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A Novel Double Cantilever Beam Test for Stitched Composite Laminates

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ABSTRACT: Through-the-thickness stitching dramatically improves the interlaminar fracture toughness of laminated composites. Currently the Double Cantilever Beam (DCB) test is being used for determining the Mode I interlaminar fracture toughness of unstitched and lightly stitched composite laminates. But the standard DCB test method is not suitable for laminates with medium to high density stitches. Due to the high bending moment at the crack-tip, the specimens fail due to compressive stresses before the delamination could propagate. In order to overcome this limitation, a new fixture has been developed and used to perform Mode I fracture toughness tests on laminates with high density stitches. An analysis method has been developed to determine the load-deflection and the load-energy release rate relationships in the new test. The new test method has been found to be successful in testing graphite/epoxy laminates containing Kevlar stitches with a density of 64 stitches per square inch. The apparent fracture toughness of these specimens is about 45 times that of unstitched specimens.

INTRODUCTION

GRAPHITE/EPOXY COMPOSITE laminates have very high in-plane strength and stiffness, but they usually exhibit poor interlaminar strength and fracture toughness, and hence are vulnerable to delamination. Various techniques have been considered to improve the out-of-plane properties by increasing the resistance to delamination. One of the most effective ways of increasing interlaminar fracture toughness is incorporation of translaminar reinforcements. Weaving, knitting and braiding processes have demonstrated considerable improvement in the fracture toughness and impact properties, but these methods reduce the proportion of fibers along the in-plane directions and create large resin pockets through-

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out the structure, which tends to deteriorate the in-plane properties. Through-the-thickness stitching [1] has been found to be very effective in enhancing compression after impact (CAI) strength, Mode I and Mode II fracture toughness and also to some extent impact resistance in thick laminates. Mignery et al. [2] investigated the use of stitching by Kevlar yarns to suppress free edge delamination in graphite/epoxy laminates. The results showed that stitches effectively arrested the delamination. Dexter and Funk [3] investigated the impact resistance and interlaminar fracture toughness of quasi-isotropic graphite-epoxy laminates made of unidirectional Thornel 300-6K fibers/Hercules 3501-6 resin and stitched with polyester or Kevlar yarns. The Mode I fracture toughness, characterized by the critical strain energy release rate, G_{IC}, was found to be about 30 times higher for the stitched laminates. Ogo [4] investigated the effect of through-the-thickness stitching of plain woven graphite/epoxy laminates with Kevlar yarn. The study showed a manifold increase in G_{IC} values at the expense of slight reduction in in-plane properties. Pelstring and Madan [5] developed semiempirical formulae relating damage tolerance of a composite laminate to stitching parameters. Mode I critical strain energy release rate was found to be 15 times greater than in unstitched laminates, and G_{IC} decreased exponentially with increase in stitch spacing. Although many researchers [6–9] have already tested stitched composites for interlaminar fracture toughness, it is usually limited to low density stitches—especially for Mode I tests. This paper describes a new test procedure that is suitable for high density stitches. An analysis procedure is derived to determine the load-deflection and load-energy release rate relationships, which can be used to determine the apparent Mode I fracture toughness of the stitched laminates.

STANDARD DCB SPECIMEN

The standard DCB specimen (Figure 1) is fabricated with a Teflon layer at the mid-plane to simulate an initial crack. When loaded, the crack propagates in the plane of delamination. The Mode I fracture toughness can be determined using one

