

Investigation of Fracture Toughness of Laminated Stitched Composites Subjected to Mixed Mode Loading

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ABSTRACT: Through-the-thickness stitching is a method that increases the translaminar strength and apparent fracture toughness of laminated composites. A novel test fixture was developed to measure mixed mode fracture toughness under combined Mode I and Mode II loadings. This fixture allowed the ratio between Mode I and Mode II to be varied in order to perform tests under a wide range of mixed mode conditions. Through testing it has been shown that stitching increases Mode I fracture toughness 20–50 times while playing a less significant role in increasing Mode II fracture toughness.

KEY WORDS: polymer–matrix composites, fracture toughness, delamination, stitching.

INTRODUCTION

GRAPHITE/EPOXY LAMINATED COMPOSITES have high stiffness-to-weight and strength-to-weight ratios that make them suitable for structural applications. The properties of these laminates depend highly on the fiber orientation and the fiber volume ratio. The strength in the translaminar (through-thickness) direction tends to be significantly smaller than in the fiber direction. For example, the tensile strength of graphite/epoxy laminates is approximately 500–800 MPa (72–116 ksi) in the fiber direction while in the translaminar direction the strength is around 20–30 MPa (2.9–4.3 ksi). This is due to the fact that under transverse loading the load is being predominately carried by the resin matrix, making the composite susceptible to delamination. This delamination is typically an interface crack or a debonded zone between two adjacent layers. Many methods have been developed to improve the translaminar strength and decrease the occurrence of delamination. These methods include 3D weaving, z-pinning, and stitching. Stitching is one of the most common techniques used to suppress delamination, which significantly increases fracture toughness on the order of a 20–50-fold increase. Mignery et al. [1] investigated the use of stitching using Kevlar yarn to suppress free edge delamination in graphite/epoxy laminates. Results showed that stitching was an effective suppressant of delamination. Dexter and Funk [2] investigated the Mode I fracture toughness of laminates reinforced with Kevlar stitches. Sharma and Sankar [3–6] studied mode I, mode

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II fracture behavior, impact resistance, and compression after impact behavior of stitched graphite/epoxy laminates. Results showed that the mode I fracture toughness increased 30-fold when compared to the unstitched laminate. The increase in mode II fracture toughness was modest, but compression after impact (CAI) strength increases significantly due to stitching.

Currently, the double cantilever beam (DCB) and end-notched flexure (ENF) tests are respectively used to determine the Mode I and Mode II fracture toughness of unstitched composite laminates. In practical applications it is rare to encounter pure Mode I or Mode II loadings. Typical loads are comprised of a combination of both Mode I and Mode II loads referred to as a mixed mode loading condition. Richards and Korjakin [7] used the traditional mixed mode setup to test the fracture toughness of unstitched laminated composites. In their experiments the ratio of Mode I to Mode II was fixed at 1.33 according to linear beam analysis. Reeder and Crews [8,9] developed a new mixed mode experimental set-up that simultaneously created a Mode I and Mode II bending load on the specimen from a single applied load. This set-up allowed for numerous mixed mode ratios to be tested. Although many researchers have used different approaches to investigate the delamination fracture toughness of composites including mixed mode fracture properties of composites, none have successfully tested the mixed mode fracture toughness of composites with dense translaminar reinforcement. The standard DCB test is not suitable for testing stitched laminates. Typically during the standard DCB test the specimen fails due to high compressive stresses caused by the large bending moment at the crack tip. Due to these problems with the standard DCB test a novel test fixture has been developed by Chen et al. [10].

This new test fixture allows the testing and investigation of composite laminates containing dense translaminar reinforcements, which previously was not possible. The fracture toughness of specimens containing two different stitch densities is presented in this article. A comparison is made between the fracture toughness of stitched and unstitched specimens. Additionally, a finite element model is presented that verifies the experimental results for fracture toughness of stitched laminates.

