Computational Materials Science 52 (2012) 95–100

Contents lists available at ScienceDirect

Computational Materials Science

journal homepage: www.elsevier.com/locate/commatsci

Modelling the effect of microstructural randomness on the mechanical response of composite laminates through the application of stochastic cohesive zone elements

I.A. Ashcroft *, Z.R. Khokar, V.V. Silberschmidt

Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, Leicestershire, UK

ARTICLE INFO

Article history:
Available online 21 March 2011

Keywords:
CFRP laminates
Delamination
Stochasticity
Cohesive zone elements
Microstructural randomness
Weibull's distribution

ABSTRACT

Fibre reinforced polymer composites (FRPCs) are being increasingly used in structural applications where high specific strength and stiffness are required. The mechanical performance of FRPCs is affected by multi-mechanism damage evolution under loading which in turn is affected by microstructural randomness in the material. Although the micro-scale fracture of a FRPC is a stochastic process, most analyses of these materials have treated them in a deterministic way. In this paper the effect of stochasticity in FRPCs is investigated through the application of cohesive zone elements in which random properties are introduced. These may be termed 'stochastic cohesive zone elements' and are used in this paper to investigate the effect of microstructural randomness on the fracture behaviour of composite double cantilever beams. It is seen from this investigation that microstructure can significantly affect the macroscopic response of FRPC's, emphasising the need to account for microstructural randomness for accurate prediction of the performance of laminated composite structures.

1. Introduction

Fibre reinforced polymer composites (FRPCs) have been increasingly used in recent decades in a range of applications, such as aircraft, high performance cars, marine vessels and sport equipment. These materials have non-uniform microstructures on a number of different scales, including the scale of the fibre diameter and that of the laminate thickness. There can also be considerable randomness in the microstructure, for example, Baxevanakis et al. [1] demonstrated a high degree of variability in the distribution of fibres in a carbon fibre reinforced polymer composite (CFRP) from the image analysis of cross sections through laminates.

Failure in FRPCs tends to be by the progression of localised damage, incorporating a variety of failure mechanisms, including matrix cracking, fibre de-bonding, fibre fracture and interfacial delamination between plies. As the localised damage is dependent on the non-uniform local microstructure it is evident that there will also be a degree of randomness in the localised damage. Such randomness in microstructure and in failure evolution is responsible for non-uniform distributions of stresses in composite specimens even under externally uniform loading, resulting, for instance, in a random distribution of matrix cracks in cross-ply laminates [2] Furthermore, it has been shown that this can result in randomness in the global performance of composites structures manufactured from these materials. Khokar et al. [3] showed that variation in the distribution of matrix cracks in a CFRP cross-ply laminate under bending could result in a significant variation in the predicted stiffness of the beam. Trias et al. [4] proposed that periodic models were appropriate for the determination of the effective properties of CFRPs but that random models should be used for the simulation of local phenomena, such as damage accumulation.

Currently, FRPC structures tend to be designed using a deterministic approach based on average properties with an empirical safety factor. Whilst this is an appropriate approach for many metals, in which variations in microstructure have little effect on the global properties, it may be less suitable for FRC's. However, if a probabilistic methodology was to be used instead then a major change in current analysis and design methods for FRPCs would be required. Hence, further research is required to investigate the effect of the microstructural randomness in FRPCs on their global behaviour in order to determine the most appropriate and efficient method of effective and safe design with these materials.

In a previous paper [5], Khokar et al. used a two-dimensional finite-element (FE) model of a CFRP double cantilever beam (DCB) to show that the introduction of randomness in the failure criterion results in scatter in the critical failure load and can also result in features such as delamination ahead of the main crack, which has been observed experimentally but is not predicted when uniform properties are assumed. This paper aims to significantly

---

* Corresponding author.
E-mail address: i.a.ashcroft@lboro.ac.uk (I.A. Ashcroft).

0927-0256/$ - see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.commatsci.2011.02.040

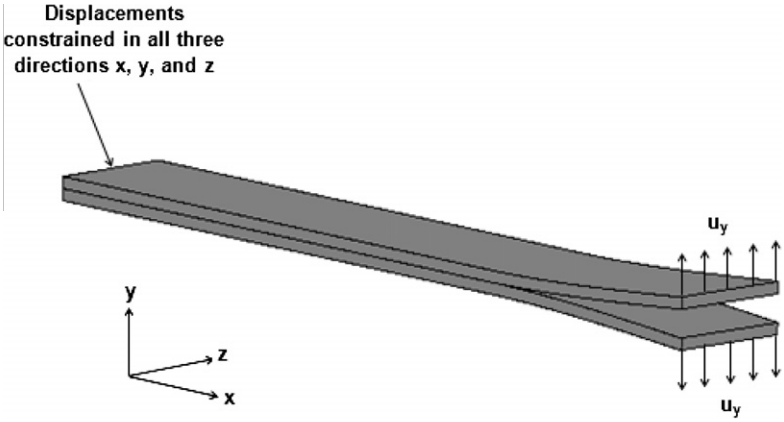

Fig. 1. Schematic of double cantilever beam.

extend that work. Firstly, by extending the analysis to a three-dimensional FE model, which behaves in markedly different way to the two-dimensional model, and secondly by introducing a statistical analysis of the output from a number of different statistical realisation of the model incorporating randomness in the failure criterion.

