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Effect of Stitching on Impact and Interlaminar Properties of Graphite/Epoxy Laminates

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ABSTRACT: Effects of through-the-thickness stitching on the impact damage resistance, impact damage tolerance, and interlaminar fracture toughness (Mode I and Mode II) of plain woven and uniweave textile graphite/epoxy laminates were investigated. The uniweave textile was formed by weaving dry carbon-fiber tows with fiberglass fill tows. The content of fiberglass fill tows was 2.5% by weight. The plain woven laminates were manufactured using resin infusion molding and the uniweave laminates by resin transfer molding. Kevlar® and glass yarns of various yarn numbers were used for stitching. Static Indentation-Flexure, Compression-After-Impact, Double Cantilever Beam and End-Notched Flexure tests were conducted. Stitching did not have any effect on the onset of impact damage. However, stitching leads to significant improvement (25–40%) in impact damage tolerance as measured by CAI strength and impact damage area. Mode I fracture toughness as characterized by critical strain energy release rate (G_{Ic}) was found to increase by at least an order higher (15–30 times) than the unstitched laminates. Mode II fracture toughness (G_{IIc}) increased by 5–15 times over the unstitched laminates. New methods to estimate the Mode II critical strain energy release rate in the stitched laminates are presented. The stitched textile advanced composites are considered potentially superior to prepregs for high-volume, low-cost and high-performance structural materials.

INTRODUCTION

DESPITE THE GREAT potential of advanced fibrous composites for diverse applications, their production volume has not risen significantly. Primary

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problem areas impeding growth can include high manufacturing cost, low impact damage resistance and impact damage tolerance [1–7], and poor interlaminar fracture toughness [8–15]. Impact damage resistance deals with the damage state caused by an impact event. Impact damage tolerance reflects the changes in structural performance due to the damage state. The impact of a foreign object on laminated composite structures causes matrix cracking and delaminations because they lack through-the-thickness reinforcement and have poor interlaminar fracture toughness. The effect of low-velocity impact on advanced composites has been extensively reported by researchers in the past several years. Jackson and Poe [1] showed the use of impact force as a scale parameter for delamination damage. Kwon and Sankar [2] studied the applicability of static indentation response in predicting damage due to large impact mass at low velocity. Mignery et al. [8] showed that stitches effectively arrest delamination. Dexter and Funk [10] investigated characterization of the impact resistance and interlaminar fracture toughness of quasi-isotropic unidirectional graphite-epoxy laminates. Ogo [13] demonstrated a manifold increase in Mode I fracture toughness (G_{IIc}) values due to stitching with a slight drop of in-plane properties. However, his results did not show any appreciable increase in Mode II fracture toughness (G_{Ic}). Meanwhile, new methods like resin transfer molding (RTM) show high potential to cut down manufacturing costs [14].

The work reported so far in the literature pertains largely to unidirectional laminates. These laminates do not take advantage of high-volume, well-proven manufacturing methods for textiles. The available test data and knowledge about the effects of stitching are extremely sparse. Therefore, the overall objective of this study was to investigate the effects of through-the-thickness reinforcement by stitching on the impact damage resistance, impact damage tolerance and fracture toughness of textile structural composites. Textile structural composites are expected to cost less due to their ease of fabrication using well-known textile technology. The concept of stitching is also compatible with textiles. The age-old skills of stitching offer both the designer and the manufacturer a variety of possible architectures for reinforcing laminates. Stitching technology can be suitably adapted for advanced composites with relatively low capital and developmental costs. Processing by RTM is more suitable for high-volume production than the conventional lay-up schemes for prepregs. Therefore, this study addresses the three primary obstacles mentioned above with a view to obtaining insight into the potential of stitched textile composites as a viable option for high-volume, low-cost and high-performance structural material needs.

MATERIAL SYSTEMS

Two material systems were studied: (1) 16-ply plain-weave graphite fabric (Hercules A193-P)/3501-6 epoxy laminates stitched with Kevlar® (1875 yd/lb) and manufactured using a modified resin infusion molding (RIM) process; and (2) 24-ply AS4 Uniweave cloth/3501-6 epoxy laminates stitched with either Kevlar® (1875 yd/lb) or glass (1250 or 750 yd/lb) and manufactured using the RTM process.