TEST FIXTURE

The innovative fixture incorporates a horizontal bar that has a series of holes corresponding to numerous mixed mode ratios (Figure 1). At the right end of the bar, a bearing reacts to create a horizontal force, which helps balance the fixture as well as reduce compressive bending stresses that might otherwise lead to premature failure of the specimen (before stitch failure). This fixture applies tension to both arms of the DCB specimen, which also reduces the compressive bending stresses. By changing the loading position, various mixed mode ratios are obtained. The ratio of Mode I to Mode II can be varied from zero to infinity in theory but for practicality the fixture is best used for Mode I dominated experiments. Mode I is achieved by loading the fixture at a hole directly inline with the specimen. By offsetting the load from the longitudinal axis of the specimen, various mixed mode ratios are achieved as the ratio of forces in each loading bar is changed. In addition, the fixture can be self-balanced by adding weights to the left side of the horizontal bar to account for errors caused by the unbalanced weight of the fixture. This fixture relies on specimen grips that can transmit both axial and transverse forces (Figure 2). The transverse component of the force is for crack opening and the axial component is used to apply the tensile force. The conventional method of bonding tabs to

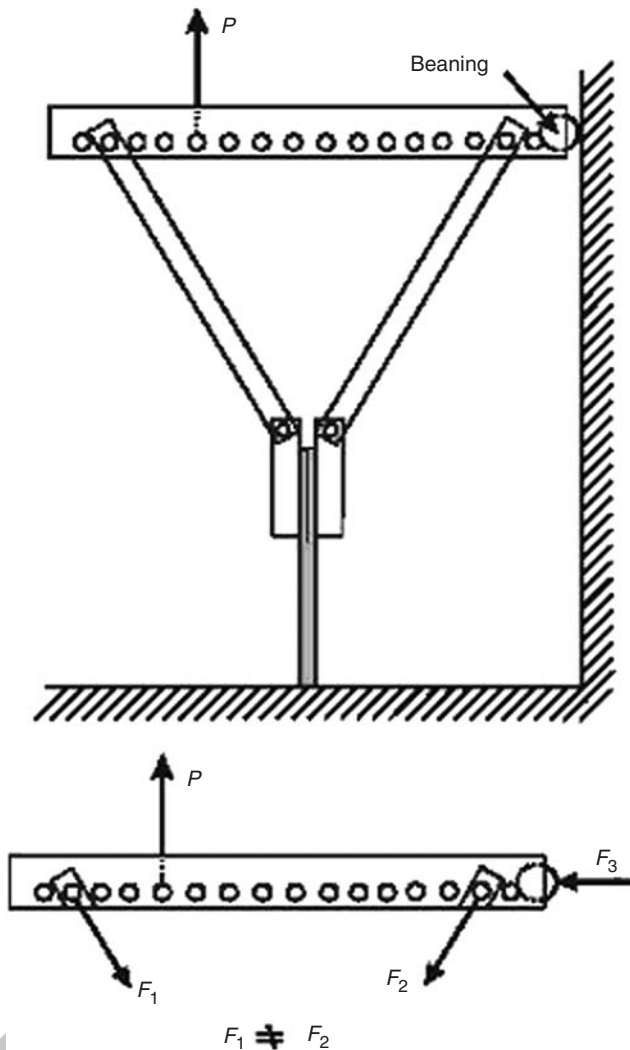


Figure 1. Mixed mode testing fixture.

the specimen does not work as the large tensile and shear stresses caused by the load required to propagate the crack simply debond the tabs. A notch in the form of a circular arc was machined in the specimen ends (Figure 2). A pair of grips that match the notch profile in the specimen were machined out of steel.

SPECIMEN PREPARATION

The stitched specimens were made of 28 plies of AS4 uniweave graphite fabric and 3501-6 epoxy resin using the RTM process by NASA Langley Research Center. The specimens were stitched with 1600 denier Kevlar 29 where there are two Kevlar yarns in each stitch. In addition, each specimen consisted of three rows of stitches. The specimens were approximately 190.5 mm (7.5 in) long and 19.05 mm (0.75 in.) wide. Two different stitch

