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An experimental investigation into multi-scale damage progression in laminated composites in bending

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ABSTRACT

In laminated composite materials fibre–matrix debonding, as an initial damage mechanism, can initiate a damage sequence that can result in catastrophic failure of its structure by promoting intermediate damage mechanisms. This paper presents an in-depth experimental investigation into each of these damage mechanisms and how they transition from one state to the next, beginning at the micro-scale with fibre–matrix debonding and crack coalescence, to transverse ply fracture at the meso-scale through to formation of macroscopic delamination.

In-situ SEM micro-mechanical testing is used to determine the onset of the aforementioned damage mechanisms and to follow their progression in laminates of both $[0/90]_s$ and $[90/0]_s$ stacking sequences. The damage progression of $[0/90]_s$ specimens is presented first, followed by the more progressive failure of $[90/0]_s$ specimens, yielding an in-depth analysis of both rapid and more progressive damage growth, respectively. The intralaminar cracking and delamination of $[0/90]_s$ laminates was found to be instantaneous and provided limited opportunity to characterise damage progression. For $[90/0]_s$ laminates, damage progression was much more progressive and various factors such as fibre positioning were shown to influence debonding initiation and crack path development before catastrophic failure and so these laminates form the bulk of the analysis presented for this paper.

1. Introduction

When designing structures for the aerospace industry, light-weight and high stiffness material properties are a priority. Laminated carbon fibre reinforced plastic (CFRP) composite materials have been used for a number of decades to meet these demands. The failure mechanisms associated with composite materials are complex, and laminate fracture is known to involve a sequential accumulation of damage under static or fatigue loading [1]. Damage generally initiates at the micro-scale with fibre–matrix debonding which leads to transverse crack growth and delamination, and eventual structural collapse.

Micro-cracking in composite materials can go undetected as the immediate loss in material stiffness is miniscule. However, in certain applications the presence of micro-cracks may constitute a technological failure. For example, micro-cracking of a composite vessel containing a corrosive agent such as sulphuric acid, used in industry to accelerate chemical processes, could allow the entry of the corrosive agent with detrimental effects on the structure [2]. In another example, during testing of the liquid hydrogen composite fuel tanks for the NASA X-33 launch vehicle, it was found that micro-cracks acted as fuel leakage sites. With no solution to this behaviour and considering the obvious risks associated with fuel leakage, the launch vehicle project was cancelled [3], resulting in a major negative impact on technological advancement with astronomical financial losses. Not only are debonding and micro-cracks considered catastrophic failure in certain applications, they also act as nucleation points for other damage mechanisms such as delamination [1,4], which can result in significant loss in load-bearing capacity of a structure. Hence, a deep understanding of composite damage mechanisms, inclusive of all observable damage mechanisms from the micro-scale to the macro scale, is urgently required by industry.

Previous research relating to composite damage mechanisms has generally focussed on a particular damage mechanism in isolation [5–7]. Previous work by the authors using similar testing techniques investigated transverse crack density and delamination lengths in detail [8]. This paper aims to examine the initiation of observable damage and its progression from one damage mechanism to the next in cross-ply laminates under bending loads. Stacking

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sequences are varied to induce intralaminar failure under normal stress, and then shear stress dominated loading. In-situ micro-mechanical testing of composite laminates is used to apply quasi-static mechanical loading, while observing in real-time the progression of damage mechanisms at the micro-scale. In-situ micro-mechanical testing has been shown to be of significant value for determining damage mechanisms in previous research [9,10].

1.1. Problem description

A micro-test tensile stage (Deben™) was used to apply a bending load to composite specimens to induce intralaminar failure. The key components of the micro-tester are shown in Fig. 1 which can apply up to 2 kN of force with a 33 μm/min displacement rate. The span length and distances between the 8 mm diameter loading and support pins for four-point bending are also shown in Fig. 1.

Real-time video footage from the SEM was recorded during testing to identify various failure events at the micro-scale. Failure mechanisms in composite laminates vary depending on ply orientation and stress state. Testing of $[90/0]_s$ and $[0/90]_s$ laminates can be used to characterise intralaminar damage in composites under normal- and shear-stress dominated failure conditions. It should be noted that all reference to normal and shear stresses in this paper are to be considered applied stresses.

