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EFFECTS OF STITCHING ON FRACTURE TOUGHNESS OF UNIWEAVE TEXTILE GRAPHITE/EPOXY LAMINATES*

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SUMMARY

The effects of through-the-thickness stitching on impact damage resistance, impact damage tolerance, and Mode I and Mode II fracture toughness of textile graphite/epoxy laminates were studied experimentally. Graphite/epoxy laminates were fabricated from AS4 graphite uniweave textiles and 3501-6 epoxy using Resin Transfer Molding. The cloths were stitched with Kevlar® and glass yarns before resin infusion. Delamination were implanted during processing to simulate impact damage. Sublaminate buckling tests were performed in a novel fixture to measure Compression After Impact (CAI) strength of stitched laminates. The results show that CAI strength can be improved up to 400% by through-the-thickness stitching. Double Cantilever Beam tests were performed to study the effect of stitching on Mode I fracture toughness G_{Ic}. It was found that G_{Ic} increase 30 times even for a low stitching density of 16 stitches/square inch. Mode II fracture toughness was measured by testing the stitched beams in End Notch Flexure tests. Unlike in unstitched beams crack propagation in stitched beams was steady. The current formulas for ENF tests were not found suitable for determining G_{IIC} for stitched beams. Hence two new methods were developed - one based on crack area measured from ultrasonic C-scanning and the other based on equivalent crack area measured from the residual stiffness of the specimen. The G_{IIc} was found to be at least 5 -15 times higher for the stitched laminates. The mechanisms by which stitching increases the CAI strength and fracture toughness are discussed.

INTRODUCTION

Though the unidirectional laminated composites have high strength in fiber direction, they lack through-the-thickness reinforcement. Hence, they have poor interlaminar fracture toughness and are susceptible to delaminations. One of the ways to reinforce a laminate through the thickness is stitching. The idea of stitching the textile preform fits well within the realm of existing textile technology. Mignery et al. [1] investigated use of stitching by

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Kevlar® yarn to suppress delamination in unidirectional graphite/epoxy laminates. The results showed stitches effectively arrest delamination. Dexter and Funk [2] investigated characterization of 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. They experimented with stitch parameters and found significant drop in damage areas of stitched laminates compared to unstitched laminates for the same impact energy. 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. Effect on Mode II fracture toughness was not investigated in this study. Ogo [3] investigated effect of through-the-thickness stitching of plain woven graphite/epoxy laminates with Kevlar® yarn. The study showed manifold increase in G_{Ic} values at the expense of slight drop of in-plane properties. However, his results did not show any significant increase (8%) in Mode II fracture toughness as characterized by the critical strain energy release rate, G_{IIc}. Pelstring and Madan [4] 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 over the unstitched laminates, and the critical strain energy release rates decreased exponentially with increase in stitch spacing. Correlation of toughness characteristics shows that predictable trend existed between strain energy release rate, damage area, and CAI strength. Byun et al. [5] conducted a finite element analysis on 3-D woven double cantilever beam (DCB) specimen and evaluated Mode I critical strain energy release rate to investigate the influence of through-the-thickness fibers on crack driving force on crack length. Chen et al. [6] proposed effective critical strain energy release rate to measure Mode I fracture toughness of stitched laminates using a finite element model. Recently, Jain and Mai [7] have analytically modeled Mode I delamination toughness of stitched laminated composites.

It is evident from above studies that through-the-thickness stitching significantly improves Mode I fracture toughness in laminates made of unidirectional tapes or plain woven fabric cloth of graphite and epoxy resin. However, effect on Mode II fracture toughness needs to be fully investigated. Further, variations of stitch density, stitch failure mechanisms and their contribution to Mode I and Mode II fracture toughness are not completely understood.

EXPERIMENTAL PROGRAM

An experimental program was conducted to understand the effects of stitching on Mode I and Mode II fracture toughness. To measure critical strain energy release (G_{Ic}) in Mode I crack propagation mode, Double Cantilever Beam (DCB) tests were performed on stitched and unstitched laminates in stroke control mode. Similarly, to measure the critical strain energy release rate in Mode II fracture (G_{IIc}), End Notched Flexure (ENF) tests were conducted. Material system for both types of tests were same as described in the following section. At least 3 and up to 12 specimens were tested for each category of specimen to study stitch failure mechanisms and ensure statistically consistent data. Guidelines suggested by Carlsson [8] were used to perform the tests. Energy-Area method was used to compute G_{Ic}. New methods to compute G_{IIc} have been explored for the stitched laminates and are presented in a later section.