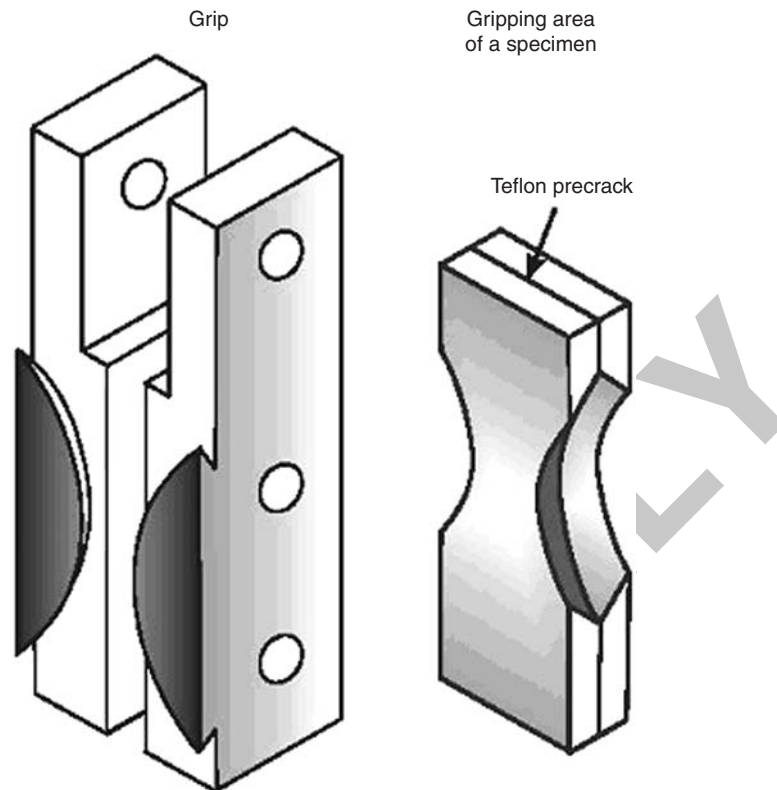


Figure 2. Specimen grips and pre-crack.

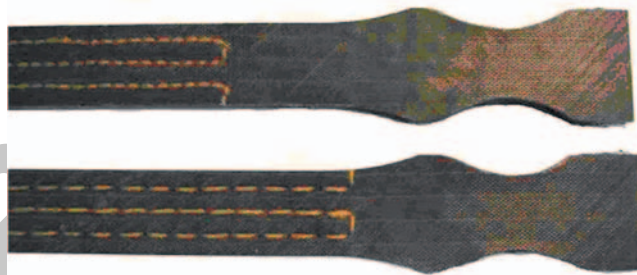


Figure 3. Specimens showing stitch densities and pre-crack lengths.

densities were used to evaluate the effects of stitch density on fracture toughness. Stitch densities evaluated were five stitches per inch (referred to as low density) and nine stitches per inch (high density). The spacing between adjacent rows of stitches was 5 mm (0.2 in.). The specimens also included a Teflon insert either 65 mm (2.55 in.) or 90 mm (3.55 in.) in length that created the pre-crack needed for delamination propagation (Figures 2 and 3). The specimen was made up of four stacks. Each stack consisted of seven plies, which were oriented at $[45^\circ/-45^\circ/0^\circ/90^\circ/0^\circ/-45^\circ/45^\circ]$. The materials used in each stack have slightly different properties (Tables 1 and 2). These differences are most likely do to variances in measurement and manufacture.

Table 1. Material properties of graphite/epoxy.

Material	E_1 (GPa) (psi)	E_2 (GPa) (psi)	ν_{12}	G_{12} (GPa) (psi)	G_{13} (GPa) psi	G_{23} (GPa) (psi)
AS4-3501-00	105 (15.3 e6)	11 (1.6 e6)	0.34	6 (0.8 e6)	6 (0.8 e6)	3.6 (0.52 e6)
AS4-3501-45	103 (15.04 e6)	11 (1.6 e6)	0.34	6 (0.8 e6)	6 (0.8 e6)	3.6 (0.52 e6)
AS4-3501-90	102 (14.88 e6)	11 (1.6 e6)	0.34	6 (0.8 e6)	6 (0.8 e6)	3.6 (0.52 e6)

Table 2. Material orientation and thickness.

Ply number	Thickness (mm) (in.)	Orientation (degree)	Material name
1	0.16 (0.00633)	45	AS4-3501-45
2	0.16 (0.00633)	-45	AS4-3501-45
3	0.32 (0.01285)	0	AS4-3501-00
4	0.18 (0.007018)	90	AS4-3501-90
5	0.32 (0.01285)	0	AS4-3501-00
6	0.16 (0.00633)	-45	AS4-3501-45
7	0.16 (0.00633)	45	AS4-3501-45

EXPERIMENTAL METHODS

Tests were conducted in a screw driven universal testing machine (MTI). The crack propagation was observed using a CCD camera. A computer monitored and recorded both force and cross-head displacement. The crack propagation length was measured using a micrometer. Once the data was taken, a plot of force vs cross-head displacement was created. The area under the load deflection plot represents the work done (ΔW) in propagating the crack. Calculation of the fracture toughness was accomplished by dividing the work done to propagate the crack by the area of crack propagation as:

$$G_{IC} = \frac{\Delta W}{b\Delta a} \quad (1)$$

where Δa is the length of crack propagation and b is the specimen width. For pure Mode I loading, the fixture is set-up with the universal testing machine attached directly in line with the specimen. The load increases until the first row of stitches break, at which time the load suddenly drops (Figures 3 and 4). Subsequent rows of stitches are loaded until failure. The cycle continues in this saw-tooth pattern until the specimen is unloaded. When testing stitched specimens, unloading can never be complete as the broken stitches protrude out of the newly created delamination surface and prevent the specimen from closing fully. In this case we assume that the unloading would have been elastic, and hence connect the current point on the load-deflection plot to the origin. As seen in Figure 3 each peak and valley corresponds to a stitch breaking. By having a peak and valley for every row of stitches in the specimen shows that the crack propagation is stable.