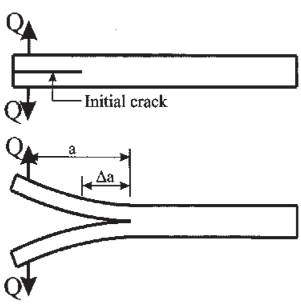

Figure 1. *The standard DCB test method.*

of the two following methods. The load at which the delamination starts propagating can be used to compute the G_{IC} as:

$$G_{IC} = \frac{F_c^2 a^2}{bEI} \tag{1}$$

where F_c is the load at which the crack propagation occurs, a is the current crack length, b is the width and EI is the equivalent flexural rigidity of the specimen. In the second method the specimen is unloaded after the crack propagates through some distance, say Δa. The area under the load-deflection diagram represents the work done ΔW in propagating the crack, and the critical energy release rate is computed as:

$$G_{IC} = \frac{\Delta W}{b\Delta a} \tag{2}$$

For instance G_{IC} of T300/3501-6 unidirectional unstitched graphite/epoxy laminates is about 1.7 lb. in/in^2 (298 J/m^2). It should be noted when testing stitched specimens, the unloading can never be complete as the broken stitches protrude out of the newly created delamination surface and prevent them from closing [1]. In that case we assume that the unloading is elastic and connect the current point in the load-deflection curve to the origin.

Unfortunately, the conventional DCB test is not suitable for medium to high density stitched composites. The reason is as follows. Stitches are very strong and large forces are required to break them or cause pullout. When the load increases, the specimen arm is subjected to large bending moment. In the end the specimen arm fails due to microbuckling on the compression side before crack propagation as illustrated in Figure 2. The energy release rate in a double cantilever beam can

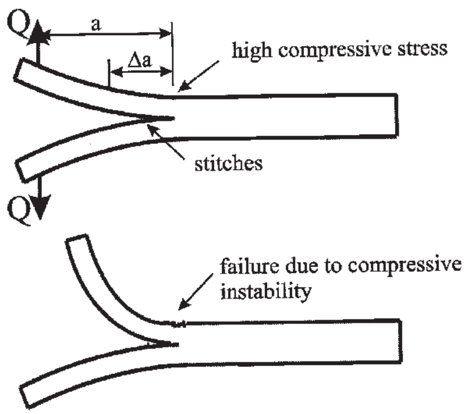

Figure 2. *The standard DCB test for high density stitched composite.*

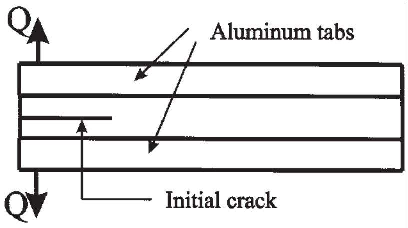

Figure 3. *Aluminum tabs bonded over entire specimen.*

be written as the difference in strain energy densities (strain energy per unit length of the beam) behind and ahead of the crack-tip [10]:

$$G = \frac{M^2}{bEI} \tag{3}$$

where M is the bending moment just behind the crack-tip. Thus the bending moment required to propagate the crack varies as $M = (G_{IC}\, bEI)^{1/2}$. Since the stitched laminates, even with low stitch density, exhibit about 25 times increase in fracture toughness, the bending moment required will be 5 times that for unstitched laminates. This factor will be much higher for medium to heavily stitched laminates. Such a high bending moment induces enormous axial stresses on the top and bottom surfaces of the sub-laminates. Since unidirectional graphite/epoxy composite has very high tensile strength, the high tensile stresses induced by the bending moment do not seem to be a problem. However failure initiated on the compressive side before the crack could propagate.

Previous researchers, for example References [1,4], have suggested incorporation of reinforcing tabs as illustrated in Figure 3. Aluminum tabs bonded to the top and bottom surfaces of the specimen can increase the load carrying capability. In theory, this allows the specimen to resist larger bending moment. But, in practice, this scheme faces another problem—when loaded, the aluminum tabs debond from the specimen due to high interlaminar shear stresses. Further, they can alter the stitch failure mechanism [1] and the measured G_{IC} may not be the true fracture toughness.