Effects of stitch yarn, stitch density and yarn denier on G_{Ic} were studied. Stitch damage mechanisms in Mode I tests were investigated using Photomicrography and Scanning Electron Microscopy (SEM). Effects of stitch yarn, stitch density, yarn number, starter crack length, crack surface and contact roller pin friction and unstitched length on G_{IIc} were studied. The unstitched length is defined as the distance of starter crack from the first stitch. Stitch damage mechanisms in Mode II tests were investigated using X-Radiography, Ultrasonic C-Scanning and Photomicrography.

MATERIAL SYSTEM

Uniweave graphite fabric preforms of 24 plies were stitched and Resin-Transfer-Molded (RTM) with epoxy 3501-6 resin to fabricate plates from which the specimens were machined. A modified lock stitch was used. This lock ensures the position of needle and bobbin stitch interlock on top surface of the laminate. Three bobbin yarns of different denier, each with two different stitch densities of 4×1/4" and 8×1/8" were used for stitching. A denier is a measure of linear density in grams per 9000 meters of the yarn. This can also be represented by yarn number which is given by yards/lb for the yarn. Further, we define stitch density in a composite laminate 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" means a stitch density of 64 where pitch is 8 stitches per inch and distance between two adjoining stitch rows is 1/8". Needle stitching yarn used in all the cases was Kevlar®-29 made by E.I. du Pont de Nemours and Co., Inc.. Top and bottom plies of the uniweave preform were covered by one layer of plain weave fiberglass cloth to act as retainer cloth for the stitches. The details of the stitch yarns used are given in Table 1. For the purposes of this document, the three bobbin stitch yarns will be referred to as: Kevlar-2790, Glass-1250 and Glass-750. In addition, one unstitched plate for each type of testing was processed for control specimens. Thus, seven plates (#24 to 30) were processed for Mode I and Mode II Fracture Toughness Tests as per details shown in Table 2 and Fig. 1. The plates were Ultrasonically C-Scanned for quality and location of teflon inserts. A schematic diagram of the DCB and ENF specimens is shown in Fig. 2 and Fig. 3 respectively.

DOUBLE CANTILEVER BEAM TESTS: RESULTS AND ANALYSIS

G_{Ic} of the Unstitched and 4×1/4" Stitched Laminates

Stitch Failure Mechanism

Crack propagation during the DCB test in case of the unstitched laminates was gradual and steady, while it was observed to be intermittent and dynamic in the case of the stitched laminates. Crack front always proceeded ahead leaving the unbroken stitches in the wake. The stitches first debond from the matrix and subsequently break as the crack continues to propagate. The failure of stitches always occurred at the position of bobbin and needle yarn stitch lock in case of Kevlar-2790 and Glass-1250. In both of these types of stitch yarns, the bobbin yarn broke at the stitch lock and not the needle yarn *like* splitting into two reinforcing stems of bobbin yarn. However, in case of the thicker Glass-750 bobbin yarn, the needle yarn failed leaving the bobbin yarn intact. Breaking of the needle yarn in such a case created a hole on the top surface where the stitch lock was located. Broken bobbin stitch yarns prevented the crack to close completely during the unloading as also indicated by a slight compressive load seen in the typical P-δ curves of a DCB test given in Fig. 4.

Increase in G_{Ic} due to Stitching

The critical strain energy release rate using energy-area approach is given by:

$$G_{Ic}=\frac{\Delta W}{\Delta A} \tag{1}$$

where, ΔW is the work done during the each incremental crack propagation and ΔA is the new incremental crack surface area created. It was assumed that the crack front follows a near straight line path and propagates in a self-similar manner. The increase in the Mode I critical strain energy release rates for various laminates are compared in Fig. 5. Increase in the Mode I fracture toughness due to a low stitch density of 4×1/4" is outstanding. The average increase in Mode I fracture toughness due to stitching is at least an order higher than the unstitched laminates. The use of Kevlar-2790 as stitching yarn improved the fracture toughness by about 15 times, use of Glass-1250 improved it by about 30 times, and the Glass-750 increased the toughness by about 21 times. The G_{Ic} value for the unstitched laminates was 302.6 J/m^2.

