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Modelling of failure in long fibres reinforced composites by X-FEM and cohesive zone model

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ABSTRACT

Crack nucleation and growth in long Fibre Reinforced Composites (FRC) are investigated using the extended finite element method (XFEM) and the cohesive zone model. This makes it possible to model cracks within a finite element without the requirement of either remeshing or aligning the mesh with the interface. The level-set concept is used to localise the fibre/matrix interfaces and to perform the enrichment. The jump in deformation, at the interface, is enriched by an absolute function and the jump in displacement is enriched by a Heaviside function. The problem is discretized by means of two-dimensional finite elements in the plane strain framework and the fibres are considered as perfectly bonded to the matrix. The transition between perfectly bonded interface and debonded interface is governed by a cohesive zone model. The obtained results were compared to the existing analytical results and then extended to more complex FRC configurations. It was found that the proposed approach is accurate and sensitive to the interaction between fibres. As a result, the crack is correctly and quite easily tracked.

1. Introduction

Fibre Reinforced Composites (FRC) show very complex failure mechanisms resulting on the one hand from the material brittleness of both constituents, the fibres and the matrix, and on the other hand from their interface behaviour. This makes it very difficult to reveal damage mechanisms from mechanical tests. Therefore, it is necessary to conduct reliable simulations to understand these complex phenomena in order to improve the mechanical properties. This typical damage can be represented in a numerical model by means of smeared crack models, where the discrete crack opening is represented by strain concentrations [1]. A second possibility is to explicitly consider the crack in the numerical model [2,3]. Traditionally, crack growth in FRC is simulated through pre-computed solutions which are only applicable for pre-defined geometries, which vastly simplify the complex stress state actually present around the crack fronts, generally leading to over-conservatism. These simplified techniques are gradually being superseded by a range of numerical methods with various degrees of simplification, most commonly based on the popular Finite Element Method (FEM). In [4], the FEM is associated with the technique of the unit cell to develop a micromechanical model for the local damage evolution and the global stiffness reduction of randomly distributed fibres composite. A Voronoi cell FEM is proposed in [5] to simulate debonding cracks in FRC. FEM was associated with the cohesive model in [6] to analyse the interactions between fibres in debonding growth process. Another alternative method to model interface damage consists of incorporating the interface law into a FEM formulation using zero-thickness interface elements. These embedded finite elements have a constitutive equation linking the relative displacement to the traction across the interface but this causes mesh dependence of the results. However, these FEM-based solutions are cumbersome to set-up, computationally intensive and notoriously lack robustness, leading to costly user intervention and lack of confidence in attempting realistic simulations. This is because traditional simulation methods, such as the FEM are not well adapted to modelling crack growth due to the rapid spatial variation of stress ahead of the crack tip, and the requirement that the mesh conform to the crack faces. The combination of these two limitations requires the FEM to regenerate fine meshes (re-meshing) at each crack growth step. Thus, most algorithms rely on a remeshing approach. Even when a mesh can be generated, the elements are often distorted which can cause the next crack advance step to abort. Moreover, the very large number of elements required around the crack front increases the computational time prohibitively.

The extended finite element method (XFEM) ([7,8]) addresses these drawbacks, enhances accuracy and offers an elegant tool to model cracks within a finite element without requiring remeshing. Indeed, XFEM is a versatile tool for the analysis of problems characterised by discontinuities, singularities and complex geometries [8], without requiring the mesh to conform to these boundaries. XFEM

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uses the concept of partition of unity [9] and the standard Galerkin procedure. The method was originally presented in [10] for enriching FEM approximations and to solve crack growth problems with minimal remeshing. Later on, Moës et al. [11] introduced a more elegant approach by adapting an enrichment that includes the asymptotic near tip field and a Heaviside function $H(x)$. Sukumar et al. [12] extended the concept to the three-dimensional static crack modelling. Since these pioneering works, XFEM has been applied to many kinds of problems such as crack and crack nucleation [13–15]; modelling of inclusions, holes and material interfaces [16]; failure analysis of micro-structured materials like functionally graded materials [17]; modelling of material interfaces such as an elastic bi-material interface cracks problem [16]; simulation of crack growth in layered composite structures, with particular emphasis on XFEM's capability in predicting the crack path in near-interfacial fracture [12,18]. More recently, XFEM has been extended [19] to the case of crack growth involving a cohesive law on the crack faces, then sophisticated numerical methodologies have been introduced to simulate cohesive crack propagation [14].

Globally, numerical simulations are of interest in dealing with complex geometries and inhomogeneous media [20–22]. Analytical [23–26] and numerical [6,27,28] models were developed earlier to characterise the growth of debonding crack. Experimental validations have also been performed on single fibre reinforced matrix [29–31] to cite only few.

This paper illustrates the application of XFEM and the cohesive model to simulate the fibre/matrix debonding growth. The level-set function is used to localise the position of the fibres within the matrix, to enrich the weak discontinuity along the interfaces and to enrich the strong discontinuity where the cracks occur. Crack nucleation and growth, along the fibre/matrix interfaces are simulated and analysed.

The paper is arranged as follows: first, the XFEM is briefly reviewed and adapted to the context of FRCs. Then, the discretization of the governing equations is reported and the non-linear problem solving procedure is given. The experimental tensile tests on [90×] composite are described and the results are presented. Finally, the numerical results are discussed.

