Woven fabric composites: Can we peel it?

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Abstract

The present work focuses on the applicability of the mandrel peel test to quantify the fracture toughness of woven fabric Carbon/PEEK composites. For this purpose, the mandrel peel test was compared to the standardized DCB test. Unstable crack propagation (stick-slip) was observed in both testing techniques. Nevertheless, each time unstable crack propagation occurs it is arrested by the mandrel. As a result more crack re-initiations were observed per unit crack length. This effect is expected to increase the statistical relevance of a single test and thereby increases the reliability of the test. As an additional advantage the mandrel peel test is very easy to perform compared to the DCB test. The crosshead speed and the peel arm width were varied in this study to obtain the influence of these variables on the test results. Fractographic investigations were performed to study the nature of the crack propagation for the two different testing techniques.

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1. Introduction

Well-accepted test methods are available to characterize the static interlaminar fracture toughness of Uni-Directional (UD) composite materials. The most frequently applied methods are the double cantilever beam (DCB)
test for mode I, and the end-loaded split (ELS) beam test for mode II crack propagation. Both tests are illustrated in Figure 1. The existence of ISO (ISO 15024, and ISO 15114) and ASTM (ASTM D 5528, ASTM D 7905) standards for both methods illustrates their maturity. The reliability of these test methods is partially due to the stable crack propagation that most UD reinforced materials show during testing. When these methods are applied to woven fabric reinforced composites the crack propagation observed is however unstable [De Baere et al. (2012), Alif et al., (1998), Gill et al. (2009)]. This is particularly true for highly tough thermoplastic composites. The unstable crack propagation (stick-slip) that is frequently observed in DCB tests for the woven material yields few GIC values. Therefore, GIC-propagation values for UD specimens are statistically more reliable than GIC-unstable propagation value for woven specimens [Compston et al. (1998)]. Moreover, the unstable crack propagation makes the interpretation of the test results rather difficult and the comparison with unidirectional questionable.

A lot of effort has been spent in understanding the mechanism behind the stick-slip phenomenon [Webb et al. (1997), Webb et al. (1998), Maugis et al. (1988), Ciccottia et al. (1998), Kinloch et al. (1998)]. The resistance to crack growth is assumed to be a function of the crack tip velocity. Stick-slip fracture has been associated with unstable and non-monotonic crack growth resistance, especially in the regions of negative slope in the crack growth resistance vs. curvature or crack speed curve. This leads to a condition where steady continuous crack growth cannot be realized. When the unstable crack starts to propagate (crack tip velocity increases), it reduces the resistance thus increases the crack speed [Webb et al. (1997), Webb et al. (1998), Maugis et al. (1988)].

The stick-slip behaviour has been treated in different researches such as in Webb et al. (1997), Webb et al. (1998), Maugis et al. (1988), Ciccottia et al. (1998), Kinloch et al. (1998). The determination of the mode-I adhesive fracture energy of structural adhesive joints using double cantilever beam and tapered double cantilever beam specimens is discussed in the ISO 25217 standard. The standard proposes that the $G_{IC}$ values of initiation, propagation and arrest has to be averaged separately.

The mandrel peel test, as shown in the right illustration in Figure 1, may be a suitable alternative to DCB test for woven fabric reinforced composites. The test is an adaptation of the $90^\circ$ peel test and was first proposed by Kawashita et al. (2004) to measure the fracture toughness of a metal-epoxy-metal peel specimen. It involves the use of a mandrel to control the bending stresses in the peel arm. The previous works in [Kok et al. (2015), Su et al. (2016), Grouve et al. (2013)] showed that this test was able to characterize the fracture toughness of UD-UD, UD-woven and UD-metal combinations.

The observed stick-slip behavior and the tedious test procedure make the DCB test unattractive for woven fabric reinforced composites. As an alternative, the present work focuses on the applicability of the mandrel peel test to quantify the fracture toughness of woven fabric Carbon/PEEK composites. For this purpose, the mandrel peel test was compared to the DCB test. The crosshead speed and the tape width were varied in this study to study the influence of these variables on the test results. Fractographic investigations were performed to study the nature of the crack propagation with the different testing techniques.
2. Experimental methods

The present section describes the preparation of the materials as well as the DCB and mandrel peel test procedures. The DCB tests were carried out according to the ISO 15024 standard. As no standard exists for the mandrel peel test, the test was carried out based on an ESIS protocol [Kawashita (2005)]. The influence of test speed and specimen width on mandrel peel toughness was characterized experimentally as well.

2.1. Materials

One Carbon/PEEK 5 harness satin weave laminate from TenCate with a [(0/90)/(0/90)]₄s lay-up was press consolidated in a Pinette press at 10 bar and 380 °C for 10 min. For the crack initiation region, a 12.5 μm thick Polyimide film (Upilex S) was inserted prior to the consolidation process. The film was added in different positions to obtain both the DCB and the mandrel peel specimens from the same laminate. In one half of the laminate the film was inserted between the two first plies in order to obtain the peel specimens, while in the other half the same film was added at the mid-plane of the laminates to obtain the DCB specimens. The repetitive unitcell of 5 harness carbon/PEEK has a dimension of 7 mm. Peel samples of width 10 mm and 18 mm were cut from the first half of the laminate. The 10 mm wide specimens contain slightly more than one unit cell of the weave pattern in the width of the specimen, while the 18 mm specimens contain more than two unit cells in the width direction. Specimens of 20 mm width were cut from the laminate to obtain the DCB specimens. The dimension of the DCB samples follow the ISO 15024 standard.