The same procedure described for Mode I was used for mixed mode loading. To achieve various mixed mode ratios the MTI machine was attached to the horizontal bar offset from the specimen. The larger the offset the greater the mixed mode ratio becomes. The average fracture toughness values for both the low-density and high-density stitched

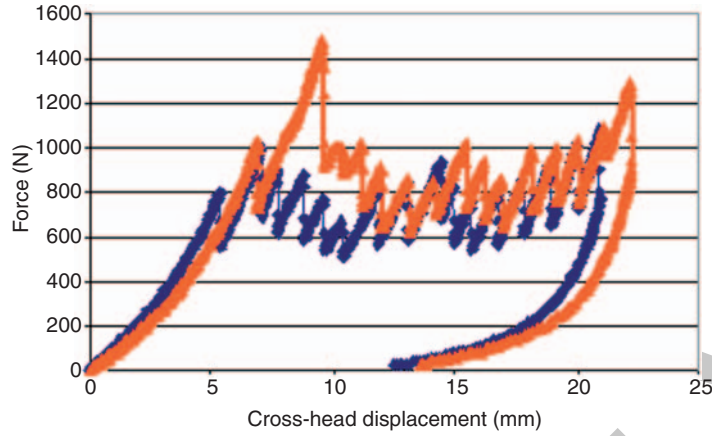


Figure 4. Sample load vs. displacement plot.

composites are listed in the results section under Tables 3 and 4. The mode mixity parameter (Ψ) is used to describe the mixed mode ratio, which is defined as:

$$\psi = \tan^{-1} \frac{K_{II}}{K_I} \quad (2)$$

where K_I and K_{II} are the Mode I and Mode II stress intensity factors, respectively. One can note that $\Psi=0$ for pure Mode I and $\Psi=\pi/2$ for pure Mode II. For mixed mode conditions $0 < \Psi < \pi/2$.

In the present work we use a simple mechanics of materials approach to estimate the mode mixity Ψ , which is based on the ratio between the forces transmitted to the specimen in each bar of the fixture. We calculate both G_I and G_{II} (energy release rates) based on strength of material calculations. A general loading can be decomposed into symmetric Mode I and anti-symmetric Mode II loading as shown in Figure 5. The energy release rate for both cases can be derived as [11]:

$$\begin{aligned} G_I &= \frac{(F_1 + F_2/2)^2 a^2}{b^2 D_{11}} \\ G_{II} &= \frac{3(F_1 - F_2/2)^2 a^2}{4 b^2 D_{11}} \end{aligned} \quad (3)$$

where a is the delamination length, b is the width, and D_{11} is the flexural stiffness of one of the ligaments of the symmetric DCB specimen. The energy release rates are proportional to the square of the stress intensity factors. Therefore, the mode-mixity can be derived as:

$$\psi = \tan^{-1} \frac{K_{II}}{K_I} = \tan^{-1} \left(\sqrt{\frac{G_{II}}{G_I}} \right) = \tan^{-1} \frac{\sqrt{3}}{2} \left(\frac{1 - (F_2/F_1)}{1 + (F_2/F_1)} \right). \quad (4)$$

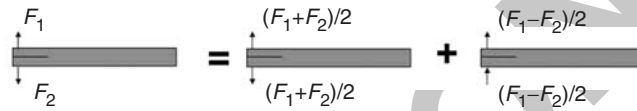
It should be mentioned that the mode-mixity derived in Equation (4) represents a nominal value based on global loading conditions. Our purpose here is to find if the apparent fracture toughness measured depends on the global mode-mixity parameter Ψ .

Table 3. Average apparent fracture toughness for low-density specimens.

Mode ratio $\psi = \tan^{-1} (K_{II}/K_I)$	Average GJ/m ² (lb-in/in ²)
0°	7083 (40.45)
8.2°	6351 (36.27)
16.0°	7557 (43.16)
29.9°	8160 (46.60)

Table 4. Average apparent fracture toughness for high-density specimens.