2. Finite-element model

2.1. Test sample

The model problem was a DCB with symmetric unidirectional CFRP laminate substrates, as illustrated in Fig. 1. The DCB is constructed of two loading arms subjected to opposed loading perpendicular to the original sample length, resulting in Mode I fracture down the centre of the beam thickness. It is used to determine the Mode I fracture toughness of materials. The mechanical properties of the unidirectional CFRP, taken from [6], are shown in Table 1. The specimen was 125 mm long and 20 mm wide with twenty-four 0.125 mm thick plies giving a total thickness of 3 mm. An initial crack length of 35 mm was introduced into the model.

2.2. Cohesive-zone model

Fracture processes in brittle matrix composites are mostly associated with the development of a narrow band of damaged material, known as the process zone. This zone arises prior to complete fracture in FRPCs. The cohesive-zone model (CZM) presents an approach to representing this damage zone as a line or plane of displacement discontinuity in which the process zone is characterised by a stress–displacement relationship across this line or plane, known as the traction–separation or cohesive law [7–9]. In this work a bi-linear traction–separation law, as shown in Fig. 2, was used. This is defined by the tripping traction, $\sigma_{\max}$, the cohesive energy (which is the area under the traction–separation curve), G_F, the critical opening displacement, δ_c, the maximum opening displacement, δ_f, and the cohesive law stiffness, K. The values of these parameters used in this work are given in Table 2. In the softening part of the curve in Fig. 2, where $\delta^c < \delta < \delta^f$, the damage accumulated at the interface is characterised by a damage variable, D, which has a zero value in the virginal (undamaged) state and attains a value of one when the material is fully damaged. The constitutive equation for this portion is given by [10]

$$\sigma = (1 - D)K\delta, \tag{1}$$

where D is:

$$D = \max_{\sigma \leqslant \sigma_{\max}} \left\{ \begin{array}{ll} 0, & \delta \leqslant \delta_c \\ \frac{(\delta-\delta_c)\delta_f}{(\delta_f-\delta_c)\delta}, & \delta_c < \delta < \delta_f \\ 1, & \delta \geqslant \delta_f \end{array} \right\}. \tag{2}$$

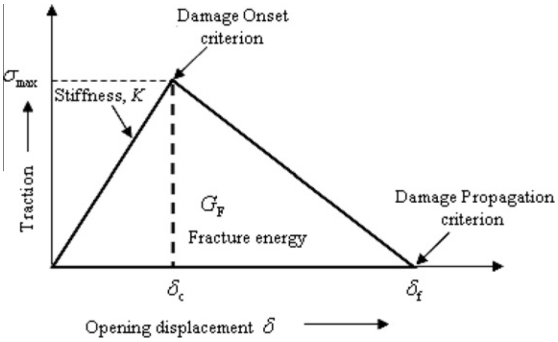

Fig. 2. Bi-linear traction–separation law.

Table 2
Cohesive law parameters.

Parameter	Value
Fracture energy, G_F	0.257 kJ/m^2
Tripping traction, $\sigma_{\max}$	50 MPa
Initial stiffness, K	1.6×10^6 N/mm^3
Critical displacement, δ_c	2.19×10^{-5} mm
Maximum displacement, δ_f	0.01 mm

Table 1
Mechanical properties of unidirectional CFRP [6].

E_{11}	E_{22}, E_{33}	G_{12}, G_{13}	G_{32}	v_{12}, v_{13}	v_{23}
137 GPa	8 GPa	4 GPa	3.2 GPa	0.31	0.52

Where E and G are direct and shear moduli and v is Poission's ratio. Subscripts 1, 2 and 3 correspond to directions x, z and y, respectively in Fig. 1.

2.3. 2D and 3D Finite elements

The commercial FE software MSC Marc was used for the FE modelling. Continuum element Type 11, which is a four-node, fully integrated, iso-parametric, arbitrary quadrilateral element used for plane-strain applications, was used in the 2D models. The cohesive-zones in the 2D models were represented by cohesive element Type 186. This element is a mechanical four-node planar interface