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USE OF A WIDTH-TAPERED DCB TO DETERMINE MODE I FRACTURE TOUGHNESS OF AN ASYMMETRIC COMPOSITE LAMINATE

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ABSTRACT

Mode I fracture toughness is a key material property that is used in modeling the damage tolerance of a composite part. Current standard measurement practice involves using a double cantilever beam (DCB) test where a precrack is introduced into a laminate and the crack is opened in tension. Load, crack opening displacement, and crack length are measured as the crack extends down the length of the coupon. Despite careful effort, the crack length can be difficult to determine accurately and the resulting calculated fracture toughness values (G_{1c}) can have significant scatter. In this study, standard fixed width DCB tests are compared to width-tapered DCB tests and in both cases the fracture toughness is calculated with the compliance method. The advantage of using a width-tapered DCB coupon is that stable crack growth occurs at a constant load so measurement of the crack length or crack tip opening displacement is unnecessary. In this study the equivalence of both the fixed width and width-tapered DCB tests is shown. Therefore, in situations where crack length or crack tip opening measurements can be difficult to obtain accurately (high rate, elevated temperature) the width-tapered DCB can be quite useful.

1. INTRODUCTION

Double cantilever beam (DCB) testing is the standard test method for determining mode I fracture toughness of fabric composites or adhesively bonded joints [1]. The industry standard is to use a fixed width DCB to perform the test and one of a number of different methods to calculate the fracture toughness [2]. One method includes the area method where the crack length is measured at distinct points throughout the test and the area of the load-unload behavior in the load-displacement curve between any two of those points is equivalent to the energy released during the crack length extension between those two points. Another is the compliance method, where

$$G_{Ic} = \frac{P^2}{2b}\frac{dC}{da} \quad [1]$$

where P = load
b = width of DCB
a = length of crack
C = total beam compliance

The advantage to using the compliance method as opposed to the area method is that the experiment is much simpler to perform. Constant monitoring of the crack length is unnecessary and the result is a continuous calculation for the fracture toughness from the inferred crack length based on simple linear elastic beam theory, the measured load, and the crack opening displacement. Of course this does assume that the cantilever beams remain linear elastic and that the cohesive process zone ahead of the crack tip does not allow significant rotations of the beams at the crack tip. The effectiveness of this assumption can be improved with proper specimen design. The area method can be tedious and produce significant scatter between the different calculated fracture toughness values. Since the goal of this study is to compare the standard fixed width DCB specimen design and procedure with the width-tapered DCB specimen, the compliance method is chosen.

The resulting load-displacement plot for a fixed width DCB specimen shows a linear loading path until the initial precrack begins to extend followed by a nonlinear softening as the crack extends. This can be difficult to interpret as the test is running. In 1978 Mostovoy designed the width-tapered DCB specimen [3]. The advantage of the width-tapered DCB specimen is that, for constant fracture toughness, the crack extends at a constant load. The angle of the taper does not change this fact; all that is needed is for a taper to exist and for the tensile load to be applied at the taper's point. This allows the operator to have instant feedback as to whether the test will yield consistent fracture toughness. In the nearly forty years since this method has been introduced, it has been used sparingly when compared to the fixed width DCB specimen [4-6]. This is most likely due to reliance upon the ASTM standard mentioned earlier. The goal of this study is to investigate how the two methods differ in their ease of use and effectiveness.

The material investigated in this study is an asymmetric composite panel with a co-cured carbon fiber reinforced polymer laminate bonded to a glass fiber reinforced polymer laminate. Since the two cantilever beams are asymmetric with varying bending stiffness, the crack opening displacement must be broken into the individual contribution from each. Brown derived the form of the fracture toughness calculation for an asymmetric DCB shown below [7]

$$G_{1c} = \left[\frac{27\delta^2}{2b^4} \left(\frac{1}{E_1 h_1^3} + \frac{1}{E_2 h_2^3} \right) P^4 \right]^{\frac{1}{3}} \quad [2]$$

where P = load
b = width of DCB
d = crack opening displacement
E_i = Young's modulus of material *i*
h_i = thickness of laminate *i*

For the width-tapered DCB, this function takes a much simpler form

$$G_{1c} = 12P^2k^2 \left(\frac{1}{E_1 h_1^3} + \frac{1}{E_2 h_2^3} \right) \quad [3]$$

where k = a/b

In this case, the fracture toughness is proportional to the load squared and the taper angle is incorporated in the constant k which is simply the ratio of the crack length, a, to the width of the DCB at the crack tip, b. In this study, both methods are performed on the same material.