2. Extended finite element method (XFEM)

The essential idea in XFEM is to add discontinuous enrichment functions to the finite element approximation using the partition of unity [11]. With regard to the problem analysed in this paper, the displacement approximation can be composed of three parts: the continuous contribution, the displacement jump through the crack and the displacement gradient jump at the fibre/matrix interface.

$$\mathbf{u}^h(\mathbf{x}) = \sum_{i\in N_u} N_i\ \mathbf{u}_i + \sum_{i\in N_a} N_i\ H_i(\mathbf{x})\mathbf{a}_i + \sum_{i\in N_b} N_i\ G(\mathbf{x})\mathbf{b}_i \tag{1}$$

$\mathbf{x}$ is the coordinates vector, $\mathbf{u}^h$ is the approximated displacement and N_i stand for the standard shape functions. N_a and N_b are the sets of enriched nodes and N_u represents the total number of nodes within the domain Ω. $\mathbf{u}_i$ represent the nodal displacement, H_i is the displacement enrichment function in the vicinity of cracks and G is the displacement enrichment function in the vicinity of interfaces, $\mathbf{a}_i$, $\mathbf{b}_i$ are additional degrees of freedom.

In this paper, the displacement enrichment function H_i is represented by the sign of the level-set function. The absolute function of the level-set function [32] is used as enrichment function G at the interface. Bear in mind that the branch enrichment function at the crack tip is not considered since the crack tip singularity vanishes in the presence of the cohesive model. Cracks are characterised by a discontinuous displacement field. Thus, the modified Heaviside function is given as:

$$sign(\mathbf{x}) = \begin{cases} +1 & if\ \ \mathbf{n}\cdot(\mathbf{x}-\mathbf{x}_{\Gamma_c}) > 0 \\ -1 & if\ \ \mathbf{n}\cdot(\mathbf{x}-\mathbf{x}_{\Gamma_c}) < 0 \end{cases} \tag{2}$$

where $\mathbf{x}_{\Gamma_c}$ are the coordinates of the node projection at the interface and $\mathbf{n}$ is the outward normal vector at that point. Since a cohesive model is used for the tractions across the crack, the stress field in the vicinity of the crack tip does not have singularity. Furthermore, this enables the interpolation to represent singular stress fields as assumed in linear elastic fracture mechanics. The zero-level ($\phi(\mathbf{x}) = 0$) is used to represent the fibre/matrix interfaces. $\phi(\mathbf{x})$ is given as:

$$\phi(\mathbf{x}) = sign(\mathbf{x})\cdot dist(\mathbf{x}) \tag{3}$$

$dist(\mathbf{x})$ is defined as the closest distance from a given point to the interface such as $dist(\mathbf{x}) = min\|\mathbf{x}-\mathbf{x}_{\Gamma_c}\|$. In order to avoid getting blending element region near the enriched elements, the enrichment function H_i in Eq. (1) is introduced as the sign of the shifted level-set as:

$$H_i(\mathbf{x}) = sign(\phi(\mathbf{x})) - sign(\phi(\mathbf{x}_i)) \tag{4}$$

Near the fibre/matrix interfaces, the modified enrichment function is used as in [32]

$$G(\mathbf{x}) = \sum_j N_j(\mathbf{x})|\phi_j(\mathbf{x})| - \left|\sum_j N_j(\mathbf{x})\phi_j(\mathbf{x})\right| \tag{5}$$

Plots of the sign and the G functions, for a square plate containing four inclusions, are depicted in Figs. 1 and 2 respectively.

2.1. Governing and discretized equations

The weak form of the equilibrium state is given as:

$$\int_\Omega \varepsilon(\delta\mathbf{u}) : \mathbf{C} : \varepsilon(\mathbf{u})d\Omega = \int_{\Gamma_t} \delta\mathbf{u}\cdot\bar{\mathbf{t}}d\Gamma + \int_{\Gamma_{c+}} (\delta\mathbf{u}\cdot\tau)^{(+)}d\Gamma + \int_{\Gamma_{c-}} (\delta\mathbf{u}\cdot\tau)^{(-)}d\Gamma \tag{6}$$

Eq. (6) is solved, in terms of displacement, under the following conditions:

$$\begin{cases} \varepsilon = \nabla_s\mathbf{u} & in\ \Omega \\ \sigma\cdot\mathbf{n} = \bar{\mathbf{t}} & on\ \Gamma_t \\ \mathbf{u} = \bar{\mathbf{u}} & on\ \Gamma_u \\ \sigma\cdot\mathbf{n} = \tau(\delta) & on\ \Gamma_c \end{cases} \tag{7}$$

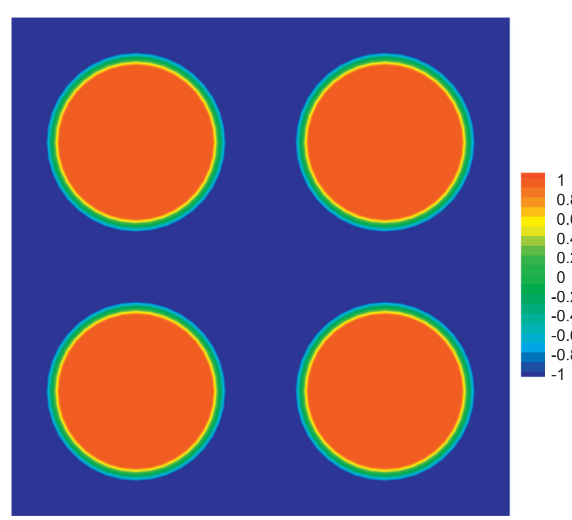

Fig. 1. Sign function for a four-fibre reinforced square matrix.