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The role of material characterisation in the crush modelling of thermoplastic composite structures

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ABSTRACT

The predictive capability of high fidelity finite element modelling, to accurately capture damage and crush behaviour of composite structures, relies on the acquisition of accurate material properties, some of which have necessitated the development of novel approaches. This paper details the measurement of interlaminar and intralaminar fracture toughness, the non-linear shear behaviour of carbon fibre (AS4)/thermoplastic Polyetherketoneketone (PEKK) composite laminates and the utilisation of these properties for the accurate computational modelling of crush. Double-cantilever-beam (DCB), four-point end-notched flexure (4ENF) and Mixed-mode bending (MMB) test configurations were used to determine the initiation and propagation fracture toughness in mode I, mode II and mixed-mode loading, respectively. Compact Tension (CT) and Compact Compression (CC) test samples were employed to determine the intralaminar longitudinal tensile and compressive fracture toughness. V-notched rail shear tests were used to measure the highly non-linear shear behaviour, associated with thermoplastic composites, and fracture toughness. Corresponding numerical models of these tests were developed for verification and yielded good correlation with the experimental response. This also confirmed the accuracy of the measured values which were then employed as input material parameters for modelling the crush behaviour of a corrugated test specimen.

1. Introduction

Thermoplastic composite materials are showing great potential for adoption within the aircraft, automotive and railway industries. It is likely that more thermoplastic composite components will be used in the near future, in lieu of thermoset composites, to replace components which were previously manufactured from metals or thermoset composites. Thermoplastic resins offer a number of advantages over conventional thermoset resins such as epoxies. Thermoplastics exhibit chemical and impact resistance; they may be used over a wide range of temperatures, and have an 'unlimited' shelf life [1]. Among many other high performance thermoplastic polymers like polyetheretherketone (PEEK), polyphenylene sulphide (PPS) and Polyethylenimine (PEI), semi-crystalline PEKK is one of the most promising polymers that can be used for structural applications because of its excellent environmental resistance and higher toughness. PEKK also has a lower processing temperature and is more economical than PEEK. It has higher mechanical properties than PPS and PEI, which makes PEKK a prospective candidate for use in fibre reinforced high performance applications. Although PEKK exhibits excellent properties, the fracture toughness database and behaviour under shear loading of this material is not available in the literature.

The fracture behaviour of laminated composites can be quantified by measuring their toughness and it can be generally classified into interlaminar or intralaminar fracture. There are several existing standard test methods to characterise the interlaminar fracture toughness. For Mode I tests, the double-cantilever-beam (DCB) test is the most widely used approach and is the method adopted by the internationally-recognised standard, ASTM D5528-01 2002 [2]. While for Mode II, the ENF test is a recently announced test method (ASTM standard D7905/D7905M [3]) for the determination of Mode II interlaminar fracture toughness of unidirectional fibre-reinforced polymer matrix composites. However, this test is characterised by unstable crack growth and only initiation fracture toughness can be obtained. Some other researchers have made use of the four-point end-notched flexure (4ENF) test [4] which can deliver a stable crack propagation to yield a resistance curve which is used to determine the propagation fracture toughness. For mixed mode fracture toughness, the mixed mode bending

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(MMB) configuration is often used for the wide range of mode mixity it can create (ASTM D6671-01) [5]. Although existing test standards are able to measure the interlaminar fracture toughness, there still remains some debate over the choice of initiation fracture toughness or propagation fracture toughness as an input material parameter to model the delamination behaviour [6].

Fibre-dominated failure is the main failure mode during longitudinal tension or compression and the energy consumed by these failure processes is much larger than for matrix-dominated failure [7]. Particularly, fibre failure usually occurs as a result of fibre breakage/fibre pull-out under tension or crushing/kinking under compression. Experimental determination of the fracture toughness associated with these fibre failure modes is significant to accurately model the fibre-dominated damage behaviour. Compact Compression (CC) and Compact Tension (CT) tests described in ASTM E399 [8] and E1820 [9] originally designed for the testing of metallic materials, can be adapted for the determination of both tensile and compressive fibre-dominated fracture toughness [7,10].

Transverse or shear loading may lead to large nonlinear deformation and subsequent matrix cracking, which can be defined as matrix-dominated failure [11,12]. Composite materials exhibit significant nonlinearity before failure, particularly with respect to shear deformation. This kind of failure was frequently observed in composite bolted joints manufactured using cross-ply and notched laminates [13,14], as well as the formation of permanent indentations after impact events [15,16]. Therefore, a model dealing with shear non-linearities is required to accurately predict failure under multiaxial loading states. The V-notched rail shear test method (ASTM standard D7078/D7078M-12) [17] is essentially a combination of the best features of two commonly used methods, the Iosipescu Shear [18] and the Two-Rail Shear test method [19], generating a relatively uniform shear stress state within a larger gauge section between the V-notches as well as eliminating edge crushing and the need of multiple loading holes.