2. EXPERIMENTATION

2.1 Material Description

Specimens were manufactured from an asymmetric composite plate which had been cured in 2008. It consists of a carbon fiber reinforced polymer (CFRP) which was co-cured with a glass fiber reinforced polymer (GFRP). At the interface between the CFRP and the GFRP a Teflon coated strip was added near slightly off center along the length of the plate. This Teflon coated strip generates the precrack necessary for DCB testing. An image of the cured laminate is shown in Figure 1.

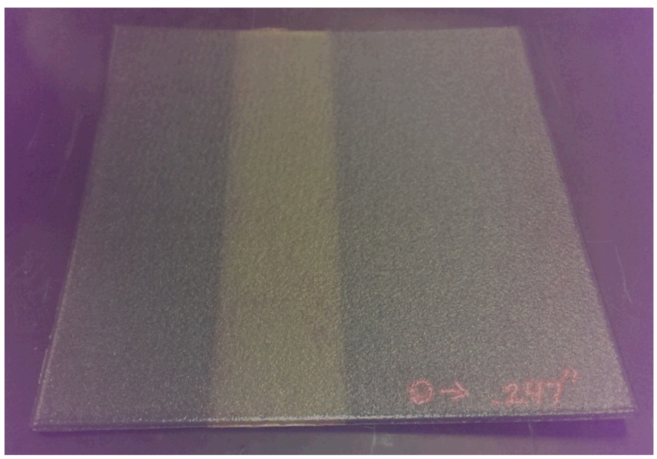


Figure 1. Co-cured CFRP and GFRP composite with Teflon coated precrack strip

The relevant material description and properties for this study are listed in Table 1. The moduli of the GFRP and CFRP were determined in a previous study [7].

Table 1. Material definition and properties

Material	Fiber	Resin	Weave	Thickness (mm)	E_1 (GPa)
GFRP	3k E-Glass Hexcel 7781	UF3362	8-harness satin	4.52	29
CFRP	1k Toray T-300	UF3360	5-harness satin	1.96	59

It is worth noting that from the CFRP and GFRP laminate thicknesses and moduli, the Teflon coated strip is not positioned at the neutral axis of this plate. The bending stiffness of the GFRP is more than four times greater than that of the CFRP. This will result in the curvature of the CFRP being much greater than that of the GFRP during the DCB testing.

2.2 Specimen Design and Manufacturing

The specimens used in this study were all made from a plate similar to the one depicted in Figure 1. The fixed width DCBs were machined from the short side of the plate when compared with the Teflon coated strip while the width-tapered DCBs were manufactured from the long side. The design of the fixed width DCBs is quite simple (Figure 2). Strips approximately 25.4mm in width were cut from the plate using a water-cooled diamond saw. Piano hinges were bonded to the either side of the specimen so the hinge was positioned approximately 25.4mm from the end of the Teflon coated strip. The adhesive used was a high toughness 2-part epoxy (Hysol 9430) and it was allowed to cure for at least 24 hours.