2. Materials and methods

2.1. Composite material

The composite material used for all specimens consisted of an isotropic epoxy matrix (Hexcel™ 6376), reinforced with anisotropic carbon fibres (Toho Tenax™ HTA). The laminates were produced using a vacuum assisted autoclave process in which the laminates were cured for two hours at 175 °C and 700 kN/m^2 pressure. Symmetrical cross-ply laminates were prepared with the following stacking sequence: $[90_4/0_7/90_4]$ specimens representing the worst case scenario for the direction of bending as the outer ply block, which sees a high tensile stress, consists of 90° plies with notably poor transverse stiffness; and $[0_4/90_7/0_4]$ specimens representing the best case scenario for the direction of bending, as the 0° plies are much stiffer and can take a much higher tensile load before failure. Both cross-ply layup types were selected to focus primarily on laminates with relatively low 90°/0° ply ratios. Initial crack growth in laminates is easier to observe when there are fewer 90° plies than 0° plies, as the presence of the relatively stiff 0° plies tended to inhibit rapid crack growth in the 90° ply block at low load levels [9]. The number of plies was limited to ensure that the load required to achieve catastrophic failure of the specimens was not greater than the 2 kN limit of the load-cell.

2.2. Sample preparation

Flat, rectangular shaped specimens were machined from the aforementioned larger flat panel using a diamond tipped composite cutting wheel. The thickness of the specimens was approximately 2 mm, and both $[90_4/0_7/90_4]$ and $[0_4/90_7/0_4]$ specimens were cut from the same laminate and polished. Polishing may introduce artefacts observed during in-situ testing which are not representative of the bulk material response. This is particularly true for 0° (longitudinal) fibres on the surface of the laminate which have their cross section and stiffness reduced during the polishing process [11]. To counteract the effects of polymer charging in the SEM in standard high voltage and high vacuum mode, the specimens were sputter-coated with a conductive gold alloy. A deposition current of 15 mA was applied for 30 s to give a deposition coating thickness of 2.5 nm.

2.3. SEM in-situ bending

The micro-tester was located in the chamber of a SEM (JEOL™ JSM-5600) with the electron source directly over the specimen. The SEM acceleration voltage was 15 kV. The specimens were loaded in four-point bending to induce theoretically pure normal loading conditions between the loading pins, and mixed-mode conditions between the loading and support pins.

3. Results and discussion

The majority of the micro-mechanical testing for this study was performed using $[90/0]_s$ laminates due to the favourably slow damage progression, which accumulated until catastrophic failure. For this research, catastrophic failure is considered as the significant loss of load-bearing capacity of the structure, identified as a load drop of 50% from the peak load. Bending of $[0/90]_s$ laminates was also performed to compare failure characteristics with $[90/0]_s$ laminates. However, the rate of damage progression in $[0/90]_s$ specimens made it very difficult to interpret the transition from one damage mechanism to the next.

The following subsections of the results and discussion will explore the failure mechanisms for cross-ply laminates. The rapid damage progression of $[0/90]_s$ specimens is presented first followed by $[90/0]_s$ specimens, from the initiation of fibre–matrix decohesion at the micro-scale, through to transverse cracking at the meso-scale, through to macro-scopic delamination, and finally concluding at catastrophic failure at the macro-scale.

3.1. Damage process for $[0/90]_s$ laminates in bending

The electron micrographs of Fig. 2 show the type of failure seen during four-point bending of $[0/90]_s$ laminates in the 90° ply block

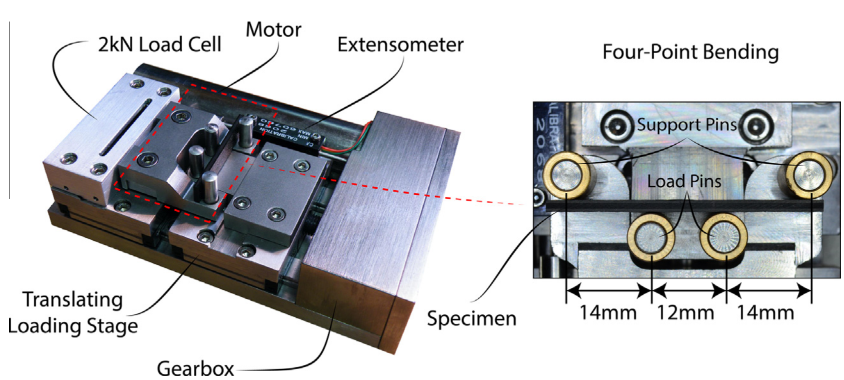

Fig. 1. Overview of Deben 2 kN micro-tester including the drive system and sensors.