G_{Ic} of the 8×1/8" Stitched Laminates

Six different hinge installation methods were tried out to make the hinge bond strong enough so that the crack propagates well before the failure of the hinge bond. Details of these methods are given in [9]. Integrally machined hinges shown in Fig. .6a worked satisfactorily. However, the fracture toughness of 8×1/8" stitched specimens was found to be so high that the specimen failed in bending about 1/4" away from the initial starter crack front line. In order to strengthen the specimen, new integrally machined tabs of steel as shown in Fig. 6b were bonded over the entire surface of the specimen. Guenon [10] has studied Mode I interlaminar fracture toughness of 3-D woven composites using a "tabbed specimen" which is similar to this one. However, it was found that this type of tabbing is not suitable for stitched laminates due to holes being created by the failure of the needle yarn as explained earlier. Therefore, it was not possible to experimentally determine G_{Ic} for 8×1/8" stitched specimens of this study using this type of DCB test. The specimens would have to be made thick enough to prevent bending failure. It is conjectured that the G_{Ic} values for these high stitch density laminates may be more by about 100 times over the unstitched laminates.

END NOTCH FLEXURE TESTS: RESULTS AND ANALYSIS

Current Method of Computing G_{IIc} and its Applicability for Stitched Laminates

A typical P-δ curve for an unstitched and a stitched laminate is shown in Fig. 7. The existing literature uses the well known formula to calculate the critical strain energy release rate [3,8] as given in the following equation:

$$G_{IIc}=\frac{9P^2Ca^2}{2w(2L^3+2a^3)} \tag{2}$$

where, a is starter crack length, L is half length of specimen, C is compliance, w is the width of the specimen and P will be the critical load at the time of crack propagation. The average value obtained by this method was 670.72 J/m^2. An energy-area approach similar to the one described earlier for calculation of G_{Ic} was also used to compare the G_{IIc} values obtained from the formula. An average G_{IIc} of 672.77 J/m^2 was obtained indicating excellent correlation between the two approaches.

While the crack propagation in an unstitched laminate is unsteady as is also indicated by the sudden drop in load on the P-δ curve, the crack propagation in the stitched specimens was observed to be steady. The P-δ curves for all the stitched laminates were observed to follow same nonlinear pattern during the loading. There is no sudden drop in load as the crack starts propagating. Compliance of the specimen gradually changes as the crack propagates. Therefore, the use of beam theory formula using nonlinear P_c and linear C as suggested by Ogo [3] will not give a correct estimate of G_{IIc} in case of stitched laminates. Two new methods to calculate G_{IIc} for the stitched laminates are presented in the following section. Preliminary photomicrographic studies of tested stitched specimens also suggested that the crack length can not be measured accurately from the visual inspection of the side edge. Then, C-Scans were taken and it was found that actual crack propagation was much more than the visually observed. Hence, the values of crack propagation measured by C-Scans were used in computations for the first of the two new methods presented.

New Methods to Determine G_{IIc} of Stitched Laminate

Two new methods have been developed for computing the Mode II fracture toughness as afunction of crack length in ENF tests. They are: (1) Area Method using C-Scan; (2) Equivalent Area Method using Compliance of the Unloading Curve.

The procedure for computing G_{IIc} using the C-scan method can be described by the following steps:

- Ensure starter crack at first stitch line
- Ensure crack propagates to at least few stitches during test
- Calculate work done (ΔW) from P-δ curve

- Find area of crack surface (ΔA) using C-scan
  $G_{IIc} = (\Delta W)/(\Delta A)$

The equivalent area method involves the following steps:

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

For $a < L$

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

For $a > L$

$$C' = \frac{-(2L - a_{eff})^3}{32EI} + \frac{L^3}{12EI} \tag{4}$$

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

Effect of Stitching on G_{IIc}

The G_{IIc} values using all the three methods described above, were calculated and the average values of the data are plotted in a bar chart given in Fig. 8. The figure also brings out the comparison of G_{IIc} values using beam theory formula and the two new methods presented above. The crack had propagated up to about center line in all these tests as found by the C-Scans i.e., about the same extent as that of the unstitched laminates. As expected, the values of G_{IIc} obtained from using beam theory formulation do not show any appreciable increase, indicating that the intrinsic Mode II critical strain energy release rate of the material remains the same. However, the stitching does significantly improve the effective or apparent G_{IIc} as indicated by the values obtained from using both of the new area methods. The energy required to propagate the crack is apparently more due to the stitches. This is because not all the energy imparted during the test directly goes to the crack front, a good amount of the energy now is also being used in other stitch damage mechanisms. The stitched laminate appears to behave more like a structure.