MODIFIED DCB TEST

New Fixture

In order to avoid the aforementioned compressive failure, one must reduce the compressive stresses. By adding tensile stresses along the in-plane fiber direction, the compressive stresses can be suppressed. Following this idea, a special fixture

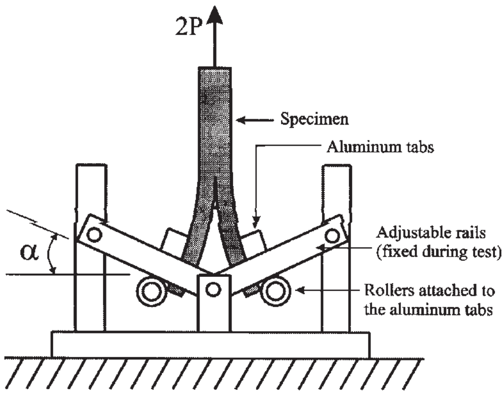

Figure 4. *Modified DCB test—fixture.*

has been developed as illustrated in Figure 4. In this fixture heavy aluminum tabs are bonded to the specimen ends. Kevlar yarns are wound over the tabs and the specimen to prevent the pull out of the tabs during testing. Two rollers attached to the tabs roll over a pair of adjustable rails. Actually the rails are fixed during the test and they are assumed rigid. As the specimen is pulled vertically the rollers follow the path of the rails opening the specimen ligaments. Thus the transverse force that opens the crack is proportional to the tensile force applied to the specimen. Figure 5 shows that the tensile force effectively cancels or reduces the compressive stresses caused by the bending moment behind the crack-tip. Bearings are used in the rollers to reduce friction.

Additionally, the angles of the rails are adjustable and hence the ratio between the vertical force and the horizontal force can be varied. For too big an angle of the

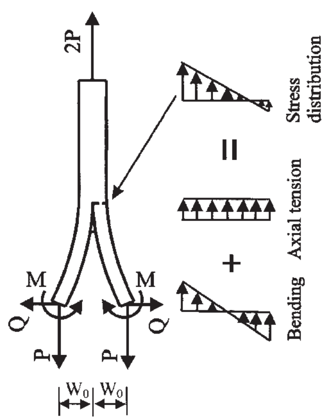

Figure 5. *Modified DCB test—loading.*

rail (defined by α in Figure 4) there will be too much transverse force and the specimen will break before the stitches break. For too small α the transverse force will be small and the specimen has to undergo very large axial force before the crack could propagate. Thus we want to find the maximum α at which stitches can break without breaking the specimen. By trial and error the optimum angle was found to be 20 degrees. An analytical method to determine the optimum angle will be part of future studies.

Specimen Preparation

The stitched specimens were made of 24 plies of AS4 uniweave graphite fabric and 3501-6 epoxy resin using the RTM process. Stitch yarns (bobbin yarn) were 1600 denier Kevlar (2790 yard/lb). Stitch density of the specimen was 8 × 1/8 inch. We define the stitch density by the number of stitches per square inch and represent this density by the stitching pattern as: (Number of stitches per inch) × (Spacing between two stitch lines), e.g., 8 × 1/8 inch means a stitch density of 64 where pitch is 8 stitches per inch and the distance between two adjoining stitch row is 1/8 inch. Needle stitching yarn used in all the cases was Kevlar-29, and modified lock stitch was used [1]. Top and bottom plies of the uniweave preform were covered by one layer of plain weave fiberglass cloth to act as the retained cloth for the stitches. A typical test specimen was about 0.26 inch wide, 0.16 inch thick and 7 inches long. There were two rows of stitches in each specimen. The bonded areas were filed to increase the friction between the tabs and the specimen, and screws were used to tighten the tab with the specimen and produce very high pressure between the tabs and the surfaces of the specimen to prevent slipping of the tabs from the bonded area of the specimen. The nominal initial crack length was 1.125 inches.

Fixture Verification

Two sets of unstitched specimens were cut from the same unidirectional 24 ply graphite/epoxy panel. Each set included 4 specimens. One set of specimens was tested by the standard DCB method and the other by the new fixture. Table 1 shows

Table 1. Comparison between two methods.