2.2. Double cantilever beam test

The double cantilever beam test was performed according to the ISO 15024 standard. The specimens were tested in a servo-hydraulic Instron 8500 universal testing machine equipped with a 200 N force cell. The crack length was measured using an automated camera system, engineered to follow the crack tip during the test, mounted on the universal testing machine. The camera was fitted with a lens having a 20x magnification.

The applied force \( F \), the displacement \( \delta \) as well as the crack length \( a \) was measured during the test, performed at a displacement rate of 1.2 mm/min. The obtained data was reduced using the corrected beam theory (CBT). As the delamination length is measured directly using the horizontal displacement of the traveling camera system, there is no need for a correction to be applied to the measurements. All DCB samples showed unstable crack propagation, the fracture toughness was calculated only for re-initiation values.

2.3. Mandrel peel test

The mandrel peel setup used in this work has a mandrel with a radius of 10 mm and a width of 18 mm. A constant displacement rate was applied using a Zwick universal testing machine in which the peel set up is fixed. The alignment force \( F_a \), necessary to conform the peel arm to the mandrel, was applied using a pneumatic actuator. It was kept constant at approximately 60 N for the 10 mm wide tapes and 108 N for 18 mm tape. Two 200 N force transducers were used to measure the alignment and peel force \( F_p \). The test consists of two steps. First, the top ply is peeled from the laminate. The critical energy rate can be calculated from the measured forces using Equation 1.

\[
G_c = \frac{1}{W} (F_p (1 - \mu) - F_a)
\]  

However, the friction present in the setup \( \mu \) is not known. Therefore, as a second step, the test is performed again on the previously peeled specimen for which \( G_c \) is equal to zero. Consequently, the friction coefficient can be obtained from Equation 1 as:

\[
\mu = \frac{F_p - F_a}{F_p}
\]
It is worth noting that the fracture toughness, evaluated using the mandrel peel test, corresponds to a mixed mode propagation. Although the exact mode mixity is unknown, it is reported to be mainly mode I [Kawashita et al. (2004)]. In order to calculate the toughness, the internal stresses of the specimen have to be taken into account. The main sources for these stresses are thermal stresses developed during the consolidation of the material. These stresses are amplified further since a single ply of woven fabric material is not per-se balanced. However, the effect of internal stresses are not taken in to account in this study.

Three sets of samples were prepared to be tested with the peel set up, each sample containing 4 specimens. The first two samples were of 10 mm width. They were tested at two different constant displacement rates, i.e. 3mm/min and 30 mm/min, to analyse the influence of this variable on the measured fracture toughness. The last set of specimens, with 18 mm width, was tested at a constant displacement rate of 30 mm/min, to study the influence of the specimen width on the test result.

3. Results and Discussion

In this section the results from the DCB and peel tests, followed by the results from the fractographic analysis, are presented and discussed.

3.1. DCB test

A typical force displacement curve for the DCB tests, as carried out in this research, is shown in Figure 2. An unstable crack propagation (stick–slip) was observed in all 4 specimens with approximately 5 to 6 re-initiation values per specimen. The average crack propagation (or slip) distance was about 20 mm. The re-initiation points, as indicated by the peaks in Figure 2, were used to calculate the average and standard deviation values for the $G_{IC}$ for each specimen. The average and standard deviation of $G_{IC}$ of the sample was then calculated using the average $G_{IC}$ of the specimens. Both standard deviations can be used to analyse the statistical relevance of the tests. The results of the DCB test and mandrel peel tests are shown in figures 5 and 6.

![Figure 2: The grey line shows a typical force displacement curve for a DCB test. The black triangles represent the crack lengths just before the unstable crack propagation starts.](image)

3.2. Mandrel peel test.

As mentioned before, mandrel peel tests were performed on three samples. All the samples consist of 4 specimens. The different test parameters for each sample are shown in Table 1. The peel distance was kept constant at a value of 60 mm in all the three cases. Figure 3 shows a typical force-displacement curve of a mandrel peel test specimen and a force-displacement curve which represents the friction in the system. The latter was obtained by redoing the mandrel peel experiment on an already peeled specimen. The friction coefficient can now be obtained from Equation 2. The friction coefficients for the three samples are reported in Table 1. Figure 4 gives the fracture as a function of the peel distance.
indicating by the peaks in Figure 2, were used to calculate the average and standard deviation values for the G IC for values per specimen. The average crack propagation (or slip) distance was about 20 mm. The re-initiation points, as unstable crack propagation (stick–slip), are presented and discussed.

The different test parameters for each sample are shown in Table 1. The peel distance was kept constant throughout the specimens. Both standard deviations can be used to analyse the statistical relevance of the test results. The results of the DCB test and mandrel peel tests are shown in Figures 5 and 6.

