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Effects of fiber orientation of adjacent plies on the mode I crack propagation in a carbon-epoxy laminates

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Abstract

The influence of ply orientation on the resistance to mode I delamination of multidirectional composite laminates can be assessed by Double Cantilever Beam (DCB) tests. However, one of the difficulties associated with such a study is the change in overall elastic parameters occurring when modifying local ply orientations. The present work uses laminates with special stacking sequences allowing for isolating the orientation parameter. Multidirectional DCB specimens were designed so as to obtain an uncoupled quasi isotropic and quasi-homogeneous elastic behavior, with the same properties for the entire laminate and the two sub laminates separated by the pre crack at mid-plane.
The results show that the toughness in term of G_{IC} is slightly affected by the variation of ply orientations at the crack interface. The differences are more pronounced in the crack propagation behavior after the initiation point. Even with the same orientation at the crack interface, different subsequent ply orientations can also lead to different crack resistance behavior.

Keywords: Fracture toughness; Delamination; DCB test; Ply orientation; QIQH laminates

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1. Introduction

Efforts in characterization of delamination resistance, in particular mode I fracture, have led to the standardization of the double cantilever beam (DCB) test for measuring the critical strain energy release rate, G_{Ic}, of unidirectional (UD) laminates [1-3]. Even though such specimens are quite convenient for testing purposes, most applications involve multidirectional (MD) laminates, where delaminations do occur between layers of different fiber orientations. Hence obtaining G_{Ic} values of MD specimens is of great importance for the development of accurate fracture criteria.

The applicability of the standard DCB specimen for delamination resistance testing of carbon/epoxy multidirectional laminates has previously been assessed [4,5]. Multidirectional lay-ups have been reported to produce crack branching and/or deviations of the delamination from the central plane, which invalidate the analysis, according to the ISO standard [2]. The migration of the delamination from the original defect plane would means that the test is no longer characterizing the interface of interest. Hence delamination resistance from DCB test on multidirectional laminates can probably be quantified for initiation only.

Some studies have concluded that the measured initiation G_{Ic} were practically independent of the fiber orientation of the delaminating interface [5], while other studies concluded otherwise [6,7]. Some researcher even indicates that not only the values of G_{Ic} are affected by the fiber orientation of the adjacent plies, but the value can also increases with the change of orientation of the sub-adjacent plies [8].

In light of such findings, it is of a great interest for this study to get more understanding on the effects of different fiber orientation of the adjacent plies on the mode I crack propagation. In such effort, the ability to eliminate or minimize other factors from affecting the crack behavior during the experimental tests would be of a great advantage. In such condition, the observed behavior of laminates delamination can be linked directly to the stacking sequence and ply orientations.

The present work uses special stacking sequences that allow for the assessment of the influence of the fiber orientation without changing the whole elastic behavior of the specimens. Multidirectional DCB specimens were designed so as to obtain an uncoupled quasi-isotropic and quasi-homogeneous (QIQH) elastic behavior, with the same properties for the entire laminate and the two arms separated by the pre-crack at mid-plane.

2. Design of MD DCB specimens

The MD specimens used in our DCB delamination tests have an initial crack at mid-thickness that separates the whole laminate at one edge into two sub-laminates (two arms). The intention is to have the entire laminate and the two arms to have an uncoupled quasi-isotropic and quasi-homogeneous elastic behavior. Two 24-ply quasi-isotropic quasi-homogeneous sequences used by Galliot et. al. [9] have been chosen for this study. Both arms of the specimens are 24 ply QIQH laminates, hence the entire laminate is a 48 ply QIQH laminate. For this study, three crack interfaces, and thus stacking sequences, are being studied, as shown in Table 1.

3. Test Procedures

During the draping process, polyester film of 15 μm thickness was embedded at mid-thickness to produce a crack starter. Laminates were cured in a hot press at 125 °C and 3.9 bar for 100 minutes. The laminates were cut into specimens whose dimensions are shown in Table 2. The specimens were loaded at room temperature with constant crosshead rate of 0.5 mm/min, and the load and displacement were recorded. For each specimen lay-up, DCB testing was performed on at least five specimens to obtain the mean value of the fracture toughness.

