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An experimental/numerical investigation into the main driving force for crack propagation in uni-directional fibre-reinforced composite laminae

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ABSTRACT

This paper presents an enriched finite element method to simulate the growth of cracks in linear elastic, aerospace composite materials. The model and its discretisation are also validated through a complete experimental test series. Stress intensity factors are calculated by means of an interaction integral. To enable this, we propose application of (1) a modified approach to the standard interaction integral for heterogeneous orthotropic materials where material interfaces are present; (2) a modified maximum hoop stress criterion is proposed for obtaining the crack propagation direction at each step, and we show that the "standard" maximum hoop stress criterion which had been frequently used to date in literature, is unable to reproduce experimental results. The influence of crack description, material orientation along with the presence of holes and multi-material structures are investigated. It is found, for aerospace composite materials with $\frac{E1}{E2}$ ratios of approximately 10, that the material orientation is the driving factor in crack propagation. This is found even for specimens with a material orientation of 90°, which were previously found to cause difficulty in both damage mechanics and discrete crack models e.g. by the extended finite element method (XFEM). The results also show the crack will predominantly propagate along the fibre direction, regardless of the specimen geometry, loading conditions or presence of voids.

1. Introduction

Composite materials are already widely used in engineering structures, especially in the aeronautical, and, indeed, the aerospace industries where their high specific strength and stiffness make them ideally suited to reduce weight. However, a major weakness of these laminated materials is that they are prone to delamination at both the interface, between the plies (interlaminar) and within plies (intralaminar). This hinders reliable prediction of their durability in service. It is therefore of primary importance to devise reliable experimental and numerical techniques to study and predict the behaviour of existing materials, as well as engineer new damage tolerant composites capable of sustaining the increasingly demanding conditions in which they are used. Composites are, by definition, made up of several phases which, together, provide the resulting material with the combined strengths of its individual components. Advanced composites are composed of stiff elastic fibres bonded together by a toughened epoxy matrix, to form a lamina; numerous lamina are then bonded together to form a laminate. At the first level of simplification, each layer (i.e. lamina) can be considered as a linear, elastic, orthotropic material. In order to predict the intralaminar failure in such a lamina, it is important to be able to accurately simulate crack performance and propagation under loading. Techniques extensively used to predict the behaviour and growth of cracks include continuum damage mechanics [1,2] or progressive damage analysis [3–5]. In these approaches, the crack or cracks are not modelled explicitly, but their effect is accounted for by locally modifying the elastic moduli of material points that have been determined to be damaged. While these approaches are relatively computationally efficient and accurate, they suffer from a number of drawbacks, such as mesh sensitivity and an inability to capture ply splitting, which is a major contributor to the size effect experienced in open-hole composites testing [6]. To alleviate these difficulties, discrete crack approaches such as those relying on the partition of unity methods (PUM) [7] can be used instead. In the PU framework, arbitrary functions are added to the standard polynomial finite element (FE) space in order to improve the approximation power of the resulting numerical method. In particular, the extended finite element method (XFEM) [8], which belongs to the class of partition of unity methods, allows simulation of crack propagation without remeshing by introducing two classes of enrichment functions: discontinuous enrichment to capture the

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displacement jump through the crack faces and near-tip asymptotic enrichment to capture the stress singularity at the crack tip in linear elastic fracture mechanics (LEFM). Although a vast body of literature has examined cracking in various types of composite materials using different techniques, for example, Rebiére et al., [9] employed a combined analytical and a three-dimensional finite element study to study transverse and longitudinal cracks in laminates, Ramanujam et al., [10] studied fatigue crack growth using a combined experimental and computational investigation and meshfree method and cracking particle methods were employed in [11–15] to study arbitrary evolving cracks in reinforced concrete structures. Yet, to date, there is only a limited amount of work in the literature which involves XFEM for crack propagation simulation in orthotropic materials. This is despite the fact that such a method, which has been shown to perform efficiently for damage tolerance assessment of complex structures [16–18] and also holds promise for the analysis of the durability of composite materials by virtue of its ability to describe arbitrary crack growth without remeshing and with relatively coarse meshes. The most significant contributions in the area of orthotropic materials have come from [19–21] who developed new crack tip enrichment functions to effectively capture the crack tip displacement fields within linear elastic orthotropic materials. Further developments in dynamics allowed the study of propagation in orthotropic materials using XFEM [22]. Other topical work has focussed on interlaminar delamination [23] and cracks in functionally graded composites [24,25].

