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A virtual experimental approach to microscale composites testing

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ABSTRACT

This paper presents a method for virtual testing composite microstructures with real fibre distributions, and compares the debonding and crack response with experimental results of identical microstructures under similar loading conditions. Prior to physical testing of HTA/6376 composite laminates, the fibre distribution of the undamaged physical specimen is automatically detected through image analysis and reconstructed as a 2D model in Abaqus software and tested following a sub-modelling approach. Once in-situ SEM micro-mechanical testing of the physical specimen is completed, the virtual and experimental crack paths can be directly compared to determine the viability of the virtual testing method. The influence of thermal residual stress on premature fibre-matrix debond initiation and crack propagation is also investigated. The results of the virtual testing presented in this paper give a strong correlation to the experimentally observed crack growth, where significant improvement on similar previously published virtual experimental results for composite materials in terms of both microstructure scale and accuracy of the crack representation, is observed. For the thermo-mechanically loaded models, thermal residual stresses were found to influence the crack path around certain fibres where localised thermal residual stresses were present, leading to a more accurate representation of damage than that given by the purely mechanically loaded models.

1. Introduction

To effectively use and take advantage of the various properties of composite materials the damage and failure mechanisms of the material should first be fully understood. Many macro-scale damage characteristics can be determined experimentally, as has been explored previously by the authors when investigating fibre-matrix debonding, microcrack growth and the relationship between transverse crack density and delamination [1,2]. The results of that experimental research have been used to make the first known comparison between experimentally measured and numerically predicted progressive matrix cracking-induced delamination on the meso-scale [3]. However, physical experiments of composite materials to investigate micro- and macro-scale damage behaviour can be very challenging, time consuming and expensive. In recent years, due to the price and performance of available computational methods numerical modelling of composite materials has become feasible to investigate damage across multiple scales.

Many current multiscale simulations of composite materials are performed by transferring damage information from one scale to the next. In most cases these simulations begin with the modelling of damage at the ply level through application of damage criterion, which reduces the stiffness of the material. This data is then transferred to the laminate level model. This method is repeated similarly from laminate level to a component level [4]. This continuum damage level approach can be very useful for simulating the overall behaviour of a component under mechanical loading. However, to understand the initiation and growth of damage on the microscale, discrete fibre level micromechanical modelling is the preferred approach as the influence of certain factors, such as the fibre distribution on fibre-matrix debonding, thermal residual stress and matrix plasticity can be captured.

In this work, a sub-modelling virtual experimental approach is taken where micromechanical models of real microstructure geometry is used to compare damage characteristics with our previously observed experimental damage of laminates in bending using a micro-mechanical testing apparatus under SEM [1,2]. The sub-modelling approach is shown in Fig. 1. A global model, homogenised at the ply level, was loaded in a manner representative of the concurrent experimental micromechanical testing (Fig. 1[a]). Where full contact mechanisms were used to introduce load and supports to the beam. This is essential as the contact stresses are significant due to the small sizes under investigation. Displacement information from the global analysis was applied to the

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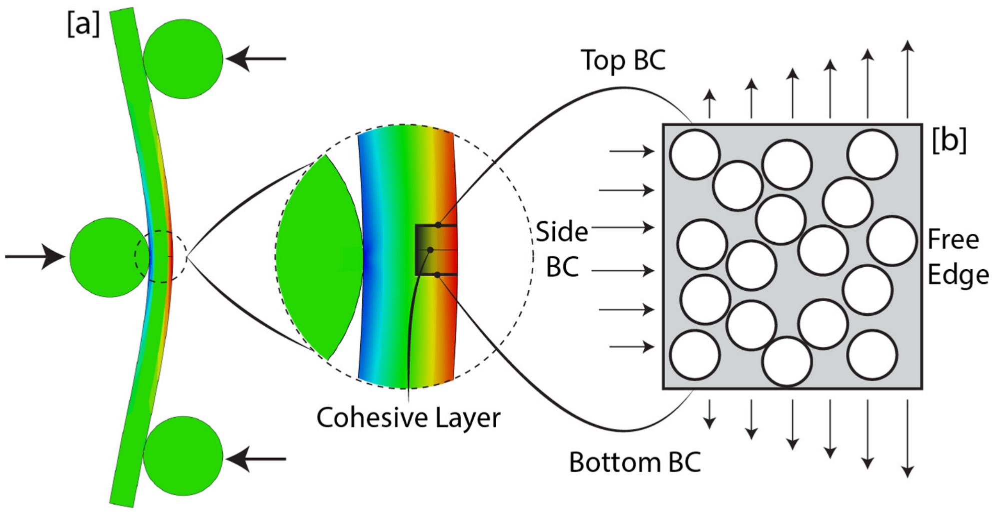

