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Modelling interfacial debonds in unidirectional fibre-reinforced composites under biaxial transverse loads

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ABSTRACT

A numerical study of the onset and growth of debonds at fibre–matrix interfaces, for a fibre bundle under far field biaxial transverse loads, is presented. The behaviour of the fibre–matrix interface cracks was studied by means of a Linear Elastic–Brittle Interface Model (LEBIM). The simplified, but representative, model of an actual unidirectional lamina considered included ten fibres embedded in a matrix cell whose external dimensions were much larger than the fibre radius. The results presented extend the results obtained by the authors in previous studies using a single fibre model. The aim was, firstly to predict the failure loads (critical loads) originating the first debond onset in a small bundle of fibres and, secondly, to verify the unstable character of subsequent debond growth under transverse loads. The failure curves obtained in this simplified problem help to elucidate some aspects of the failure mechanisms of an actual composite material subjected to these kinds of loads.

1. Introduction

The use of composite materials in the manufacturing of engineering components and structures (in a wide variety of industries such as aeronautical, automotive, naval, wind energy and others) has increased significantly over the last few years. Nowadays, in the aeronautical industry, composites are included in critical parts of commercial aircrafts, thus the structural responsibility for these kinds of materials is very high.

Current knowledge about damage and failure mechanisms in composite materials is not advanced enough to develop physically based criteria for some types of failure. Nevertheless, the use of composite materials is becoming more and more widespread. These facts make it especially interesting and useful to carry out research in this area. The use of alternative models based on assumptions different to those made in classical Linear Elastic Fracture Mechanics (LEFM), seems to be a promising approach, firstly, to complement the understanding of the different failure mechanisms involved within composite materials and, secondly, to help with predictions of failure loads in the design of composite structures.

It is evident that the interfaces between the constituents of composite materials play a significant role in failure mechanisms [1–5]. Particularly at the microscale, the level in which interaction between fibres and matrix takes place, the role of interfaces and interphases is well recognised, see [6–8] and references therein. Experimental, numerical and semi-analytical studies of the inter-fibre failure (also called matrix failure) of a single fibre embedded in a matrix under biaxial transverse loads developed by the present authors and coworkers can be found in [8–10]. These studies show the influence of a secondary transverse load (tension or compression) on the generation of the damage dominated by a primary transverse tension when the secondary load is applied perpendicularly to the primary transverse tension (creating a biaxial stress state).

Numerical studies for a single fibre embedded in a large matrix based on the Boundary Element Method (BEM), a numerical technique very suitable for micromechanical analyses, and interfacial fracture mechanics were carried out in [11–14].

The present authors, in some recent studies [8,15], have made advances in the quantitative prediction for the influence of the secondary transverse load on the single fibre configuration, obtaining a failure curve in which both tensile and compressive loads are considered. The BEM and the Linear Elastic – (perfectly) Brittle Interface Model (LEBIM) were used to study and characterise the behaviour of the fibre–matrix interface in these investigations.

The aim of the present study is to make further advances regarding our understanding of inter-fibre failure in a unidirectional composite lamina (by means of a convenient combination of BEM and LEBIM), by modelling a more representative problem of an actual unidirectional lamina. Thus, a bundle of ten fibres, embedded in a matrix whose external dimensions are much larger than the radius of the fibres, is studied in this investigation.

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An extensive review of the literature concerning the problem of an elastic circular inclusion embedded in an elastic matrix with or without a partial debond can be found in [4,7]. Details of the LEBIM implementation in a BEM code are presented in [7,15]. Additional details about the weak formulation used to impose interface conditions are presented in [16,17]. Some fundamental results regarding the computation of the Energy Release Rate (ERR) in the LEBIM can be found in [8,18–21].

Many authors have studied different approaches to model the fibre–matrix interface behaviour in order to investigate the problem of multiple fibres embedded in a matrix. The problem of an infinite matrix with circular elastic inclusions, using the Galerkin Boundary Integral Method and considering spring-like interface conditions, is solved in [22] and considering a linear elastic material between matrix and fibres (interphase) in [23]. A multifibre model and a non-linear finite element code to obtain effective elasto-plastic transverse properties for a unidirectional composite is used in [24]. An analytical and numerical model comparison, which included periodically dispersed cylindrical fibres, was later presented in [25] to obtain effective transverse properties. A cohesive zone formulation along fibre matrix interfaces and a matrix plastic deformation are included in a finite element analysis to study the effect of compressive transverse loads in [26] and its combined effect with out-of-plane shear loads in a representative volume element of a composite in [27]. The effect of the interface properties included in a cohesive zone formulation in a random distribution of fibres under transverse tension is studied in [28]. Damage models for studying fibre–matrix debonds and matrix cracking by means of a cohesive interface element formulation are used in [29] and for obtaining a meso-scale traction-separation curve in [30]. An analytical method for studying interface cracks in a multifibre model is developed and compared with an interface cohesive zone formulation in [31–33].

According to [34,35], periodic distributions of fibres may be used to predict effective properties of composites. However, due to the significant influence of the stochastic nature of these materials on the microscopic distribution of stresses and strains, proper random distributions of fibres are necessary for modelling debond initiation, growth and subsequent matrix cracking.