Standard DCB Tests	New Fixture Tests
Specimen1 G_{IC} = 1.63 lb·in/in^2	Specimen1 G_{IC} = 1.78 lb·in/in^2
Specimen2 G_{IC} = 1.81 lb·in/in^2	Specimen2 G_{IC} = 1.97 lb·in/in^2
Specimen3 G_{IC} = 1.57 lb·in/in^2	Specimen3 G_{IC} = 1.99 lb·in/in^2
Specimen4 G_{IC} = 1.67 lb·in/in^2	Specimen4 G_{IC} = 1.77 lb·in/in^2
Average: G_{IC} = 1.67 lb·in/in^2	Average: G_{IC} = 1.88 lb·in/in^2

the comparison between the two methods. GIC from the new method is slightly greater than that from conventional DCB tests. Because the new fixture incorporates rails and bearings, the friction in the mechanisms consumes some energy. Currently the fixture design is being modified so that friction can be kept to a minimum.

Testing of Stitched Specimens

Tests were conducted in a screw-driven universal testing machine. The crack propagation was observed by a CCD camera and a computer is used to record the images corresponding to various displacements. The load, crack extension and crack opening were determined corresponding to each displacement step. Figure 6 shows a series of pictures taken from one of the tests. For this specimen, the optimum rail angle was found to be about 20 degrees. When the grip of the machine moves up, the bearings on the specimen follow the rails of the fixture and open up the crack surfaces. The stitches typically break or pull through the composite. The horizontal components of the reactions on the bearings tend to open the crack