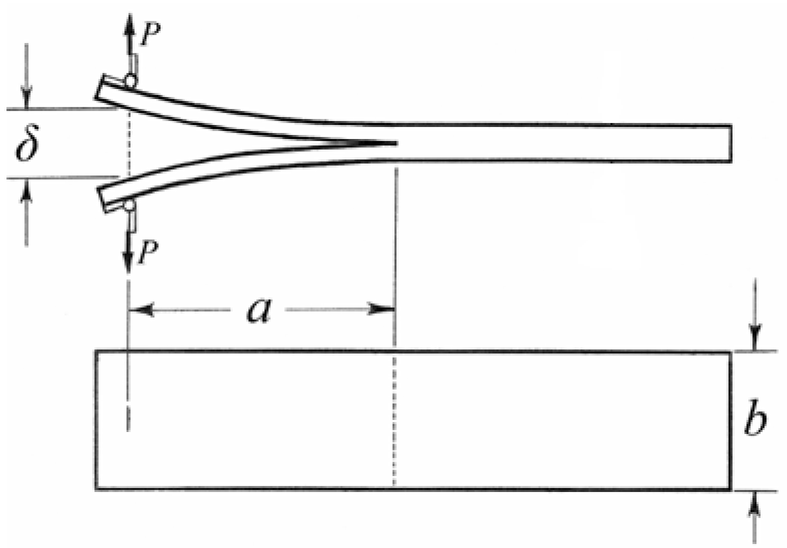


Figure 2. Fixed width DCB specimen design

The width-tapered DCBs have a more complex geometry. The design used was suggested by Fenner and Daniel (Figure 3) [8]. Theoretically the width-tapered beam should come to a point where the load is then applied. Due to the impracticality of that situation, a wide rectangular tab section is machined into the end so the hinge has some area to be bonded. The specimens used in this study have a much longer tabbed region than the one depicted in Figure 3 because the hinge was bonded facing away from the direction of crack extension. So the dimension of 6.4mm is actually 25.4mm in this study. This was done so the hinge itself does not provide added stiffness to the beams.

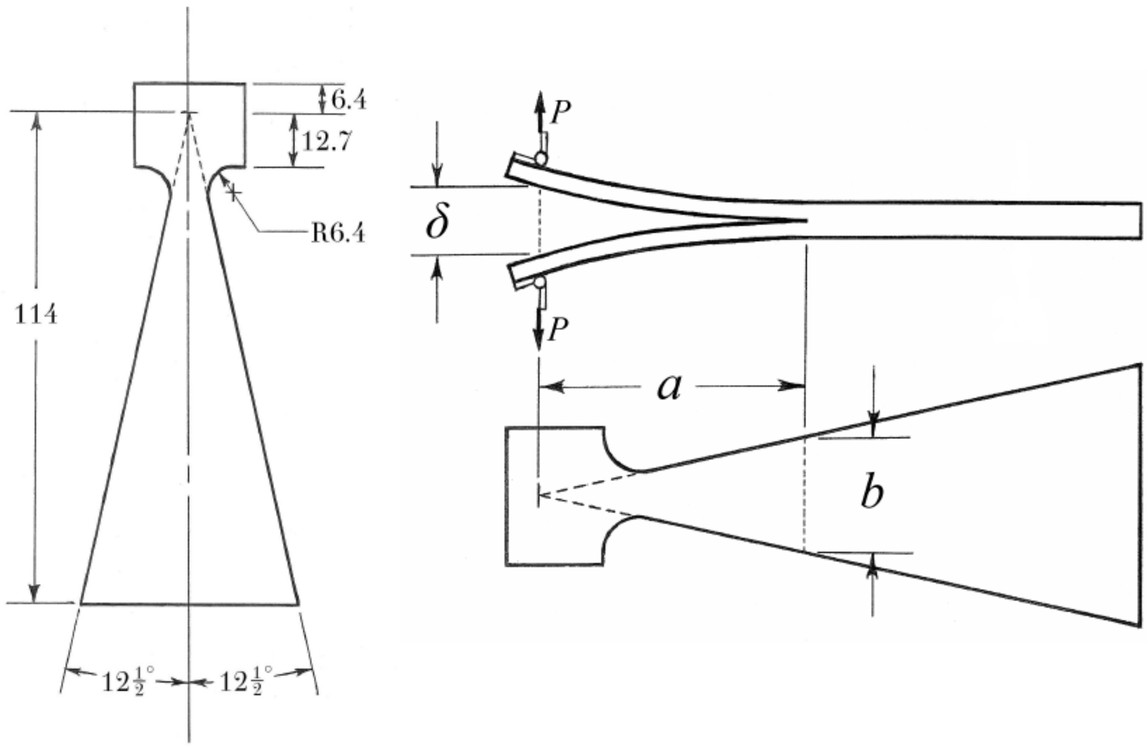


Figure 3. Width-tapered DCB design

The major drawback of performing a study that employs width-tapered DCBs is the added time and effort needed to machine its complex geometry when compared to the relatively simple fixed width DCBs. Approximately 50.8mm strips were cut from the co-cured laminate using the water-cooled diamond saw. These strips were then placed inside a custom designed milling fixture shown in Figure 4. The upper half of the fixture is used to provide compressive support as a composite end mill machines each side of the width-tapered DCB. This support keeps the machining process from pulling up on the top surface and producing small cracks that would damage the specimen. The CNC mill saves significant time and effort and produces specimens of the exact geometry specified. The edge of the Teflon coated strip is positioned just beyond the radius of the coupon so that is where the initial crack is started.