The first type of material system will be referred to as Group I laminates and the second type as Group II in this paper. Both groups used an out-of-balance lock stitch [13,14] between the bobbin and the needle yarn. The needle yarn was single-ply Kevlar for all laminates. We define the stitch pattern as (stitches per inch) × (distance between two stitching rows in inches)—e.g., 4 × 1/4 means 4 stitches per inch in each of the stitch rows separated by 1/4″. The stitch pattern represents the areal stitch density for a given yarn. For Group I, it was 8 × 1/4 and 5 × 1/4; for Group II, 4 × 1/4 and 8 × 1/8. Group I typically represents small batch production methods and were processed at the Center for Studies of Advanced Structural Composites, University of Florida. Group II represents industry standard high-volume/low-cost manufacturing methods suitable for any type of industry—*viz.*, automotive, rapid transit systems, and aircraft.

APPROACH

The Group I laminates were used to conduct Static Indentation-Flexure (SIF) tests followed by Compression-After-Impact (CAI) tests to understand impact damage resistance and impact damage tolerance. The Group II laminates were used to conduct Mode I and Mode II fracture toughness tests to understand interlaminar fracture properties. Double Cantilever Beam (DCB) and End-Notched-Flexure (ENF) tests were carried out. In addition, the effect of the following variables was investigated: support ring diameter for SIF tests, specimen height and width for CAI tests, starter crack length in DCB tests, frictional effects in ENF tests. The number of specimens used for each test was as follows: 9–12 specimens for SIF and CAI, 4–6 for DCB, and 6–12 for ENF tests. Stitch failure mechanisms and crack front propagation were investigated using photomicrography, X-radiography, ultrasonic C-scanning, and scanning electron microscopy.

STATIC INDENTATION-FLEXURE (SIF) TEST

The SIF test can be used to study damage response due to impact of large masses at very low velocities [2]. These tests simulate quasi-static impact conditions. In addition, they offer greater opportunity to study progressive damage propagation during the impact event. The specimens were simply supported. Contact load and indenter displacement data were acquired. The effect of stitching on impact damage area and damage progression was studied. Ultrasonic C-scans were taken to assess the damage area. Photomicrographs were taken to see the damage to the matrix and stitches. The plates were loaded up to different load levels in order to assess the damage response. The effect of support ring diameters (2″, 3″, and 4″) used to provide the simple support conditions was studied for 8 × 1/4 laminates. Having observed the effect of plate size on the 8 × 1/4 laminates, the ring diameter for all 5 × 1/4 specimens was maintained at 3 inches. The details of the test fixture, specimen manufacture, experimental procedures, and data reduction are given in [17].

Analysis and Results

Figure 1 shows a typical load-displacement (P-δ) curve for three different loading levels. There is no sudden drop in the load at the initiation of damage as in

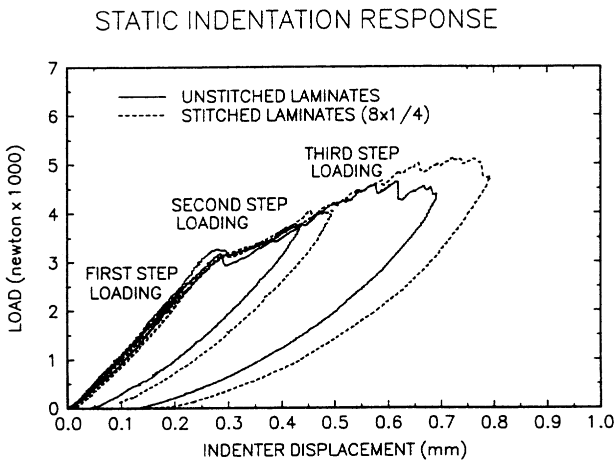

Figure 1. *Typical load-deflection curves in static-indentation-flexure tests.*

tape laminates, indicating that damage initiation and progression in textile laminates are similar to yielding in ductile materials. It is observed that there is no significant difference between stitched and unstitched plates with regard to the onset of damage, indicating that stitching does not affect damage resistance. A possible reason for this could be the low thickness of laminates. The reinforcement through-the-thickness apparently is not fully effective in thin laminates. A slight increase in the ultimate load of the stitched plates was noted, but that could also be due to the increased thickness of the stitched laminates compared to that of the unstitched laminates. The difference in damage area between the unstitched and 8 × 1/4 stitched laminates was not investigated due to the sparse data for a given load, as the loading was done to three different levels. However, the 5 × 1/4 laminates demonstrated about 40% less damage area compared to unstitched specimens for the same load (Figure 2). Though stitching does not seem to affect impact damage resistance, it can significantly restrict damage progression. The optimum density for the maximum damage tolerance for a given impact load was not investigated.