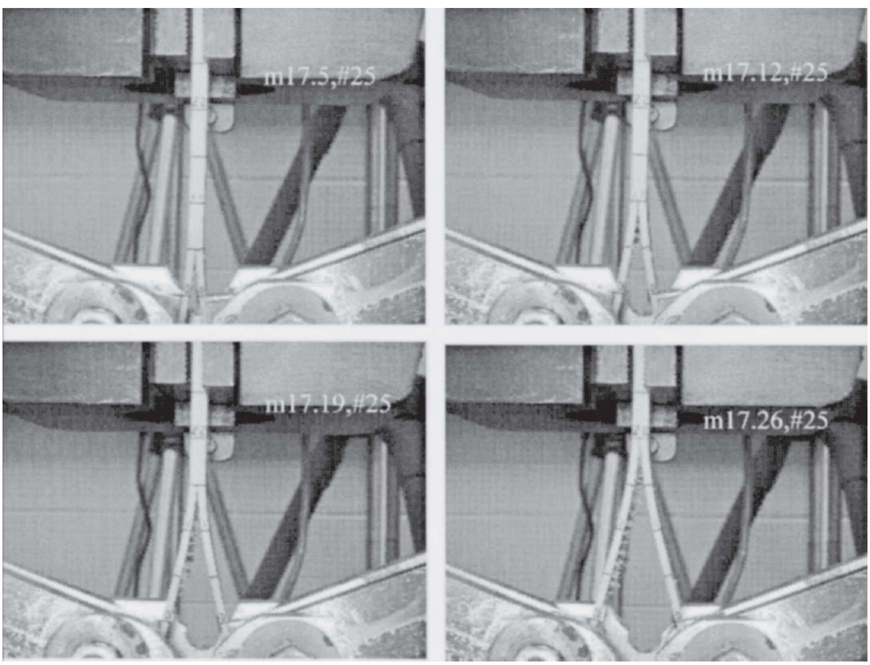

Figure 6. *A sequence of the pictures taken during modified DCB test.*

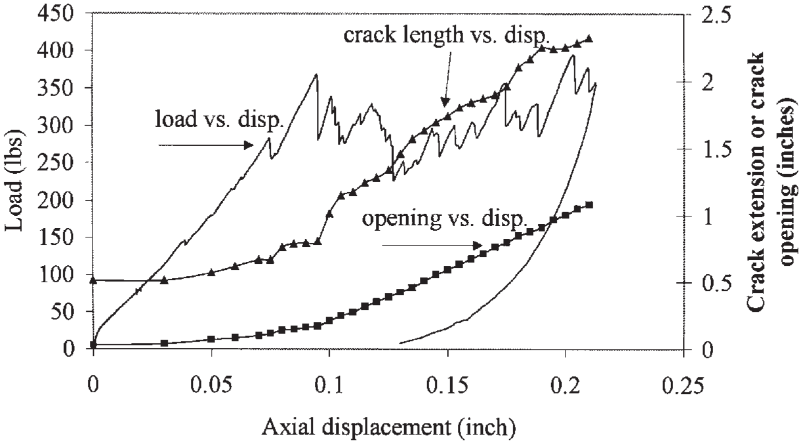

Figure 7. *Axial displacement vs. load, crack extension and opening.*

while the vertical component provides the tensile forces to reduce the compressive stresses induced by the bending moment. Using this fixture, we were able to test specimens with medium as well as very high stitch densities.

Typical measurements obtained using the new fixture are shown in Figure 7. During the test the load, displacement in the direction of applied load, crack surface opening displacement and the crack length are all measured. It should be mentioned that the crack-surface opening displacement is measured at a reference point near the end of the tabs. The crack length is defined as the distance between this reference point and the crack-tip. As a sample, the load, crack length and crack opening displacement are plotted against the axial displacement for one of the tests in Figure 7. From the load-displacement diagram, one can note that initially the load increases almost linearly with the displacement. When the stitches break, the crack begins to propagate and there is a sudden drop in the load. As the loading is continued, the load goes up and down as the stitches break and as the crack propagates intermittently. This saw tooth behavior of the load-deflection curve is due to the stitches breaking and new stitches offering resistance to crack propagation. The area under the load deflection curve represents the energy used in breaking the stitches and propagating the delamination.

ANALYSIS

Governing Equations

The G_{IC} can be determined using one of two methods. In the first method, the area under the load-deflection diagram is divided by the crack extension area:

$$G_{IC} = \frac{\Delta W}{b \times \Delta a} \tag{4}$$

where ΔW is the work of fracture, Δa is the crack extension and b is the width of the specimen. This method relies completely on experiments. As mentioned earlier the energy released during unloading is obtained by joining the current point in the load deflection curve to the origin.

The second method involves an elastic beam analysis of the specimen. A large deflection nonlinear analysis is performed to derive the load-deflection relation of the test specimen. Then from the analysis results, an expression for the strain energy in the beam can be derived. The critical energy release rate at any given load (or deflection) then can be obtained as:

$$G_{IC} = -\frac{dU}{b \times da} \tag{5}$$

where U is the strain energy in the beam as a function of crack length a, load/deflection and other beam properties. The analysis procedure is described below.

Due to symmetry we model one of the ligaments of the DCB specimen (see Figure 4). We use Timoshenko beam theory which accounts for transverse shear deformation. The two governing equations in the variables w and ψ, transverse deflection and rotation respectively, are:

$$A_{55}\left(\psi + \frac{\partial w}{\partial x}\right) = Q$$

(6)

$$D \cdot \frac{\partial \psi}{\partial x} = M + P \cdot (w_0 - w) - Q \cdot (a - x)$$

where A_{55} is the transverse shear stiffness, D is the flexural stiffness, P is the axial load, and Q and M are the shear force and bending moment at a given cross section, and w_0 is the transverse deflection at the aforementioned reference point. It may be noted that term $P(w_0 - w)$ accounts for the stress stiffening of the beam due to the axial force P. The solution to these equations can be derived as:

$$w = C_1 \cdot \sinh(\lambda x) + C_2 \cdot \cosh(\lambda x) + \frac{Q \cdot x}{P} + \frac{(M + P \cdot w_0 - Q \cdot a)}{P}$$

$$C_1 = \frac{Q \cdot \left(\frac{1}{A_{55}} - \frac{1}{P}\right)}{\lambda}$$

(continued)

$$C_2 = \frac{(M + P \cdot w_0 - Q \cdot a)}{P} \tag{7}$$

$$\lambda = \sqrt{\frac{P}{D}}$$

Once expressions for $w(x)$ and $\psi(x)$ are obtained the force and moment resultants can be easily derived using the beam constitutive relations.

