dependency provided that unstructured meshes are used.

1. Introduction

Although a large number of numerical models are available in literature for modeling cracks in quasi-brittle materials (e.g. concrete and rocks), each one with their own advantages and limitations, this topic is still a challenge, mainly when numerical simulations of multiple cracks in 3D analysis is desirable.

In the context of the Finite Element Method (FEM), the available models can be usually classified into the “smeared crack model” or the “discrete crack model”. Both approaches were introduced for modeling cracks in concrete in the late 1960s, the

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Nomenclature

$n,\ s,\ t$	components of the local Cartesian cordinate system
$\mathbf{n}$	unit vector – normal to the interface FE
h	height (thickness) of the interface FE
$\mathbf{B}$	strain–displacement matrix
$\mathbf{t}$	interface stresses
$\mathbf{d}$	nodal displacement vector
$d,\ \tilde{d}$	scalar damage variables
f_t	material tensile strength
A	area of the base of the tetrahedron FE
$q,\ r$	stress and strain-like internal variables
G_f	fracture energy
$\mathbf{x}^{(i)}$	vector that collects the coordinates of the node (i)
$x_n^{(i)},\ x_s^{(i)},\ x_t^{(i)}$	coordinates of the node (i)
$u_n^{(i)},\ u_s^{(i)},\ u_t^{(i)}$	displacement components of the node (i)
$[\![\mathbf{u}]\!]$	relative displacement between the node (1) and its projection on the element base (1′)
$[\![u]\!]_n,\ [\![u]\!]_s,\ [\![u]\!]_t$	components of the relative displacement
$\mathbb{C}$	fourth order elastic tensor
$\tilde{\mathbb{C}}^{tan}$	algorithmic tangent operator
E	Young's modulus
ν	Poisson's ratio
$\boldsymbol{\varepsilon}$	strain tensor
$\tilde{\boldsymbol{\varepsilon}},\ \hat{\boldsymbol{\varepsilon}}$	components of the strain tensor
$\boldsymbol{\sigma},\ \bar{\boldsymbol{\sigma}}$	nominal and effective stress tensors
$\sigma_{nn},\ \bar{\sigma}_{nn}$	nominal and effective stress components normal to the base of the interface FE
$\phi,\ \bar{\phi}$	damage criterion functions
$\bar{\tau}$	equivalent effective stress
$\mathscr{A}$	softening parameter

former by Rashid [1] and the latter by Ngo and Scordelis [2]. Basic characteristics of both models and a comparison between them can be found in [3–5].

In the smeared crack model, a fixed Finite Element (FE) mesh is used and the effects of the cracks are incorporated into the constitutive model (stress–strain relation) adopted to describe the material, which is usually nonlinear with a softening regime after the failure (maximum) criterion is reached. This approach is also known as a continuum type representation and the crack zone is considered to be distributed in a certain strain localization (continuum) region of the solid. Models of this class can be formulated using fixed or rotating crack approaches [6–8,4,9]. It is known that the main drawback of standard smeared crack formulations is the mesh sensitivity. To remedy problems of mesh size dependency presented by the models of this class, several regularization procedures have been proposed [10]. Some research papers [11,12] have proposed fracture mechanics concepts that lead to fracture energy release regularization. However, the loss of objectivity associated with the deformation pattern is still observed. Other strategies for dealing with the mesh dependency problem have been addressed using non-local models [13,14] and gradient-enhanced approaches [15].

Discrete models, also referred to as discontinuous models by some authors, are characterized by the introduction of displacement or strain discontinuities into standard finite elements to represent cracks. In general, these methods can be divided into two groups, defined by the location of the displacement discontinuities. Hence, one group gathers the approaches where cracks are embedded into existing bulk finite elements [16–20], and in the other group are the approaches with interface elements in which the cracks are expected between standard bulk finite elements [21–26]. A combination of the two groups is proposed by Radulovic et al. [27]. Models of the former group are usually derived using a nodal-based formulation (e.g. eXtended Finite Element Method – X-FEM) [20,28–30] or element-based formulation (e.g. Strong Discontinuity Approach – SDA) [31,17,32,18,33,34]. A comparative study of these approaches is presented by Oliver et al. [35]. Both methods require techniques to track the crack path during the analysis in order to provide information about the position of the crack surfaces for the discontinuous kinematic enrichment. These techniques are relatively simple to represent few cracks in 2D analyses, but can be very complex and even unsuitable for problems involving multiple crack surfaces in 3D analyses [36–38]. In the X-FEM, the level set method introduced by Osher and Sethian [39] has been used to track cracks.

The necessity of crack tracking schemes can be avoided by using discrete approaches based on the use of interface elements (with a zero thickness, e.g. [21–23,40–44]). In this approach the kinematics of a crack is described by a displacement discontinuity (crack opening width) and a cohesive law is used to describe the material degradation. The use of this kind of approach allows complex crack patterns (crack branching, intersecting cracks and fragmentation) to be simulated automatically.