COMPRESSION-AFTER-IMPACT (CAI) TEST

The residual post-impact strength can be characterized by the CAI test. An existing NASA post-impact-compression-fatigue testing fixture [18] was modified, and a new CAI fixture was designed, redesignated the University of Florida Compression After Impact (UF-CAI) test fixture, it is shown schematically in Figure 3. The new fixture allows testing of plates of various widths and heights and also allows delamination propagation in the entire width of the plate during testing. The design considerations for the UF-CAI fixture, fabrication, and validation details are given in [17].

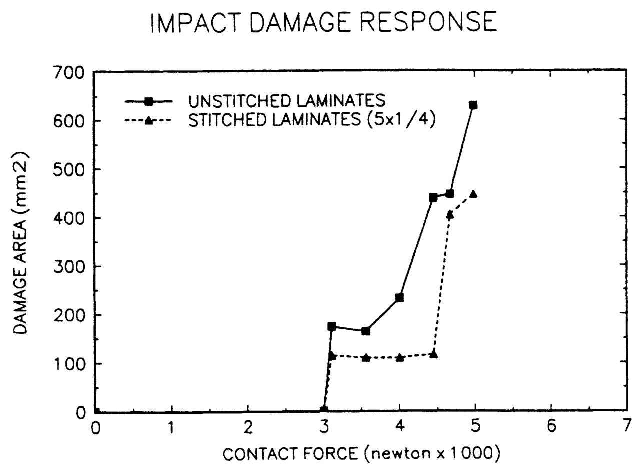

***Figure 2.** Effect of stitching on damage.*

Analysis and Results

The effect on CAI strength for 8 × 1/4 laminates was not noticeable. The effect of different specimen heights on CAI strength was not appreciable within the range of gage lengths tested. For the 5 × 1/4 specimens, the CAI strength was about 25% higher than the unstitched for the maximum impact load (Figure 4). The stitch density seems to play a critical role in maximizing CAI strength.

MODE I FRACTURE TOUGHNESS TEST

DCB tests were conducted following guidelines given by Carlsson [16], and details are given in [17]. Preliminary tests indicated intermittent crack propagation as the stitches broke. It is difficult to contain crack propagation between two successive stitches to record the critical load for crack propagation. The crack front also moves ahead of unbroken stitches during loading. The stitch failure mechanisms and crack propagation sequence are discussed in detail in [17]. Therefore, the energy-area approach was selected to calculate an effective critical strain energy release rate (G_{Ic}) rather than using the beam theory formula. It was considered that this approach would give a better estimate of G_{Ic} for the stitched laminates, as these can not be treated in accordance with beam theory formulation due to partially broken stitches remaining in the wake of the crack front. The critical strain energy release rate can be calculated by $G_{Ic} = (\Delta W)/(\Delta A)$, where ΔW is the work done during each incremental crack propagation, and ΔA is the new incremental crack surface area created. The work done was deduced from the area under the P-δ curve. It was assumed that the crack front propagates in a self-similar manner symmetric about the center line.