Fig. 1. [a] Global laminate model in three-point bending which provides the boundary conditions (BC) for [b] the microstructure sub-model.

boundaries of the sub-model, which was resolved at the fibre-level (Fig. 1[b]), and the cracking pattern obtained from numerical result was then compared with the experimental results. Modelling of the discrete fibre, matrix and interphase regions is considered to be an appropriate method to investigate the response to applied loading on the micro/macro levels [5].

The virtual experiment described in this paper was developed to compare the transverse crack growth from a real experimental sample to the simulated crack growth of an identical numerical microstructure. Virtual experiments have a number of advantages from a mechanical perspective over actual experiments of composite materials under similar thermo-mechanical loading conditions. Each detail of the simulated failure can be analysed in detail and the influence of the constituent properties and geometry on damage behaviour can be investigated [6]. This technique is valuable for industry, providing a novel method for non-destructive virtual testing of composite structures. Statistically equivalent randomly generated microstructures for use in numerical models are of value for determining the overall macro-scale loading response and have been studied comprehensively elsewhere [7–9]. However, unlike virtual experiments the microscale damage cannot be directly compared with experimental results due to the fundamental difference in fibre distribution [10].

The virtual experiment described in the following sections will follow a similar approach to that taken in previously published work by performing in-situ SEM testing, reconstruction of the undamaged microstructure resolved at the individual fibre level and simulating the loading of RVE's to compare fibre-matrix debonding and matrix crack growth with experimental results [4,6]. The aim of this current work is to improve the accuracy of the simulated crack paths, while also increasing microstructure size. While the results of previous research were representative of real composite microstructure behaviour, the simulated crack paths often did not closely resemble the real experimental crack path, and so further work is warranted.

2. Virtual-experiment modelling strategy

To have confidence in the results of a numerical microscale damage analysis of a laminated composite material, the response of the constituent materials to applied loading and the distribution of the fibres should be representative of the real microstructure. In this research a virtual microstructure, based on the actual topology of an existing specimen, is created in Abaqus 6.13-1 FEA and solved implicitly. The numerical model is then loaded in a similar bending configuration to the experimental specimen, and the damage initiation and growth are compared. Loading of the virtual model is firstly purely mechanical, then compared with a thermo-mechanical model. The steps for building the virtual model are discussed in detail in the following sections.

2.1. Virtual microstructure geometry generation

To create a numerical model of a real microstructure, the position and size of fibres within the model must closely correspond with the real microstructure to realistically represent the stress concentrations found for certain fibre configurations. This is of great importance when predicting the global material behaviour [6]. Microstructure topology is a critical factor in damage progression, but also influences other aspects of failure such as the ageing process of the material [11]. In previous research, microstructure topology has been determined through methods such as holotomography [12] and X-ray tomography [13]. For the work presented here, light microscopy was used to capture micrographs of microstructures prior to mechanical testing. Prior to imaging, the surface of the composite specimen was prepared by wet sanding with 1200 grit paper, followed by polishing with 1 μm, then 0.05 μm diamond suspension on microcloth discs.

A Matlab script was developed to analyse micrographs using a Circle Hough Transform (CHT) [14] as part of the process to create a virtual representation of the microstructure. The CHT is specialised in detecting circular shapes in an image, and this is ideal for many composite materials including HTA/6376, as the fibres are highly circular when viewed along their longitudinal axis. Certain parameters, such as the fibre diameter range and description of circularity, are required to be established first for the CHT to operate effectively. The CHT uses edge detection techniques to detect points on the perimeter of a fibre. With enough perimeter points and knowing the fibre diameter range, likely fibre centre points can be identified.

Fig. 2 shows the individual steps involved in the virtual model geometry generation for the microstructure under investigation. The specimen lay-up was $[90_2/0_7/90_2]$. This was chosen as, from the experimental perspective, a lower 90°/0° ply ratio made initial crack growth easier to observe due to the relatively stiff 0° ply block preventing rapid crack growth [15]. In addition, from a numerical modelling perspective, modelling two plies thick was deemed a sufficient increase in microstructure size from previous