In this paper, a new tool based on the extended finite element method (XFEM) which allows to simulate the growth of arbitrary cracks in orthotropic materials is devised, analysed and validated experimentally. The technique builds on recent work of Asadpoure and Mohammadi [19], which concentrates on the calculation of stress intensity factors (SIFs) and extends it to allow the accurate simulation of crack growth through an orthotropic material. The model is thoroughly validated by a bespoke test series and further applied to more complex problems to study the driving factors for crack propagation in orthotropic laminae.This work relies on the key postulate that an orthotropic material definition is suitable for simulation of a uni-directional composite lamina and validates this postulate experimentally. The present paper employs a modified maximum hoop stress criterion to calculate the direction of crack propagation as well as a new domain integral method for heterogeneous materials. The proposed model is capable of dealing with multi-material structures under complex loading conditions. The outline of the paper is as follows; Section 2 briefly outlines the stress and displacement theory for an orthotropic body. In Section 3, the extended finite element method is presented for modelling of strong and weak discontinuities in orthotropic materials. Section 4 poses the fracture criteria of the model, while Section 5 introduces the experimental test series. Sections 6–9 present validation and further numerical examples using the model developed. The major conclusions are drawn in Section 10.

2. Stresses and displacements at the crack tip of an orthotropic body

Assume an anisotropic body with a crack subjected to arbitrary forces with general boundary conditions. According to Lekhnitskii [26] by using the equilibrium and compatibility conditions, a fourth-order partial differential 'characteristic' equation can be obtained;

$$a_{11}\mu^4 - 2a_{16}\mu^3 + (2a_{12} + a_{66})\mu^2 - 2a_{26} + \mu a_{22} = 0 \quad (1)$$

where $a_{11}, a_{22}, a_{16}, a_{12}, a_{26}, a_{66} \in \mathbb{R}$ and are the elastic compliances. The roots of Eq. (1) are always complex or purely imaginary ($\mu_k = \mu_{kx} + i\mu_{ky}$, $k = 1,2$) and occur in conjugate pairs as μ_1, $\bar{\mu}_1$ and μ_2, $\bar{\mu}_2$ [26]. From these, Sih et al. [27] derived the two-dimensional displacement and stress fields in the vicinity of the crack-tip using analytical functions and complex variables. These stress components and displacements are later employed in this work for calculation of SIFs using an interaction integral. Full details of these fields may be found in [27], or indeed more recently in [19].

3. Enriched finite element approximations for linear elastic orthotropic fracture mechanics

The principle of the extended finite element method is to locally enrich the standard FEM basis through a local partition of unity, enabling the exact reproduction of these enrichment functions by the enriched approximation. These enrichment functions are chosen so as to best replicate known features about the exact problem. In particular, for crack problems treated by the extended finite element method (XFEM), the displacement field is augmented by a discontinuous function, allowing to describe the displacement jump across the crack faces without requiring the mesh to conform to those, and asymptotic enrichment functions enabling the approximation to reproduce, with coarse meshes, the large gradients near the crack tips.

3.1. Enrichment functions

The enriched approximation is thus designed to take account of any discontinuities, known behaviour or any *a priori* knowledge about the solution sought. It was recently demonstrated by Menk and Bordas [28,29] that numerically determined enrichment functions can be used to simulate arbitrary cracks and wedges in composite or anisotropic materials.[1] For crack modelling, two classes of analytical enrichment functions are used. The Heaviside, step function or split enrichment function,

$$H(x) = \begin{cases} -1 & x \leqslant 0 \\ +1 & x > 0 \end{cases} \quad (2)$$

confers the approximation the power to reproduce any discontinuous function, and thus the jump in displacement through the crack faces. In order to model the crack tip singularity, the nodes about the crack tip (s) are enriched with crack tip or branch functions, first proposed in [8]. These branch functions span the first order terms of the Williams' expansion [34] of the asymptotic displacement field around a crack tip in a linear elastic material. For orthotropic materials, attempts have been made to derive the crack tip enrichment functions by [19] (See also Menk and Bordas [28] where those are computed numerically). The asymptotic fields for orthotropic materials are given in [19] as,

$$\{F_\alpha\}_{1\leqslant\alpha\leqslant4}(r,\theta) = \sqrt{r}\left\{\cos\frac{\theta_1}{2}\sqrt{g_1(\theta)}, \cos\frac{\theta_2}{2}\sqrt{g_2(\theta)}, \sin\frac{\theta_1}{2}\sqrt{g_1(\theta)}, \sin\frac{\theta_2}{2}\sqrt{g_2(\theta)}\right\} \quad (3)$$

where θ_1, θ_2, $g_1(\theta)$ and $g_2(\theta)$ are functions of θ, the angle about the crack tip, and are given as,

$$g_k(\theta) = \sqrt{(\cos\theta + \mu_{kx}\sin\theta)^2 + (\mu_{ky}\sin\theta)^2} \quad (4)$$

$$\theta_k = \arctan\left(\frac{\mu_{ky}\sin\theta}{\cos\theta + \mu_{kx}\sin\theta}\right) \quad (5)$$

[1] This idea is similar to spider XFEM [30] and parametric enrichment [31]. Ultimately, a posteriori error estimators could be used to help derive the enrichment functions ([32,33]).