The area method using C-scan seems to give the upper bound of G_{IIc} values while the equivalent area method using compliance of the unloading curve gives the lower bound. The increase in apparent G_{IIc} values is very impressive regardless of the stitch yarn. It is about 5-15 times that of the unstitched laminates using the conservative lower bound values. It appears that the crack length detected by the C-Scanning is smaller than the effective crack propagation length. With each stitch yarn the apparent G_{IIc} increases with increase in the stitch density except for Glass-750, where the change is insignificant due to increased stitch density, pointing towards a possible optimum. Thus it can be concluded that stitching significantly improves the Mode II fracture toughness. The possible stitch failure mechanisms observed are discussed in a later section which further explain the rise in G_{IIc}.

Variation of G_{IIc} with Increase in Crack Length

The slope of the nonlinear loading part of the P-δ curve can be very 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 propagates was investigated using this part of the curve. Mode II fracture toughness at each data point of the acquired signal was calculated using the energy area method ($\Delta W/\Delta A$). The ΔW is work done from the P-δ curve to propagate the crack length by a total increment of Δa. The total increment of propagated crack length is a_{eff} minus the initial starter crack length a_o. The a_{eff} at each point was computed by using Equ. 3, wherein the C' would be the nonlinear compliance at that point. The variation of G_{IIc} with the crack length for all the stitch yarns used in this study is shown in Fig. 9. The effect of stitching on Mode II fracture toughness can be studied from this curve. Initially, there is very little effect of the stitches and the value of G_{IIc} is about the same as that of an unstitched laminate. As the crack starts propagating, more and more stitches start becoming effective by added energy dissipation due to matrix deformation, thereby, making the material system tougher. The rate of rise of the G_{IIc} for all the 4×1/4" stitch density is less than 8×1/8" density laminates.

The variation of G_{IIc} was also studied in one more way by calculating the ΔW for each of the two successive load increments and dividing this incremental work done by the corresponding incremental increase of ΔA between only those two successive points. A typical curve in case of Glass-750 is shown in Fig. 10 and represents instantaneous variation of G_{IIc} with crack length.

Stitch Failure Mechanisms

Stitch yarn contribution towards increase in Mode II fracture toughness and the associated failure mechanisms were investigated. The crack space is very narrow in the ENF tests of these laminates and visual resolution is much less than the actual extent of crack front propagation. Therefore, the technique of painting side edges with white paint does not work accurately. Ultrasonic C-Scanning did reveal the crack length but as we have seen in the preceding section that this technique seems to measure less than the effective crack length. X-Radiography of crack surface was also attempted. X-Ray opaque fluid solutions of Zinc Iodide, Barium Chloride and Conray® were tried in varying concentrations. The capillary action does not seem to be adequate to obtain good contrast. Variation in X-Ray intensity were also conducted using the facilities at the University's Medical Center. Changes in the distance of the specimen, soaking time for capillary action, X-Ray exposure times, and different photographic films were tried without satisfactory results. Primary problem appears to be the inability of the X-ray opaque dye to penetrate into the extremely narrow crack space or the relative opening of the crack was not sufficient so that opaque solution was concentrated enough. Future experimental work may explore a more accurate method.

However, physically cutting the specimens in small incremental steps starting from the undamaged end confirmed that even the first stitch line did not break though the crack as seen from the C-scan had propagated at least up to center line of the specimen. The type of stitches used in this study did not break or at best, it is conjectured that perhaps first one or two stitches may have partially broken. The crack front appears to have travelled around the stitch yarn. Due to the uniweave architecture of the fabric there was no additional resistance except that of the matrix and the glass fill yarn (2.5%) typically used in the uniweave cloth during fabric manufacture. This is analogous to stitch yarn "ploughing" through the matrix. The "ploughing" represents plastic or elastic-plastic deformation of the matrix. This explains about the same amount of fracture toughness increase by Kevlar-2790 and Glass-1250 which are closer to each other in diameter, while the Glass-750 being the thicker yarn gives higher rise in fracture toughness for 4x1/4" stitch density. The thicker the yarn, the more there was deformation of the matrix. Also the fracture toughness increases with increase in stitch density indicating increased matrix deformation, except for Glass-750. In the case of 8x1/8" Glass-750, the fracture toughness in fact drops compared to 4x1/4" Glass-750, this may be due to excessive density of this thick yarn making the available matrix volume easier to "plough". This also indicates that there is a possible optimum stitch density for desired fracture toughness and design loading requirements.

