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Test Method

Interlaminar fracture toughness of 5HS Carbon/PEEK laminates. A comparison between DCB, ELS and mandrel peel tests

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ABSTRACT

The present work focuses on the applicability of the mandrel peel test to quantify the interlaminar fracture toughness of 5 harness satin woven fabric Carbon/PEEK composites. For this purpose, the Mandrel Peel (MP) test was compared to the Double Cantilever Beam (DCB) and End-Loaded Split (ELS) test in terms of experimental procedure and results obtained. The interlaminar toughness of the 5 harness Carbon/PEEK was measured both parallel and perpendicular to the predominant fibre direction at the interface. While stable crack propagation was observed in the ELS test, unstable crack propagation (stick-slip) was observed during both the DCB and the mandrel peel tests. In the case of the mandrel peel test, however, the unstable propagation was immediately arrested by the mandrel, limiting the instability and providing numerous crack re-initiation values per unit of crack length. This effect is expected to increase the statistical relevance of a single test and thereby to increase the reliability of the measured values as compared to DCB tests. A fractographic analysis was performed to study the nature of the crack propagation for the different testing techniques. The mandrel peel test was found to be a potentially plausible alternative to the DCB test for woven fabric reinforced composites.

1. Introduction

Woven fabric composites are sometimes preferred to unidirectional tape materials for their simpler handling and better drapeability. Woven fabric composites are also known to be more damage tolerant than their unidirectional counterparts in the presence of a delamination [1]. The higher damage tolerance is often explained by the irregular interlaminar structure of woven fabric composites, which forces a delamination (crack) to interact with the matrix regions and the weave structure during its propagation, leading to a more tortuous crack path [2,3]. The fracture toughness of woven fabric composites is determined by a number of factors, which include the structure of the weave, referred to as weave index [2–5], the stacking sequence and the direction of crack propagation [4,6–8].

Although interlaminar failure of composite materials is a well-known problem, limited data is available on the toughness of woven fabric reinforced composites. This is partly caused by the difficulty associated with experimental characterization. Various test methodologies, all based on Linear Elastic Fracture Mechanics (LEFM), have been developed for unidirectional fibre reinforced composites. Some of the more accepted ones are the Double Cantilever Beam test (DCB) for mode I, and the End-Loaded Split (ELS) or End Notch Flexure (ENF) for mode II. Fig. 1 schematically represents the DCB and ELS tests. The existence of ISO and ASTM standards for both methods, although restricted to unidirectional composites in the longitudinal direction, illustrates some maturity of these testing techniques. While the DCB test for mode I is well accepted, this is not (yet) the case for the ELS and ENF tests for mode II, as the introduction of the standards is relatively new. Also, both tests suffer from some experimental difficulties, such as the inability to accurately measure crack length and the lack of a clear method to account for the friction between the arms of the specimen. Moreover, crack propagation is not always stable which further complicates the analysis [9,10].

Although standardised for UD laminates, some difficulties arise when the DCB test method is used to characterise woven fabric composite laminates. In particular, woven fabric reinforced composites often show unstable crack propagation (stick-slip). This is true for both thermoset [2,6–8] and thermoplastic [11–13] composites. The unstable crack propagation yields only a few G_{IC} values per test specimen. Therefore, G_{IC}-unstable propagation values for woven fabric reinforced laminate specimens are statistically less reliable than G_{IC}-stable propagation values for UD specimens [14]. Moreover, the unstable crack

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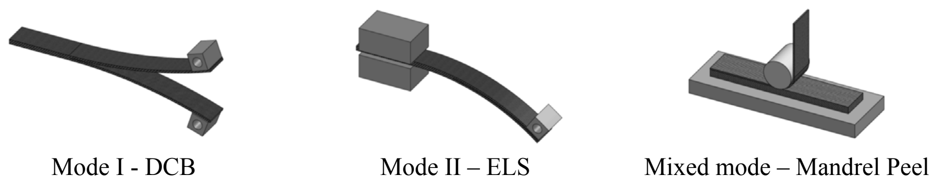

Fig. 1. DCB, ELS, and Mandrel Peel test scheme.

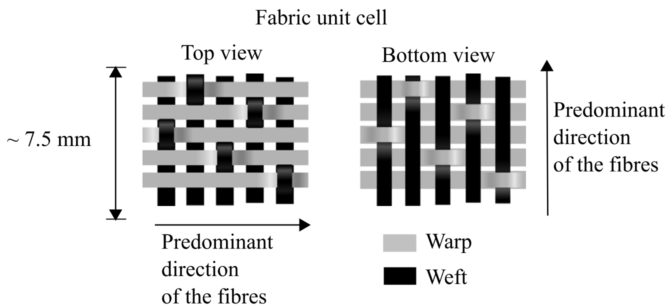

Fig. 2. Schematic view of a unit cell for a 5 harness satin top and bottom view.

propagation makes the interpretation of the test results rather difficult and the comparison with unidirectional materials questionable. The stick-slip behaviour has been treated from a theoretical point of view by different researchers, such as in Refs. [15–19]. Hine et al. reported that unstable crack propagation in woven fabric composites is caused by local regions of high toughness [20]. When the crack tip reaches one of these tougher regions, crack propagation is slowed down until the stored elastic energy is sufficient to propagate the crack further. Once this region is passed, the elastic energy stored is higher than required for stable propagation. As a result, the crack propagation rate increases, resulting in unstable crack propagation. For woven fabrics, the tougher regions have been correlated to the areas where the crack passes over a transverse fibre bundle [7].