Analysis and Results

The reduced data for G_{Ic} showed about 7% variation for the unstitched and up

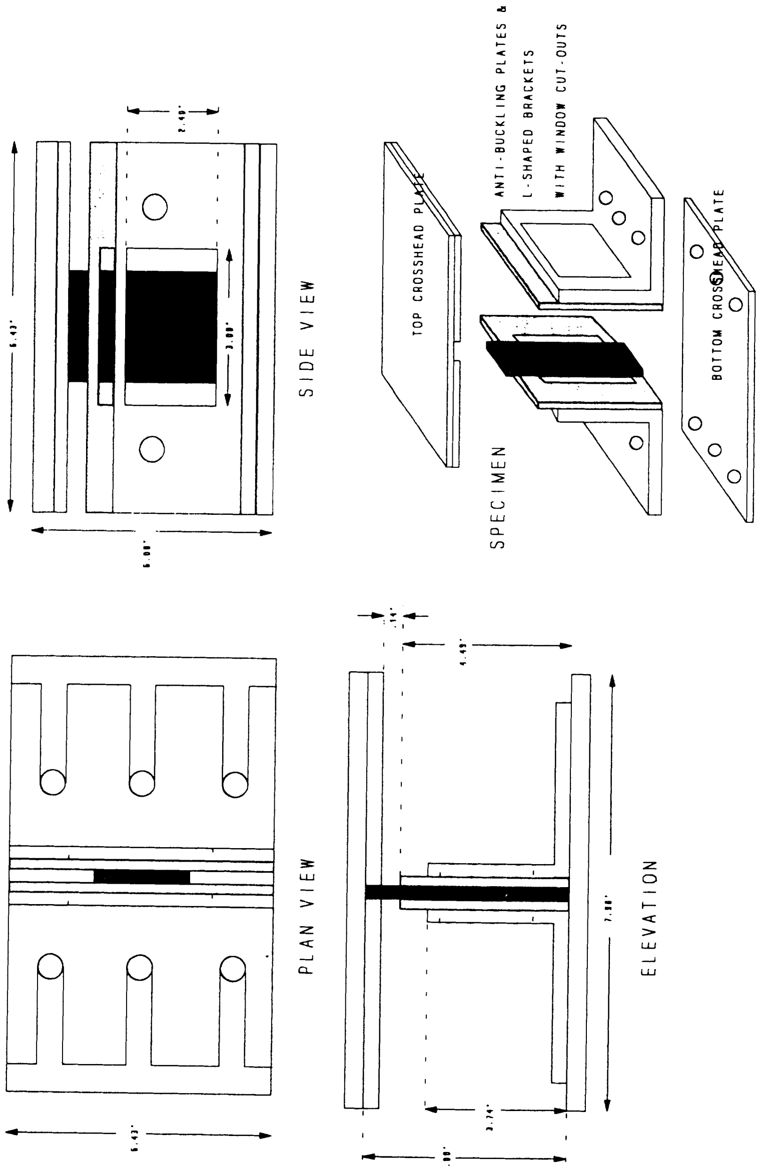

***Figure 3.** The University of Florida–compression after impact (UF-CAI) test fixture.*

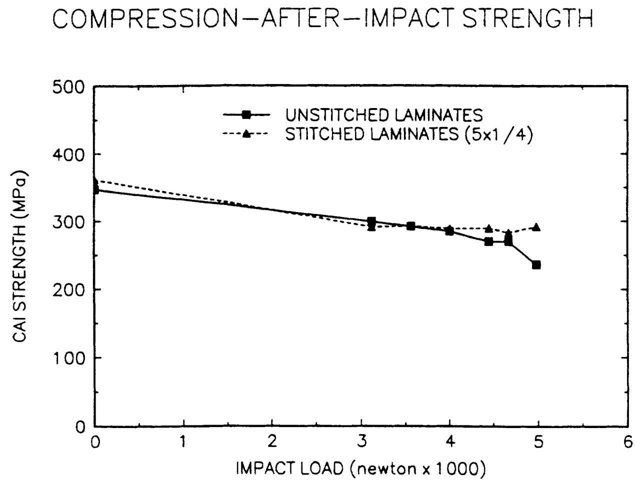

Figure 4. *Effect of stitching on damage tolerance.*

to about 25% in the stitched laminates. The variation in the stitched case is due to G_{Ic} values being less for the first one or two incremental crack propagations, but it stabilized at an average peak value later. This could be due to the first line of stitches not being perfectly aligned during manufacture. Subsequently, as the crack front progresses in a self-similar manner, the values of G_{Ic} stabilize. The average G_{Ic} values for the unstitched and stitched laminates are compared in Figure 5. The use of Kevlar (1875 yd/lb) stitching yarn increased G_{Ic} by about 15 times, glass (1250 yd/lb) by 30 times, and glass (750 yd/lb) by 21 times. The G_{Ic} value of unstitched laminates was 302.6 J/m^2. The evaluation of G_{Ic} for higher stitch density (8 × 1/8) laminates could not be completed due to specimens failing in bending as the load was applied. The stitches would not allow the crack to open.