Although, as shown above, several investigations have been devoted to the study of the fibre–matrix interface debond problem, some questions still remain to be answered. Some of these questions are related to the following: the prediction of the failure loads, the load biaxility effect, the accuracy of the interfacial stress field, the effect of randomness in the fibre distribution, the fibre size effect, the mesh dependency of the sequence of interface failures and the study of the instability of the debonds growth. In the present study some of the above questions are investigated. This paper is organised as follows. Firstly, the LEBIM and the interface failure criterion used are briefly described. Secondly, the plane strain problems for a group of circular inclusions (representing an actual bundle of parallel long fibres taken from a micrograph), under a remote biaxial transverse loading, are introduced. Thirdly, the BEM is applied to obtain a numerical solution for a sequence of fibre–matrix interface debond onsets and growths at different fibres in the above mentioned problem. The numerical results include a study of the crack path formed by the sequence of debonds in the fibre–matrix system. Finally, failure curves for a bundle of fibres under biaxial transverse loads are obtained and discussed.

2. LEBIM interface failure criterion

As shown in [7,8,15], the LEBIM can be used in microscale models to simulate damage initiation and propagation at the fibre–matrix interface. In this section, the LEBI constitutive law and the interface failure criterion developed in [7,8,15,36] are briefly reviewed. The continuous spring distribution that models an elastic layer (interphase) along a fibre–matrix interface is governed by the following simple linear elastic-(perfectly) brittle law[1] written at an interface point x:

$$\begin{array}{lll} \text{Linear Elastic} & \begin{cases} \sigma(x) = k_n\delta_n(x), \\ \tau(x) = k_t\delta_t(x), \end{cases} & G(x) < G_c(\psi(x)), \\ \text{interface(undamaged)} & & \\ \text{Broken} & \begin{cases} \sigma(x) = k_n\langle\delta_n(x)\rangle_-, \\ \tau(x) = 0. \end{cases} & \\ \text{interface} & & \end{array} \tag{1}$$

where $\sigma(x)$ and $\tau(x)$ are, respectively, the normal and tangential components of the tractions in the elastic layer along the interface, and where $\delta_n(x)$ and $\delta_t(x)$ are, respectively, the normal and tangential relative displacements between opposite interface points. k_n and k_t denote the normal and tangential stiffnesses of the spring distribution.

It is assumed that the crack tip at x advances (or the interface breaks at point x) when the corresponding ERR $G(x)$ reaches the critical ERR value $G_c(\psi(x))$, that is $G(x) = G_c(\psi(x))$, where $\tan^2\psi = \frac{G_{II}}{G_I}$ for $G_I > 0$. The extended energetic fracture-mode-mixity angle ψ is defined by (see [8]):

$$\tan\psi = \sqrt{\xi^{-1}}\tan\psi_\sigma = \sqrt{\xi}\tan\psi_u, \tag{2}$$

where $\xi = k_t/k_n$, $\tan\psi_\sigma = \tau/\sigma$ and $\tan\psi_u = \delta_t/\delta_n$, ψ_σ and ψ_u being the stress and relative displacement based fracture-mode-mixity angles, respectively. The ERR of the linear elastic interface at a point x is defined as, cf. [8,18–21]: $G(x) = G_I(x) + G_{II}(x)$, with

$$G_I(x) = \frac{\sigma(x)\langle\delta_n(x)\rangle_+}{2}, \qquad G_{II}(x) = \frac{\tau(x)\delta_t(x)}{2}, \tag{3}$$

verifying $G_I = 0$ for $\delta_n \leqslant 0$. The functional dependence of G_c on the fracture-mode-mixity angle ψ is defined as in [37] with a slight modification [8] as follows,

$$G_c = G_{Ic}[1 + \tan^2((1-\lambda)\psi)], \tag{4}$$

where

$$G_{Ic} = \frac{\bar{\sigma}_c\bar{\delta}_{nc}}{2} = \frac{\bar{\sigma}_c^2}{2k_n} = \frac{k_n\bar{\delta}_{nc}^2}{2} \tag{5}$$

corresponds to the fracture energy in pure opening mode I. λ is a fracture-mode-sensitivity parameter (usually obtained from the best fit from experimental results), $\bar{\sigma}_c > 0$ and $\bar{\delta}_{nc} > 0$ are the critical normal component of traction and critical normal relative displacement in mode I, i.e. $\bar{\sigma}_c = k_n\bar{\delta}_{nc} = \sigma_c(\psi = 0)$ and $\bar{\delta}_{nc} = \delta_{nc}(\psi = 0)$.

In summary, it can be seen that the LEBIM needs the input of four independent variables: $\bar{\sigma}_c, G_{Ic}, \xi$ and λ. Typical range $0.2 \leqslant \lambda \leqslant 0.3$ characterises interfaces with moderately strong fracture-mode-dependence [37]. Further details on the deduction of the above criterion are presented in [7,8,15,36].

3. Description of the problem

When an actual continuous fibre-reinforced composite is intended to be modelled, several options exist. The most common ones are the following: (i) application of periodic boundary conditions for a bundle of fibres embedded in a matrix cell whose external dimensions are given by the bundle size, (ii) homogenised composite surrounding the bundle of fibres embedded in a matrix

[1] The positive and negative part of a real number δ are defined in the present study as $\langle\delta\rangle_\pm = \frac{1}{2}(\delta \pm |\delta|)$. $\langle\cdot\rangle_+$ is also referred to as Macaulay brackets or ramp function.