Table 1. Stacking sequences studied.

Specimen	Stacking sequence
(90/0//0/90)	[90/0/-45/45/-45/45/0/45/90/-45/90/0/90/0/45/0/-45/90/-45/45/-45/45/90/0]sym
(-45/45//45/-45)	[-45/45/0/90/0/90/45/90/-45/0/-45/45/-45/45/90/45/0/-45/0/90/0/90/-45/45]sym
(90/45//45/90)	[90/45/-45/0/-45/0/45/0/90/-45/90/45/90/45/0/45/-45/90/-45/0/-45/0/90/45]sym

Table 2. Mean values of specimen dimensions (standard deviation in brackets)

Specimen	Width (*mm*)	Thickness (*mm*)	Initial crack length (*mm*)
(90/0//0/90)	20.28 (0.18)	6.94 (0.07)	70.02 (0.30)
(-45/45//45/-45)	19.89 (0.13)	7.05 (0.07)	70.16 (0.68)
(90/45//45/90)	20.26 (0.15)	7.06 (0.05)	70.34 (0.66)

4. Results and Discussion

4.1. Data reduction methods

For DCB mode I tests, the interlaminar fracture toughness in term of the critical strain energy release rate can be determined by the Irwin-Kies s formula:

$$G_{Ic} = P_c^2/2b \ dC/da \qquad (1)$$

where specimen compliance C is the ratio of the load point displacement   to the applied load P; P_c is the critical load at crack initiation; b is the specimen width and a is the initial crack length.

Different models for calculating G_{Ic} have been evaluated during round-robin testing [1]. These consisted of a modified beam theory (MBT), a Berry s compliance calibration method (CC) and a modified compliance calibration method (MCC). None of the three is considered to be clearly superior to the others [1], and the experimental calibration of compliance is necessary in multidirectional DCB tests for accurate results [8]. For this present study, the modified compliance calibration method (MCC) will be used for G_{Ic} calculations. The equation is as follows:

$$G_{Ic} = nP_c \ _c/2ab \qquad \textit{with Berry s compliance calibration: } \ C = \ a^n \qquad (2)$$

4.2. Experimental Results

From the DCB tests performed, the force versus displacement plots were obtained. They are presented in Fig. 1. One obvious observation from the results is that all the specimens undergo unstable crack propagation at their crack initiation, where sudden jump occurred. This would directly impact the consequent behavior of the crack propagation. However, there are still much to be analyzed from the comparison of crack propagation behavior observed between the three sets of specimen.

Fiber bridging was observed to be more intense for the specimens with 45°//45° crack interface, as compared to that of 0°//0° interface. The curves for 45°//45° crack interface present a strong scattering due to the uncertainties of bridging phenomena, which are unique from one particular specimen to another. Obviously we cannot say that the crack propagation behavior observed from each specimen to be intrinsic property of such lay-up, but the observation on how the pattern differ from one set of specimen to another does give some insight into whether the difference in ply orientation induce any difference on crack initiation and crack propagation behavior.

For such conclusion to be made, the tests need to be isolated from other factors that may affect crack behavior. As mentioned earlier, the stacking sequences were designed so that the laminates are quasi-isotropic for their overall elastic behavior, both in the two arms and the entire specimens. For direct comparison of the plot, on top of the selection of the stacking sequence, the specimen dimensions need to be the same, if possible. Using manual cutting process to produce the specimens from the plate, the task would be to minimize any variation in dimensions between the specimens. The mean value for the specimen dimensions are as shown in Table 2. Table 3 presents normalized compliances measured on all of specimens. The difference between these values is around one percent, so the same elastic properties can be confirmed for three sets of specimens.