EFFECT OF STITCHING ON SUBLAMINATE BUCKLING OF DELAMINATED UNIWEAVE TEXTILE GRAPHITE/EPOXY LAMINATES

Sublaminate Buckling Tests

Sublaminate buckling is an important failure mode in fiber composite laminates that affects compression-after-impact (CAI) strength [11]. This study investigated effects of stitching on sublaminate buckling behavior which is expected to correlate with the CAI strength. Specimens with different stitch densities and known delaminations were subjected to compression loading. The delaminations simulate the impact damage and were created by inserting teflon film strips during the processing in between various ply interfaces in the 48 ply $[(45/0/45)_s]_{4s}$ uniweave textile graphite/epoxy laminates as shown in Fig. 11. Five different types or degrees of damage were simulated (serially #zero to 4, where #zero is the control specimen without any damage), stitch yarns and the variation in stitch densities were same as that for the fracture toughness tests described earlier. The specimens of a gage length of 2.4 or 2.9" and a width of 1.5" were cut from these plates. The loading ends were machined flat and parallel. Back-to-Back strain gages were mounted to study global instabilities. The University of Florida Compression-After-Impact (UF-CAI) test fixture was used for the tests. The fixture allows end compression loading and can be adapted for different gage lengths as shown in Fig. 12. The fixture evolved from an existing NASA post-impact compression fatigue test fixture at the Center for Studies of Advanced Structural Composites, University of Florida. The design considerations and its experimental validation are given in [9]. A typical stress-strain curve of the test is shown in Fig. 13. A total of 131 specimens were tested.

Effect of Stitching on CAI Strength

The average values of CAI strength normalized for 2.4" gage length are given in Table 3. The variation in CAI strength data was not exceeding 5% in 90 specimens out of the 126 valid tests, and it did not exceed 10% in the remaining showing good consistency in test results. Variation of CAI strength with different types of damage for the unstitched laminates is plotted in Fig. 14. The CAI strength drops significantly with increase in delaminations for unstitched laminates. The effect of stitching with different yarns of 4×1/4" stitch density is shown in Fig. 15. The effect of increased stitch density 8×1/8" can be observed from Fig. 16. The CAI strength of delaminated stitched laminates showed excellent improvement over the delaminated unstitched laminates. The improvement in case of the worst delaminated specimens (Damage type #4) stitched with high stitch density like 8×1/8" was as much as 400% over the unstitched laminates. It is also clear from the CAI strength data and the above mentioned graphs that all the three different stitch yarns seem to improve the CAI strength to about the same extent when their stitch densities are equal. This may be due to the fact that any through-the-thickness stitch yarn with sufficient breaking strength and stiffness is able to restrain buckling of the sublaminates by holding them together. More evidence of this is discussed in next section on the sublaminate buckling failure mode. To study a comparative trend of the improvement in CAI strength data due to stitch density, the data were curve fitted using a locally weighted linear regression (Axum software) and the curves are plotted in Fig 17. Here, it was assumed that the different delaminated states (i.e., Damage types #Zero to 4) simulate impact damage of an increasing order.

Effect of Stitching on Sublaminate Buckling Failure Mode

It was observed that the damaged unstitched laminates tended to fail by buckling of the sublaminates. This could be seen from the white painted side edge surfaces. The painted surface opens up at the teflon inserted interplies and the laminate buckles, but the laminate regains its geometry after the unloading. This failure mode is sketched in Fig. 18. However, stitching tends to hold the sublaminates together thus prevent buckling. The stitch yarns will be subjected to tensile loading in the process of trying to restraint sublaminate buckling. Therefore, the failure mode is drastically changed to typical small kink zone formation and subsequent fiber fracture. This also explains the impressive gains in CAI strength due to 8×1/8" stitch density as compared to 4×1/4" density. This type of failure is schematically shown in Fig. 19.