Mode ratio $\psi = \tan^{-1} (K_{II}/K_I)$	Average GJ/m ² (lb-in/in ²)
0°	14323 (81.80)
12.1°	16950 (96.80)
23.3°	17640 (100.74)

**Figure 5.** Schematic of forces used for calculating mixed mode ratio.

EXPERIMENTAL RESULTS

Average apparent fracture toughness for both low-density and high-density specimens can be found in Tables 3 and 4 respectively. As the mixed mode ratio increases from Mode I to Mode II the apparent fracture toughness value increases significantly over that of an unstitched specimen and remains fairly constant over the mixed mode range with a decrease most likely appearing near the pure Mode II loading condition.

From Tables 3 and 4 it can be seen that the average fracture toughness values for low-density and high-density specimens is of the order of 7000 J/m² (40 lb-in/in²) and 16,000 J/m² (100 lb-in/in²), respectively. For an unstitched specimen made of graphite/epoxy the average Mode I fracture toughness is on the order of 300 J/m² (1.7 lb-in/in²) [6]. This clearly demonstrates that stitching increases the average fracture toughness by 20–50 times.

One may notice that no fracture toughness value can be found for high-density specimens above the mixed mode ratio of 23.3°. This is due to the fact that at mixed mode ratios higher than this, the specimen would break either from compressive breakage in one of the arms or in shear at one of the end grips.

Figure 6 shows a plot of the fracture toughness vs the mode-mixity angle for low-density stitched specimens. A linear trend line has been fitted to the experimental data to show the trend of the fracture toughness with respect to the mode-mixity angle. As the mode-mixity angle increases there is a slight increase in the fracture toughness value over a 30° mode-mixity range. The Mode II (90°) fracture toughness value was found for a stitched specimen using an end-notch-flexure test by Chen et al. [10]. The dotted trend line is shown as an illustration that the fracture toughness will eventually decrease to the Mode II value. The exact shape of this trend line between 30° and 90° (dashed line in Figure 6) at the present moment is unknown.

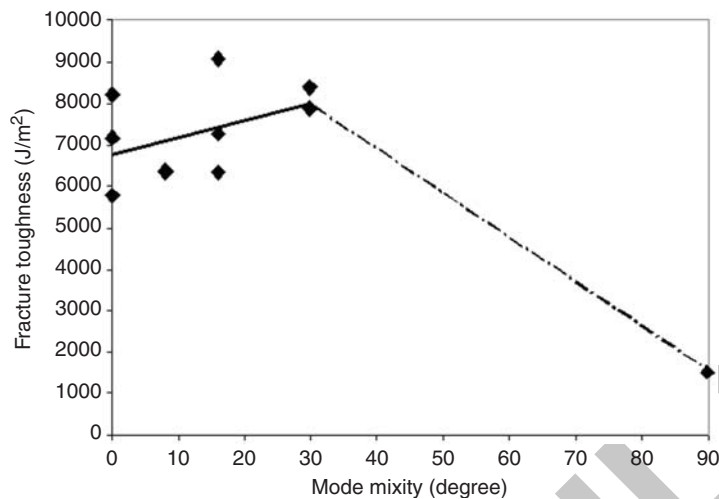


Figure 6. Fracture toughness vs. mode mixity.

CONCLUSIONS

Specimens containing both low density and high density stitching have been evaluated and show a dramatic improvement in the average fracture toughness when compared to unstitched specimens. This clearly demonstrates that stitching improves the delamination resistance and inhibits crack propagation significantly. Fracture toughness values increased from approximately 300 J/m^2 (1.7 lb-in/in^2) to 7000 J/m^2 (40 lb-in/in^2) and $17,500 \text{ J/m}^2$ (100 lb-in/in^2) for low and high density stitched specimens, respectively. Furthermore, it was found that the fracture toughness increases as the mode mixity changes from Mode I to Mode II. Even a small amount of Mode II component increases the fracture toughness.

As a result of this study, the following conclusions were reached.

1. Stitching effectively increases the apparent fracture toughness of stitched composites. The increase is on the order of 20-fold for low-density stitched specimens and 40-fold for high-density stitched specimens.
2. For the limited global mode-mixity range observed ($0^\circ < \Psi < 30^\circ$), the apparent fracture toughness G_c seems to increase slightly with increasing Ψ . This agrees with theory as stitches are most effective in tension and keep the fracture toughness value fairly constant.

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