Figure 6 shows a photograph of the cracked surface of glass (750) stitched laminates. The bobbin yarns failed close to the stitch lock location in all cases. In addition, the glass (750) yarn did not fail by splitting at the stitch lock like the other two cases: instead, it broke the needle yarn, thereby creating holes on the top side of the laminate. The failure of the yarn at the lock suggests failure due to the stitch lock stress concentration. This factor should be kept in mind while deciding the type of stitch lock to be used during manufacture. A stronger needle yarn may further enhance fracture toughness by delaying needle yarn failure. Variation of needle yarn properties and the effect of different stitch locks were not studied in this program.

MODE II FRACTURE TOUGHNESS TEST

End-Notched-Flexure (ENF) tests were conducted to assess Mode II fracture toughness. The behavior of crack propagation in unstitched and stitched lami-

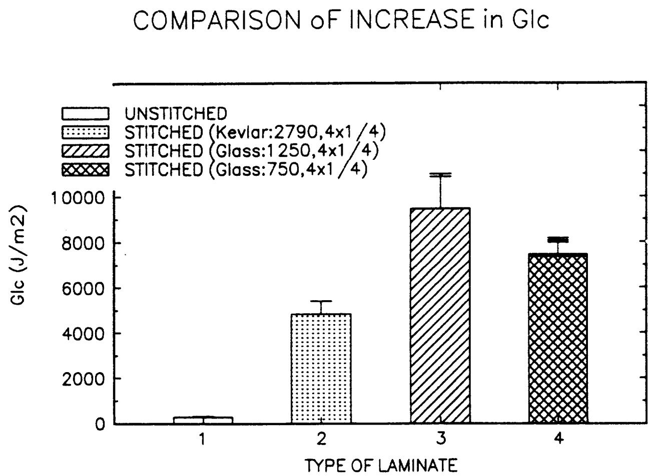

Figure 5. *Effects of stitching on Mode I fracture toughness.*

nates was studied. The limitations of calculating the critical strain energy release rate (G_{Ic}) of stitched composites using existing standard beam theory formulation were investigated. New methods to determine the G_{IIc} for stitched composites are presented. The tested specimens were C-scanned to confirm the crack propagation front.

Analysis and Results

A representative load-displacement curve for an unstitched and a stitched lami-

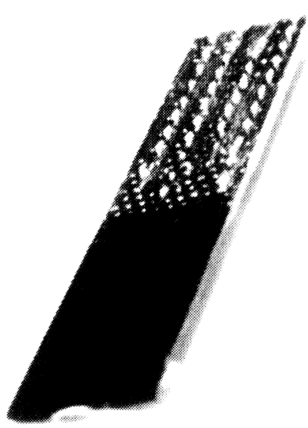

Figure 6. *Photograph of glass-750 bobbin yarn in a failed DCB specimen.*

nate is shown in Figure 7. By using the critical load (P_c) to initate crack propagation, compliance (C) from the P-δ curve the critical strain energy release rate for unstitched laminates was calculated using existing well-known elastic beam theory formula [13,16]:

$$G_{IIc} = \frac{9P_c^2 Ca^2}{2w(2L^3 + 3a^3)} \quad (1)$$

where w, L and a are the width, half length, and crack length of the specimen respectively. This formula is valid for unstitched laminates. The average value obtained by this method was 670.72 J/m². An energy-area approach similar to the one described for DCB tests was also used to compare the G_{IIc} values obtained from the formula. An average G_{IIc} of 672.8 J/m² was obtained, indicating excellent correlation between the two approaches.

Crack propagation in unstitched uniweave laminates is sudden and unsteady; in contrast, in stitched laminates, it is gradual and steady. There is no sudden drop in load as the crack starts propagating. Compliance of the specimen gradually changes as the crack propagates. Therefore, using beam theory formula with nonlinear P_c and linear C will not give a correct estimate of the G_{IIc} as suggested by Ogo [13]. Preliminary photomicrographic studies of stitched specimens suggested that the crack length can not be measured accurately from the side edges visually. C-scans were taken, and it was found that actual crack propagation was much more than visually observed. Two new methods to calculate G_{IIc} for the stitched laminates are presented.