The observed stick-slip behaviour and the tedious test procedure make the DCB test unattractive for woven fabric reinforced composites. The Mandrel Peel (MP) test is investigated as an alternative test to measure the interlaminar fracture toughness of woven fabric thermoplastic composites, in the present work. The mandrel peel test is an adaptation of the standard peel test, which is used to measure the bond strength of an assembly of two adherents where one adherent is flexible and the other is rigid [21]. The adherents are pulled apart at a steady rate in such a way that separation occurs progressively along the length of the bonded adherents. When the peel test is used for tough composite materials, the radius of the peel arm near the crack tip becomes too small during the loading phase of the test, resulting in the fracture of the peel arm before crack propagation. The mandrel peel test was first proposed by Kawashita et al. [22], as an adaptation of the peel test, in order to measure the fracture toughness of a metal-epoxy-metal peel specimen. Previous research showed that this test can also be used to characterise the fracture toughness of UD-UD [23,24], UD-woven [24], and UD-metal [25] interfaces. The peel arm, which was a UD tape in these cases, was forced to conform to a mandrel by using an alignment force. The radius of the mandrel was chosen such that the maximum strain in the peel arm does not exceed its failure strain. It should be noted that the fracture toughness evaluated using the mandrel peel test corresponds to mixed mode propagation. Although the exact mode mixity is unknown, it is reported to be mainly mode I [22]. This means that the interlaminar fracture toughness values measured from the mandrel peel test are expected to lie between the values measured by the DCB test (pure mode I) and the ELS test (pure mode II), although closer to DCB values than ELS ones.

The present work focuses on assessing the applicability of the mandrel peel test to quantify the fracture toughness of woven fabric based composites. A 5 Harness-Satin (HS) woven fabric Carbon/PEEK laminate was chosen as a basis material. DCB and ELS test results were compared to mandrel peel test results for the same material system. Two directions of crack propagation were investigated. In the first case, the crack propagates parallel to the predominant fibre direction at the interface, while in the second case the crack propagates perpendicular to the predominant fibre direction. Finally, a microscopic analysis was performed to study the fracture surfaces of the different samples. The fractographic features observed in the test pieces were compared in order to identify the dominant failure modes during the mandrel peel test.

2. Experimental methods

The present section describes the specimen preparation, as well as the procedures followed to characterise the interlaminar fracture toughness.

2.1. Specimen preparation

The material used in this research was a CETEX® 5 HS woven Carbon fabric reinforced PEEK powder coated semi-preg supplied by TenCate. The fabric comprises 3 K T300JB Carbon fibre bundles with an equal amount of bundles in the warp and weft direction. The resulting repetitive unit cell has a dimension of 7.5 × 7.5 mm^2, as shown in Fig. 2. The figure also illustrates that a satin weave structure has a predominant fibre direction on each side of the fabric. On one side, e.g. the top view in Fig. 2, this predominant fibre direction corresponds to the warp bundles, while on the other side the predominant fibre direction corresponds to the weft bundle direction.

A stacking sequence of $[(0/90)/(0/90)_r]_{4s}$ was used, in which r indicates a flipped or reversed ply, to prepare a single laminate from which all specimens were cut. As mentioned earlier, two crack propagation directions were tested, parallel (//) and perpendicular (⊥) to the predominant fibre direction. Thus, two sets of specimens were prepared for each of the three testing techniques (DCB, ELS, and MP tests). All the test specimens required a pre-crack, which was in this case made by inserting a 13 μm thick Polyimide (PI) film (Upilex-S from UBE) during stacking of the semi-preg material. The PI films were inserted in four locations, as illustrated in Fig. 3. The PI films were added at the mid-plane to obtain the ELS and DCB specimens, while the films were added between the first and second ply for the mandrel peel specimens. It was

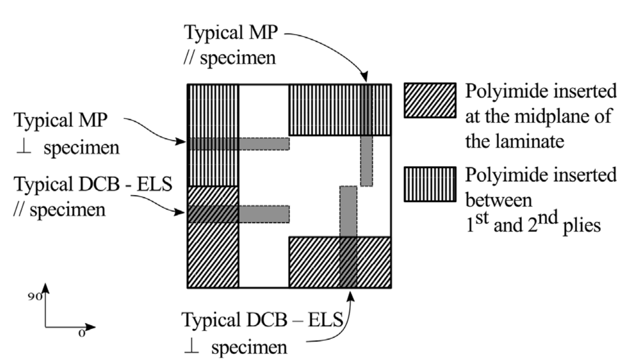

Fig. 3. Schematic view of the position of the polyimide films placed before consolidation. The 0° corresponds to the warp direction. MP: Mandrel Peel, DCB: Double Cantilever Beam, ELS: End-Loaded Split.//: Parallel. ⊥: Perpendicular.