From the results the strain energy in the beam can be calculated using numerical integration of the following expression:

$$U = 2\int_0^a \left(\frac{M^2}{2EI} + \frac{P^2}{2bhE} + \frac{Q^2}{2bA_{55}} \right) dx \tag{8}$$

Then the critical energy release rate in Equation (5) can be obtained by numerical differentiation of $U(a)$ with respect to the crack length a.

Verification of the Model

Figure 8 illustrates the comparison of the analytical solution with the test data. The dashed line represents the crack extension vs. crack opening data from a test. We used the loads and crack extension from the test data to calculate the crack surface opening which is plotted as a solid line in Figure 8. The relative error between the measured opening and the calculated opening is below 10 percent. Because our analysis results are close to the experimental data, we use this method with confidence to obtain the instantaneous critical strain energy release rate G_{IC}. From Figure 8, one can note that for a give crack length the experimental crack-opening is

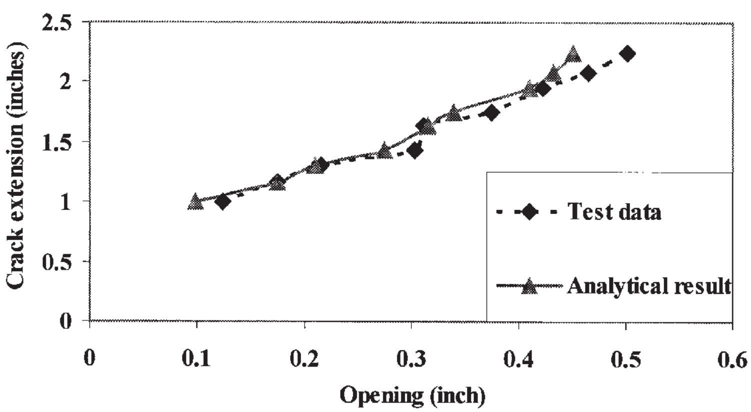

Figure 8. Crack extension vs. opening.