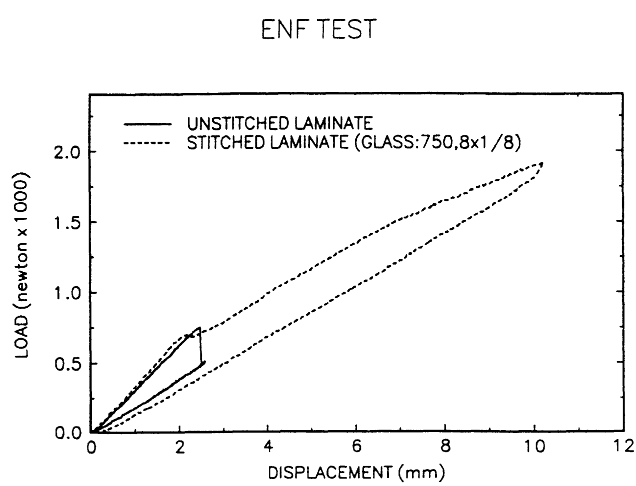

Figure 7. *Comparison of load-deflection curves in ENF tests.*

New Methods to Determine G_{IIc} of Stitched Laminates

AREA METHOD USING C-SCAN

Steps:
- Ensure starter crack at first stitch line
- Ensure crack propagates to at lest a few stitches during test
- Calculate work done (ΔW) for P-δ curve
- Find area of crack surface (ΔA) using C-scan
- $G_{IIc} = (\Delta W)/(\Delta A)$

AREA METHOD USING COMPLIANCE OF UNLOADING CURVE

Steps:
- Calculate EI from linear compliance (C) of the loading curve
- Calculate compliance of unloading curve (C') at 500 N line (i.e., approximately 20% less load than the P_c of linear loading curve)
- Calculate effective crack length (a_{eff}) using C' and following formulae

For $a < L$

$$C' = \frac{(2L^3 + 3a_{eff}^3)}{96EI} \tag{2}$$

For $a < L$

$$C' = \frac{-(2L - a_{eff})^3}{32EI} \quad \frac{L^3}{12EI} \tag{3}$$

- Select appropriate a_{eff} out of the two calculated above
- Calculate crack surface area (ΔA) using the selected a_{eff}
- $G_{IIc} = (\Delta W)/(\Delta A)$

Figure 8 shows the effect of stitching on G_{IIc} calculated from all three methods—i.e., beam theory formula and the two new area methods. It can be observed that using beam theory formula predicts virtually no effect of stitching. The area method using C-scan seems to give an upper bound of increase in Mode II fracture toughness, while the second method using compliance of unloading curve is lower bound and conservative. The lower bound seems to indicate an effective increase in G_{IIc}, as it represents the material at the end of the loading cycle. The conservative increase in G_{IIc} is about 5 to 15 times. At the beginning of the unloading curve, a slight drop in load was observed, as also seen in Figure 7. This could be due to contact friction at loading and support pins. A 5–30% load drop was observed in a total of 48 specimens. We suggest a 20% reduction in the lower bound G_{IIc} values to obtain the Mode II fracture toughness of stitched laminates to account for frictional effects.

The slope of the nonlinear part of the P-δ loading curve can be useful in predicting some of the material properties. This curve represents gradually changing compliance as the crack length increases. Variation in G_{IIc} as the crack propa-