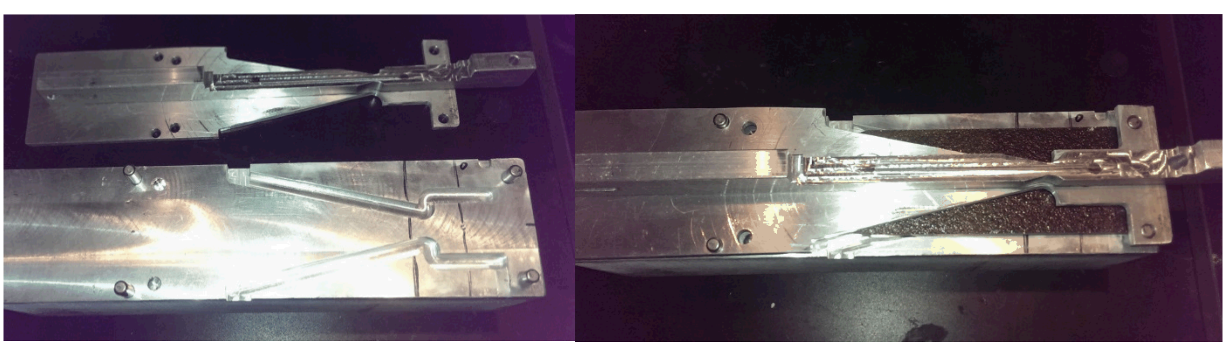


Figure 4. Width-tapered DCB machining fixture

Since it is critical to load from the point of the tapered beam, a custom hinge bonding fixture was designed and 3D printed (Figure 5). This allows the hinge to be placed inside a pocket that can then be aligned with the taper of the specimen. Since both halves interlock, the result is a specimen with perfectly aligned hinges.

Figure 5. 3D printed hinge bonding alignment fixture

One of the advantages of the width-tapered DCB is that a long fixed width section can be left at the end of the taper. Once the test has been completed, this specimen can then be re-machined with a new taper and the test can be resumed with a sharp crack tip. The result of the specimen manufacturing and machining can be seen in Figure 6.

Figure 6. Finished fixed width and width-tapered DCB specimens

2.3 Experimental Procedure

The experiments were performed using an MTS Bionix axial-torsional test system. Since the loads expected were small, a secondary 122N load cell was used in line to provide a more accurate, higher resolution load signal. The upper hinge was supported on a pull rod that had a ball joint attached to it. This allowed it to both self-align along the machine loading axis and rotate so any torsional load on the hinge was minimized. The crack opening displacement was measured by use of a laser extensometer. Laser tape was applied to the hinge fixture so any rotation of the ends of the beams did not produce an error. An image of this setup can be seen in Figure 7 with the actuator located above the specimen and the secondary load cell mounted below.