As mentioned before, mandrel peel tests were performed on three samples. All the samples consist of 4 plies of woven fabric material, with a laminate thickness of 1.5 mm. The first two samples were of 10 mm width. They were tested at two different constant displacement rates, i.e. 3 mm/min and 30 mm/min, to analyse the influence of this variable on the measured fracture toughness. The last set of samples, with 18 mm width, was tested at a constant displacement rate of 30 mm/min, to study the influence of the specimen width on the test result.

Stick-slip behavior can be observed in the force displacement curves shown in Figure 3 and 4. In Figure 4, the grey squares show the values used to calculate the toughness. As in the DCB test the maximum peaks were used to calculate the toughness.

As the standard deviation. Similar results are shown in Figure 6, which shows the fracture toughness for the different samples with standard deviation.

In the same way as with the DCB test, a toughness value per specimen was calculated. After which, an average toughness value per sample was calculated. The results of the calculations for both the DCB and the mandrel peel tests are shown in Figures 5 and 6, and discussed in the next section.

### 3.3. Interlaminar Fracture Toughness

Figure 5 shows the average fracture toughness values measured for each specimen with the standard deviation, which is close to 20% for all the specimens (both DCB and mandrel peel test). The DCB specimens show a slightly lower standard deviation than the mandrel peel specimens. For the two rates tested, the mandrel peel results were not affected by test rate, whereas an increase in specimen width results in a decrease of mandrel peel toughness as well as the standard deviation. Similar results are shown in Figure 6, which shows the fracture toughness for the different samples. It can be noted, however, that the sample standard deviation is much lower than the specimen standard deviation.
deviation. The DCB samples and mandrel peel samples, with a peel arm of 10 mm width, show similar toughness values. The peel test with a wider peel arm shows a slightly lower toughness. Further research is required to understand these results.

3.4. Distance between the instabilities

As elaborated above, crack propagation showed stick-slip behavior during both the mandrel peel test and the DCB test. Two different cases were observed during peeling, as is shown in Figure 7. In the first case, the crack does not propagate (stick) and as a result conformation of the peel arm to the mandrel cannot be maintained (see Figure 7 A). In the second case, the crack propagates (slip) with the peel arm completely conforming to the mandrel (Figure 7 B). Both cases were alternatingly observed during testing.

![Figure 7: Schematic illustration of the peel arm behaviour during testing. A) Represents the situation before an unstable crack propagation occurs, where the peel arm does not conform to the mandrel. B) Represents the situation after an unstable crack propagation, where the peel arm conforms to the mandrel.](image)

The distance between these instabilities can be measured from the distance between the peaks in the force-displacement curves. The measured distances are shown in Table 2. The average propagation distance for the DCB tests is reported in the same table for comparison. The DCB test shows 20 times larger distance between the instabilities in comparison with the mandrel peel test. Thus, less material is required to measure the same number of unstable points in the mandrel peel test. Within the mandrel peel tests it seems that the distance between instabilities reduces by increasing the speed of the test and the width of the specimen. Nevertheless further research is required to understand these phenomena.

The distance between the instabilities can be observed in the micrographs as well. Typical beach marks could be observed in the fracture surfaces of both the DCB and mandrel peel test specimens. Figure 8 shows a typical example in which two types of crack propagation zones can be observed as distinguished by color. The white lines, perpendicular to the direction of the crack propagation, relate to local plastic deformation of the matrix as described by Frassine et al. (1995), where this area was correlated to a small region of stable crack propagation. Adjacent to these regions, a long path of dark area is present which is correlated to an unstable crack propagation.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Average distance between peaks</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCB</td>
<td>20.3 mm</td>
<td>2.2 mm</td>
</tr>
<tr>
<td>3mm/min 10 mm W</td>
<td>0.94 mm</td>
<td>0.1 mm</td>
</tr>
<tr>
<td>30mm/min 10 mm W</td>
<td>0.83 mm</td>
<td>0.07 mm</td>
</tr>
<tr>
<td>30mm/min 18 mm W</td>
<td>0.72 mm</td>
<td>0.06 mm</td>
</tr>
</tbody>
</table>

Table 2: Average distance between peaks for the different samples tested
4. Conclusion

The feasibility of the mandrel peel test to characterize the fracture toughness of woven fabric reinforced thermoplastic composites was studied by comparing it to the standardized DCB test. The mandrel peel test can be considered to be an easy and fast test compared to the DCB test. Both testing techniques yielded similar fracture toughness values and have shown similar stick slip behavior. However, the mandrel used in the peel test limited the unstable crack propagation distance. Consequently, a single mandrel peel test has produced more than 20 times the amount of data points per unit crack length than the DCB test. Hence, the mandrel peel test can be considered to be more statistically relevant than DCB test. Nevertheless, this is in contradiction with the slightly higher standard deviation observed in the mandrel peel test with respect to the DBC test.

The mandrel peel test seems to be a good alternative to the DCB test for woven fabric reinforced composites. However, further research is required to understand the effect of mode mixity, internal stresses in the sample, and test parameters on the measured results of the mandrel peel test.

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