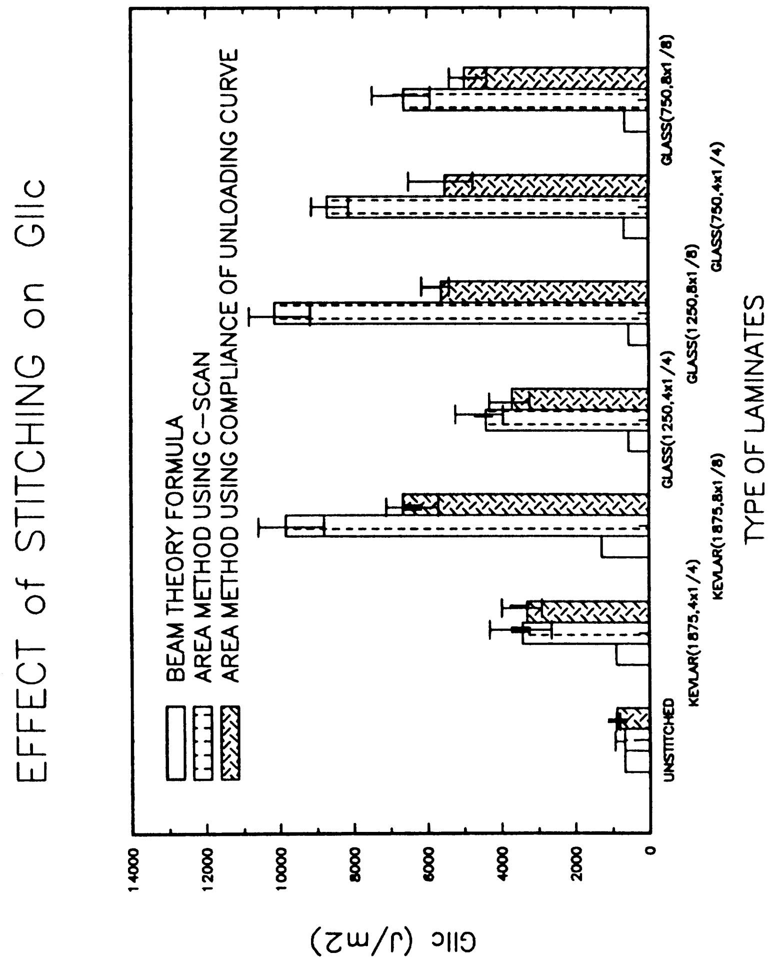

Figure 8. *Effect of stitching on Mode II fracture toughness.*

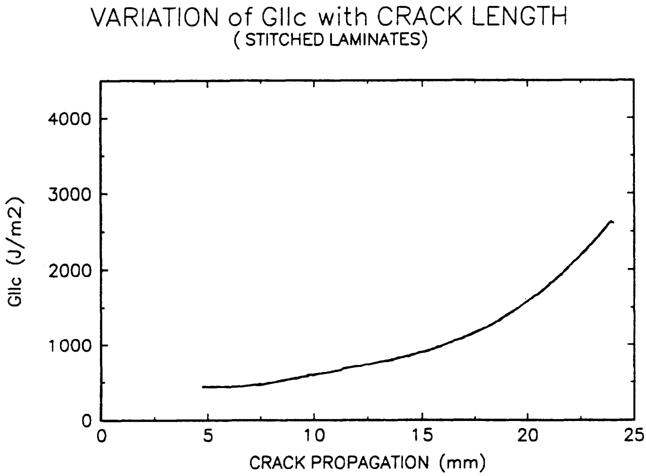

Figure 9. *Mode II fracture toughness as a function of crack length in stitched laminates.*

gates was investigated using this part of the curve. Mode II fracture toughness at every incremental point of the nonlinear curve was calculated using the formula in Equation (1), where a was the effective crack length calculated from Equation (2), and P and C were the nonlinear load and compliance respectively at that point. A typical behavior is shown in Figure 9. It can be seen that Mode II fracture toughness increases as the crack propagates. A detailed description of the method of the above computation is given in [17].

CONCLUSIONS

The impact damage resistance of textile laminates is not appreciably affected by through-the-thickness stitching. Impact damage tolerance improves significantly, as seen in the reduction in damage area and increase in CAI strength. Stitch density plays a critical role in improving impact damage tolerance. A new CAI test fixture, designated the UF-CAI test fixture, has been developed. Stitching improves the Mode I fracture toughness by at least an order higher than that of the unstitched laminates. For the laminates tested in this program, we found an increase of 15 to 30 times in their G_{Ic} value. Two new methods to calculate effective G_{IIc} have been developed. The increase in Mode II fracture toughness was observed to be 5 to 15 times for the laminates studied. Stitched textile structural composites manufactured using the RTM process hold great promise for high-volume, high-performance applications at low cost.

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