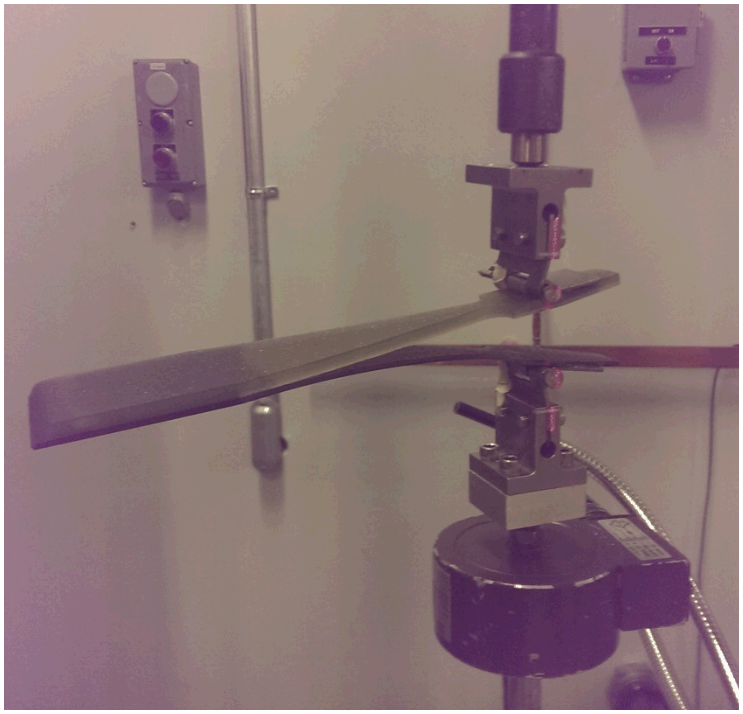


Figure 7. Experimental setup

All tests were conducted in displacement control with a displacement rate of 0.5 mm/min. Data acquisition was performed at 100 Hz. For the fixed width DCB specimens, a crack opening displacement was set at 25mm while the width-tapered DCB tests were monitored and stopped before the crack extended beyond the tapered portion of the beam.

3. RESULTS

In this study, three specimens were tested using both the fixed width and the width-tapered DCB coupons. In both geometries some minor fiber bridging could be seen during the test as the glass fiber appeared to pull out while the crack extended (Figure 8). Fiber bridging corresponds to a rising resistance curve; fibers bridging the crack will lead to higher loads so the fracture toughness will appear to increase with the crack length. As will be shown below, any effect from fiber bridging appears to be minor.

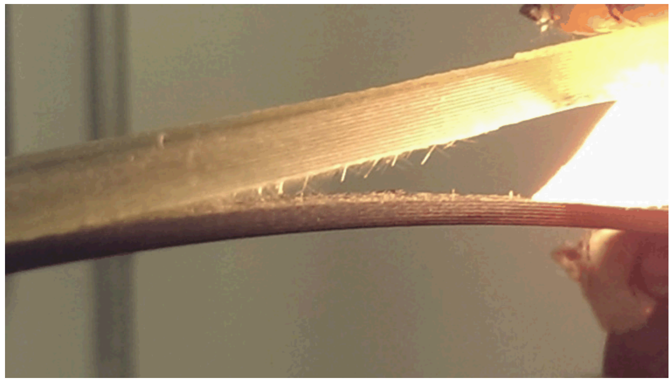
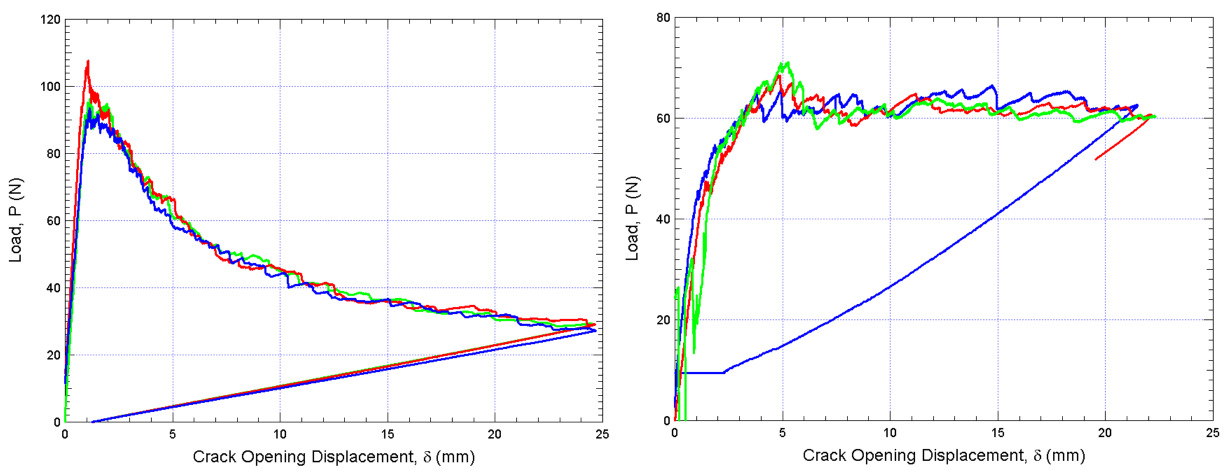


Figure 8. Minor fiber bridging during test

The test produces very consistent data from specimen to specimen as evidenced in the load-crack opening displacement curves (Figure 9). For the fixed width DCB tests, the load is nonlinear with displacement; once the crack begins to extend, it starts to drop so at longer crack lengths, it takes less load to extend the crack. For the width-tapered DCB tests, there is an initial region where the crack begins to extend and the load is not constant. This is due to the narrow region at the beginning of the test producing more scatter in the fracture toughness. Once the crack reaches a certain length, there are a sufficient number of unit cells of the fabric across the width and the load flattens out. In some of the early testing, the loading of the width-tapered DCB tests is not very linear. This is because the ball joint on the upper tension rod was not rigid enough to support the weight of the coupon. In subsequent tests, the end of the beam was lightly supported until the applied load added enough rigidity to the fixturing to keep the coupon end from falling and then the support was removed. The effect of this method of support can be seen in the fixed width DCB test data.