Table 3. Mean values of normalized compliance and G_{Ic} for corresponding specimen lay-up (standard deviation in brackets)

Specimen	Normalized Compliance (10^{-3} mm/N)	G_{Ic} (N/m)
(90/0//0/90)	93.68 (2.75)	473.38 (17.05)
(-45/45//45/-45)	93.61 (3.70)	497.34 (33.86)
(90/45//45/90)	92.57 (2.37)	442.60 (58.86)

Concerning the measured values of G_{Ic} on three interfaces, some differences can be observed, but they cannot be considered as really significant (Table 3).
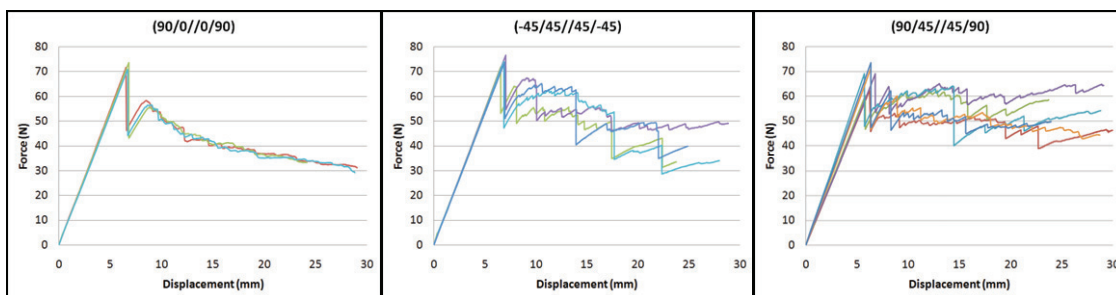

Fig. 1. Force versus displacement plots for (a) specimen (90/0//0/90); (b) specimen (-45/45//45/-45); (c) specimen (90/45//45/90)
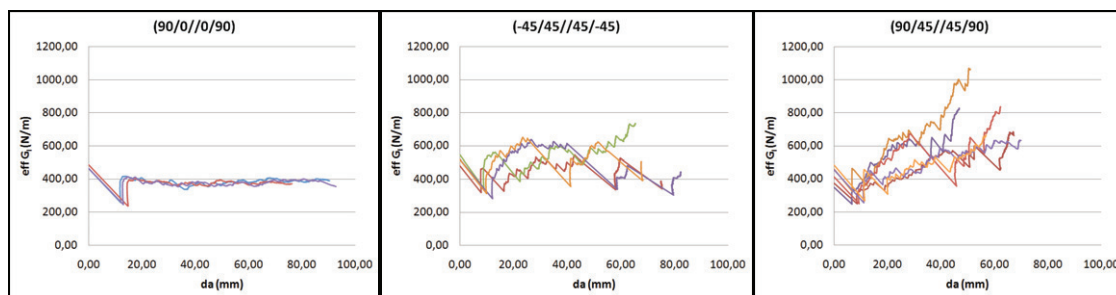

Fig. 2. Effective strain energy release rate G_I as crack propagates for (a) specimen (90/0//0/90); (b) specimen (-45/45//45/-45); (c) specimen (90/45//45/90)

However, R-curves, which characterize resistance to crack propagation, look quite different between the three specimen sets. The plots are as shown in Fig. 2. The sudden jump in crack extension accompanied by a drop in G_I value at the beginning of each curve is due to the sudden unstable crack that occurred at crack initiation, which was mentioned earlier.

After the onset of delamination, very clear difference can be observed in the pattern of the plots. For crack interface of 0°//0°, the fluctuation of G_I value is very small compared to that of specimens with crack interface of 45°//45°. G_I value stabilizes and fluctuates around 400 N/m. The stabilized state can be associated to the state where the occurrence of bridging is at a stable rate as crack continues to propagate. In fact, during DCB tests on (90/0//0/90) specimens, very small amount of bridging was observed, and they are concentrated at the small region near the crack front.

As for specimens with crack interface of 45°//45°, big and unstable fluctuations can be observed. This can be associated with the significantly greater amount of fiber bridging that occurred during the experimental tests. The increment in G_I value can be associated with the increase of bridging occurrence, while the sudden jump in crack extension accompanied by the drop in G_I value can be associated to the breakage of the bridging that occurred as the displacement steadily increases.