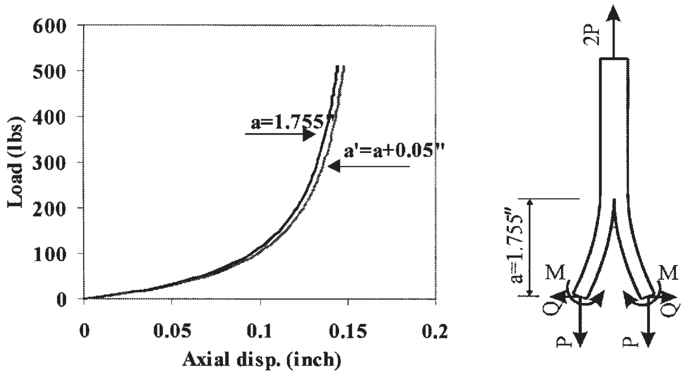

Figure 9. *Load vs. displacement.*

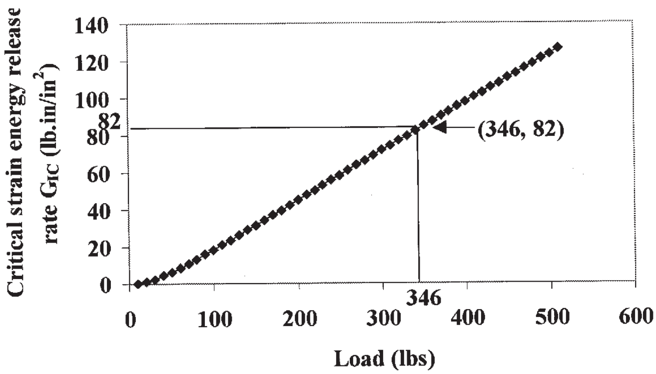

Figure 10. *Critical strain energy release rate vs. load.*

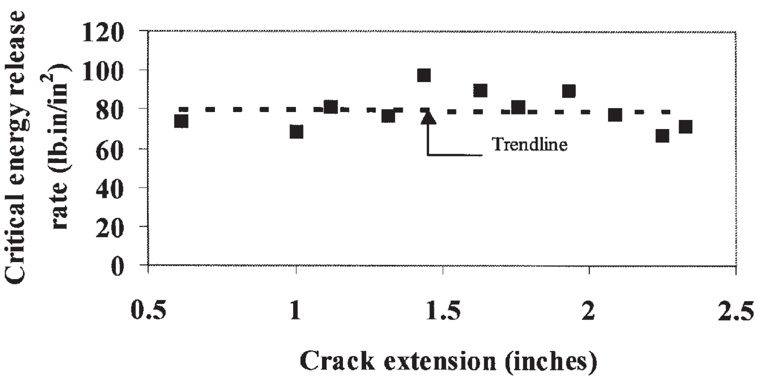

Figure 11. *Critical strain energy release rate (G_{IC}) vs. crack length.*

Table 2. Instantaneous **G_{IC}** ***variation with crack length.***

Crack Extension (inch)	Load (lb)	Energy Release Rate (lb·in/in^2)
0.611	378	74
1.000	321	69
1.120	370	82
1.313	333	77
1.438	413	98
1.631	370	90
1.755	346	82
1.930	370	90
2.086	320	78
2.246	275	67
2.328	293	72

slightly more than that predicted by the model. This could be due to the elasticity of the fixture and also clearances in various joints, which are not accounted for in the model.

Instantaneous G_{IC}

In this method the analysis described above is used to obtain two sets of load-deflection curves, one for a crack length a and another for $a + \Delta a$, where Δa is a small but arbitrary increment. A set of sample load-deflection curves are shown in Figure 9. Then from the two curves the critical energy release rate can be obtained numerically using Equation (5). The variation of G_{IC} as a function of the load for a given crack length is shown in Figure 10. The value of G_{IC} corresponding to the load at which crack began to propagate is the fracture toughness of the stitched specimen at that instant. This procedure can be repeated for various crack lengths and the fracture toughness of the stitched specimen can be determined as a function of the crack length. Figure 11 shows the fracture toughness remains almost constant with respect to the crack length and the average value is equal to 80 in. lb/in^2 (14,000 J/m^2). The same data is presented in Table 2 also. By comparing to the G_{IC} of unstitched specimens (Table 1), one can note that the Mode I fracture toughness increases by more than 45 times due to stitching. In a previous study [1] we found that the G_{IC} increased by about 15 times for 4 × 1/4 stitches of the same material system.

CONCLUSION

A new test method has been developed for determining the Mode I interlaminar fracture toughness of laminated composites with medium to high density stitches.

In this method an axial tension is applied to the specimen in addition to the transverse forces that open up the crack. These tensile forces suppress the high compressive stresses induced by the bending moment in the vicinity of the crack-tip, and prevent the specimen from breaking before crack propagation. An analysis method has been developed to compute instantaneous G_{IC} from the new test method. It is found that G_{IC} dramatically increases due to stitching. With 64 stitches per square inch Kevlar stitches the G_{IC} of graphite/epoxy laminates increases from about 1.7 lb-in./in^2) to 80 lb-in/in^2 (14,000 J/m^2).

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