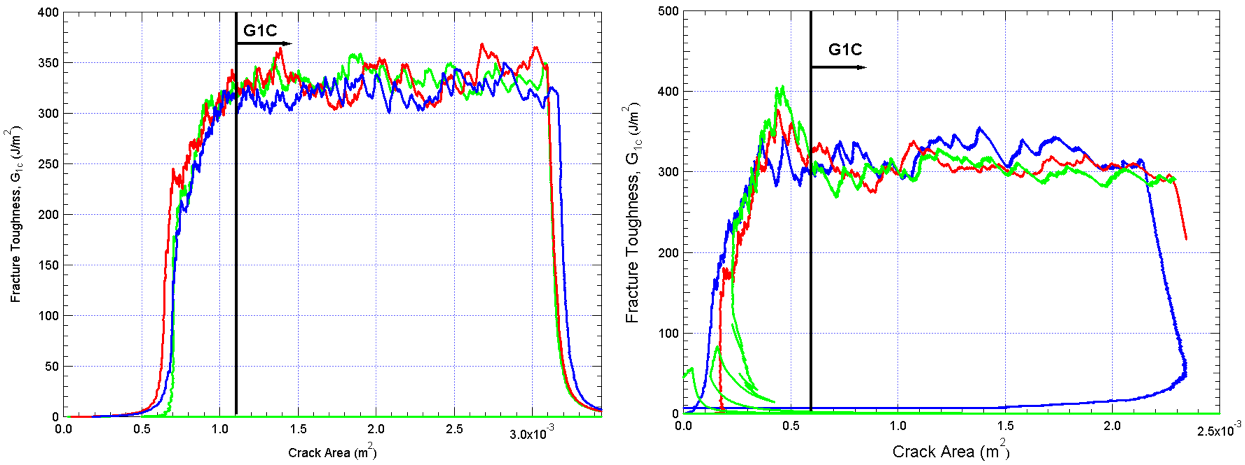
(a) (b)

Figure 9. Load-crack opening displacement curves for (a) fixed width and (b) width-tapered DCB specimens

Using equations [4] and [5] the fracture toughness for the two testing methods could be calculated (Figure 10). Typical test data is plotted against either crack length, a, or crack opening displacement, d. However, since the geometry of both specimens was quite different it was decided that crack area would be a more useful parameter. For the fixed-width DCB specimen this value is proportional to the crack length, a, but for the width-tapered DCB the crack area grows nonlinearly as the crack length increases.

$$Area = ab \qquad [4]$$

$$Area = \frac{a^2}{2k} \qquad [5]$$



(a) (b)

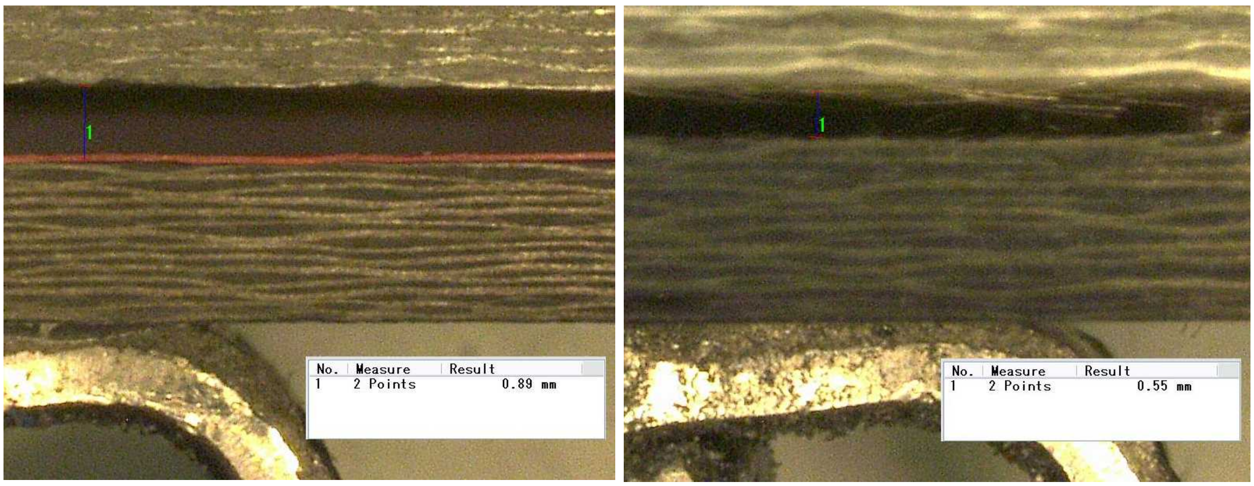
Figure 10. G_{1C}-crack area curves for (a) fixed width and (b) width-tapered DCB specimens