In the case of (-45/45//45/-45) specimens, it can be observed that when the fiber bridging is saturated, fiber breaking occurs, the G_I value has a tendency to drop back to around 400 N/m, which is the value where the G_I value for (90/0//0/90) stabilizes. The fiber bridging immediately builds up again, which leads to the increase of G_I value. This cycle continues as crack extension increases.

Compared to (-45/45//45/-45) specimens, the increase in G_I value for (90/45//45/90) specimens is more pronounced, and the maximal value of G_I can reach higher levels. Herein the fiber bridging was observed to be more pronounced and associated with crack shifting. The effects of these contrasting phenomena can be observed from the fractured surfaces of the specimens, which are shown in Figure 3.

The surfaces of (90/0//0/90) specimens do not present much indication of fiber bridging, while surfaces of both (-45/45//45/-45) and (90/45//45/90) specimens appear to be more rough , with indication of fiber bridging occurrences. The crack shifting is clearly observable for (90/45//45/90) specimens but occurred in an unpredictable manner, sometimes at the beginning of the crack propagation, sometimes after a longer time, as illustrated by figures 3 d) and c). The presence of 90° layers behind the 45° layers in the case of (90/45//45/90) specimens allows for an easier crack shifting mechanism. In the case of (-45/45//45/-45) specimens, it would be more difficult for this phenomenon to occur.
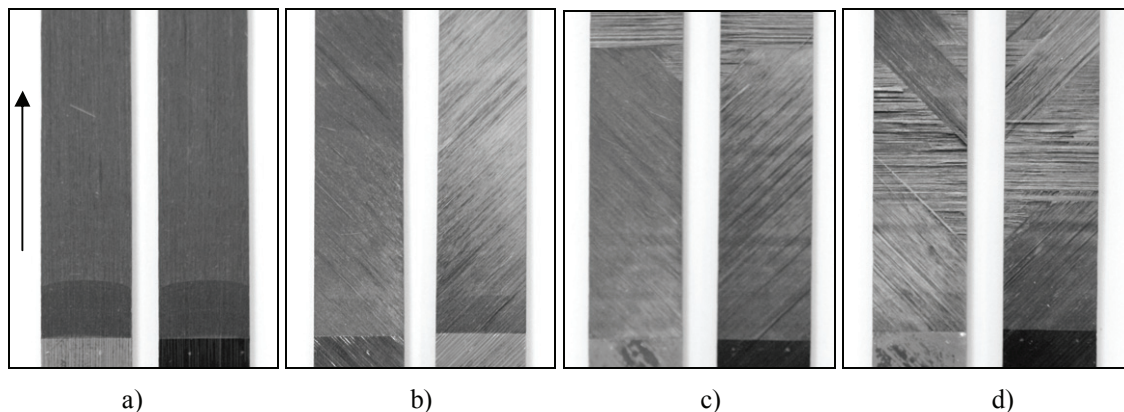

a)   b)   c)   d)

Fig. 3. Fracture surface of: a) specimen (90/0//0/90); b) specimen (-45/45//45/-45); c) and d) two samples of (90/45//45/90) specimens illustrating crack migration occurring at different crack extension. The arrow shows the crack propagation direction.

These observations indicate that ply orientation at the crack interface does have an effect on the crack initiation and crack propagation behavior of carbon-epoxy laminates. Furthermore, the results pointed out that the behavior is affected not only by the orientation of the ply at the crack interface, but also by the orientation of the subsequent ply. However, to fully understand and characterize how the ply orientation combinations would alter the mode I crack behavior, more ply orientation combinations need to be tested.

5. Conclusion

An experimental study was conducted on mode I interlaminar fracture of carbon-epoxy multidirectional laminates. Three stacking sequences that give quasi-isotropic and quasi-homogeneous specimens were selected. DCB tests were performed and crack initiation and propagation behavior were observed. The toughness in term of G_{IC} is slightly affected by the variation of ply orientations at the crack interface. Even with the same orientation at the crack interface, different subsequent ply orientations can also lead to different crack resistance behavior. The effect of ply orientation variations of both plies at the crack interface and the subsequent plies are more obvious in the crack propagation behavior after the initiation point.

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