While the potential superior energy absorbing capacity of carbon-fibre composite structures is repeatedly demonstrated in Formula One racing [9], the design of a cost-effective crashworthy carbon-fibre reinforced polymer (CFRP) automotive passenger cabin has yet to be realised. A major challenge in the development of land-based mass-transportation fibre-reinforced polymer composite vehicles is ensuring a prescribed level of crashworthiness [27].The complex interacting failure modes, associated with carbon fibre composite material under crushing, present numerous challenges in predicting the crashworthiness of composite structures. A model that can capture the physical damage and deformation will be beneficial to the design and development of energy absorbing composite structures by providing a more detailed representation of the damage process.

In this study, a roadmap from material characterisation to crush modelling is presented, which builds on the work of the corresponding author's research group [15,20–23]. A series of tests have been conducted for the measurement of interlaminar and intralaminar fracture toughness as well as the non-linear shear behaviour of AS4/PEKK composite laminates. A cohesive zone model [24] and an intralaminar damage model [15,21,23,25–27] were implemented with the obtained fracture toughness values and non-linear behaviour to accurately predict the failure behaviour of composite test specimens under various loading conditions. Verification of the material parameters was carried out by simulating the material characterisation tests themselves. This confirmed the accuracy of the measured values which were then employed as material parameters for the computational modelling of the crushing behaviour of corrugated-shaped composite specimens. Excellent qualitative and quantitative correlation was achieved between the numerical models and experimental results. The fidelity of the computational models was able to provide detailed information on the evolution and propagation of splaying and fragmentation of the crushing composite, involving a complex interplay of fibre fracture, matrix cracking and delamination.

2. Material and model

2.1. Specimen preparation

The specimens used in this study were manufactured from unidirectional carbon fibre (AS4D 12K)/polyetherketoneketone (PEKK) tape provided by Cytec Engineered Materials® with a volume fraction of 60% [28]. Cross-ply AS4/PEKK composite plates were fabricated using a Collin® heated press.

Interlaminar fracture toughness specimens were prepared from 180 mm × 180 mm unidirectional panels ($[0°]_{24}$). High temperature polyimide film (Kapton® 50HN with a thickness of 12.7 μm, coated with a release agent Freekote® 700NC on both surfaces) was implanted in the middle of the layup to create a starter crack of length 65 mm for DCB and 4ENF specimens, and 40 mm for MMB specimens. Once the mould was prepared (as shown in Fig. 1a; a flat mould surface for coupon tests and corrugated mould surface for crushing tests), the prepreg laminate was wrapped along the longitudinal (fibre) direction with a high temperature polyimide film (Kapton®), which restrains the transverse flow of the resin out of the mould during the consolidation cycle and ensures a better surface finish of the final laminate. The wrapping keeps the two transverse sides of the laminate open and facilitated bleeding of any excess resin during consolidation. Intralaminar CC, CT specimens with a lay-up of $[90°/0°]_{8s}$ and shear test specimens with a lay-up of $[0°/90°]_{6s}$ were similarly prepared.

The consolidation cycle involves three main steps (melting, consolidation and solidification) in accordance with the processing profile shown in Fig. 1b. The laminated composite plates were heated at a constant rate of 15 °C/min to 372 °C and held at this temperature for 30 min under 7 bar pressure. Afterwards, the composite plate was cooled to 120 °C at 2 °C/min under the same pressure (7 bar) which was subsequently released and the composite plate cooled to room temperature in ambient conditions. After the consolidation cycle finished, the various interlaminar and intralaminar specimens were cut using a diamond coated circular saw blade.

2.2. Typical failure modes

Physically-based failure models are proposed for each failure mode in laminated fibre-reinforced composites. The failure modes may be classified as intralaminar (matrix cracks and fibre pullout/breakage) and interlaminar (delamination) damage, as shown in Fig. 2a. Fibre-dominated and matrix-dominated damage, which represent longitudinal (denoted by '11') and transverse damage behaviour (denoted by '22', '12', '23' and '31') of a unidirectional lamina, are illustrated in Fig. 2b.

2.3. Brief overview of the computational composite damage model

2.3.1. Damage initiation

A strain-based damage initiation function is used to model the material response in the longitudinal direction. The failure initiation criterion, based on Puck and Schürmann's [29] and Catalanotti et al. [30], was used for predicting matrix damage behaviour. A brief summary of fibre-dominated and matrix-dominated failure criteria are given below. Full details of the criteria may be found in [15,20,21] and are not repeated here for brevity.

$$\text{Fibre-dominated } \varepsilon_{11} > 0,\ F_{11}^{T}(\varepsilon_{11}) = \left(\frac{\varepsilon_{11}}{\varepsilon_{11}^{0T}}\right)^2 \geqslant 1 \quad (1)$$