The value of G_{1C} was then averaged over the portion of the test where the crack length is valid. For the fixed width DCB, this is when the effect of the blunt crack tip is overcome at the beginning of the test (crack area of 1100mm^2). For the width-tapered DCB this is a combination of when the effect of the blunt crack tip, the added stiffness of the tab region as compared to a perfectly tapered beam, and when the number of unit cells across the width of the beam is adequate (crack area of 600mm^2).

Table 2: G_{1C} Test Results

	Specimen	**Mean (J/m^2)**	**St. Dev.**		**Specimen**	**Mean (J/m^2)**	**St. Dev.**
Fixed Width DCB	1	334	9.3	**Width Tapered DCB**	1	307	11.8
	2	335	15.7		2	301	11.6
	3	322	10.9		3	321	15.0
	Total	330	12.3		Total	310	12.9

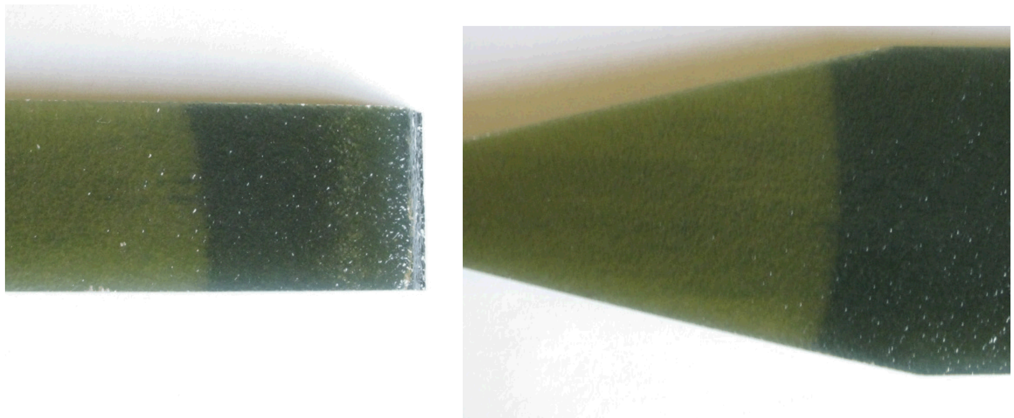
The two methods show similar consistency in the calculated fracture toughness when comparing sample to sample and method to method. Producing an accurate figure for the mode I fracture toughness of a composite laminate is highly dependent on both the calculation method and specimen geometry. Numerous studies have shown that the same test can produce a range of fracture toughness values depending on whether it was analyzed using the area method, the compliance method, the load method, or the displacement method. In this study, the compliance method was used to analyze both method types. The fixed width DCB produces a fracture toughness of 330 J/m^2 while the width-tapered DCB produces a fracture toughness of 310 J/m^2 as is shown in Table 2. Both methods produce a similar standard deviation with the coefficient of variation being slightly higher in the width-tapered DCB experiment. The discrepancy between average fracture toughness can be partially explained by the underlying assumptions in the DCB test and the compliance method.



(a) (b)

Figure 11. Measure of inelasticity after test completion in (a) fixed width and (b) width-tapered DCB specimens

The DCB test assumes that the cantilever beams remain elastic throughout the test and that the inelastic effect of the cohesive process zone ahead of the crack tip is small compared to the energy stored in the beams themselves. The compliance method in particular relies on simple beam theory to calculate the stored energy in each of the cantilever beams. All of the measured crack tip displacement is elastic. However, as shown in Figure 11 once the test is completed, the inelastic deformation produces a 0.89mm opening at the hinge in the fixed width DCB while in the width-tapered DCB it is only 0.55mm. If all of the bending in the beams was elastic, there should be no opening at the hinge. This means that the compliance method is assuming that the beams are storing and releasing more energy associated with a given crack length and will thus overestimate the fracture toughness; the larger the opening, the larger the overestimation. Now both tests were not conducted in exactly the same manner, the fixed width DCB tests were taken to a larger crack tip opening displacement (25mm compared to about 21mm) and the crack length is slightly longer than that of the width-tapered DCB (124mm compared to 105mm) but these slight differences should not be able to account for the large discrepancy between plastic crack tip opening. So qualitatively it makes sense that the fixed width DCB would produce a higher value of fracture toughness.



(a) (b)

Figure 12. Uneven crack front during DCB testing

A major source of error associated with DCB testing is the shape of the crack front. All of the analysis methods assume that the crack extends perpendicular to the beam's length, or at the very least remains linear. Unless nondestructive methods, such as X-ray or ultrasonics, or a penetrating dye are employed, in most cases the best measurement of crack length can be achieved by marking the edges of the specimen as the test is conducted. For these tests, the glass is translucent while the carbon is opaque. This allows the crack front across the entire specimen to be observed. The fractured area appears lighter in color as light can pass through on the surface as well as at the fractured interface. As shown in Figure 12 both specimens have a crack front that is not linear or perpendicular to the beam's length. This produces a slight error in the calculation of fracture toughness. One advantage of the width-tapered DCB is that the crack widens as it extends which tends to average out this effect.

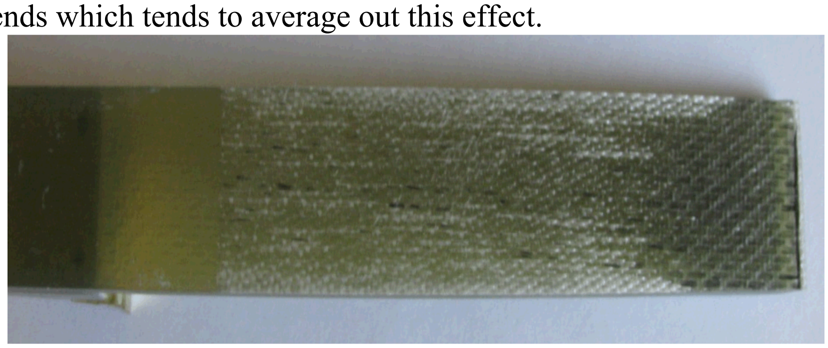


Figure 13. Adhesive failure in epoxy-glass interface

For this material in particular, the fracture toughness is fairly low. This is most likely due to the mode of crack extension. As shown in Figure 13 the fractured surface appears to have dry glass fibers. This suggests that the interface between the E-glass fibers and UF3362 resin is not very strong and leads to adhesive failure at that interface. It is also possible that the UF3360 resin in the carbon prepreg does not bond well to the glass fiber.

4. CONCLUSIONS

In this study it was determined that the width-tapered DCB is equivalent to using a fixed width DCB experiment. The mode I fracture toughness can be calculated using the width-tapered DCB using only the measured load necessary to extend the crack. For such experiments where it may be difficult to obtain an accurate measurement of the crack opening displacement, such as in high rate experiments or at high temperature, the width-tapered DCB can prove quite useful. For the same laminate design, the particular geometry of the width-tapered DCB in this study, it can also remain elastic at higher loads than the fixed width DCB. The width-tapered DCB also gives instant feedback to the operator as the test is being performed. In the fixed width DCB test, the load is very nonlinear with crack opening displacement so it takes further analysis to get a sense as to whether the fracture toughness calculated from the experiment will have much variation. For the width-tapered DCB the measured load is proportional to the fracture toughness, so the calculated fracture toughness will vary as much as the load does. Any investigator that is looking to quantify the fracture toughness of a composite laminate should at least consider using the width-tapered DCB for its ease of analysis.

5. ACKNOWLEDGMENTS

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