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The Effect of Nylon and Kevlar Stitching on the Mode I Fracture of Carbon/Epoxy Composites

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***Abstract*—**Composite materials are widely used in aviation industry due to their superior properties; however, they are susceptible to delamination. Through-thickness stitching is one of the techniques to alleviate delamination. Kevlar is one of the most common stitching materials; in contrast, it is expensive and presents stitching fabrication challenges. Therefore, this study compares the performance of Kevlar with an inexpensive and easy-to-use nylon fiber in stitching to alleviate delamination. Three laminates of unidirectional carbon fiber-epoxy composites were manufactured using vacuum assisted resin transfer molding process. One panel was stitched with Kevlar, one with nylon, and one unstitched. Mode I interlaminar fracture tests were carried out on specimens from the three composite laminates, and the results were compared. Fractographic analysis using optical and scanning electron microscope were conducted to reveal the differences between stitching with Kevlar and nylon on the internal microstructure of the composite with respect to the interlaminar fracture toughness values.

***Keywords*—**Carbon, delamination, Kevlar, mode I, nylon, stitching.

I. Introduction

COMPOSITE materials have been employed in many aeronautical, aerospace, automotive, and constructional applications due to their superior properties such as the high specific strength, corrosion resistance and flexibility to be manufactured in complex geometries [1]. However, composites face the major failure mode of delamination (interlaminar fracture), which is a separation between the plies of the laminated composite due to high stresses generated between them. Several techniques have been developed to mitigate delamination in composites, such as stitching, Z-pinning, 3D weaving, braiding and utilizing nano-particles and nanofibers [2]. Stitching is one of the most frequently reported methods which requires sewing the dry fabrics through-the-thickness using high strength threads such as Kevlar, Vectran, Dyneema or natural types of threads such as flax [3]–[7]. Stitching is a valid method in alleviating delamination and improving Mode I and Mode II interlaminar fracture toughness [3], [8]–[14].

Stitching materials are usually limited to expensive materials such as Kevlar or Dyneema, or can be difficult to stitch through the thickness composed of carbon fiber tows. Therefore, the objective of the current study is to improve the interlaminar fracture toughness of carbon fiber composite by stitching with inexpensive and easy-to-stitch material; therefore, nylon was chosen for this application. To achieve this objective and to verify the effectiveness of nylon in improving the interlaminar fracture toughness, two stitched laminates were manufactured using resin infusion process; one stitched with nylon and the other stitched with a well known stitching material (Kevlar). An additional unstitched laminate was manufactured for comparison purposes. Double cantilever beam (DCB) tests were conducted on stitched and unstitched specimens. The tensile properties of the different stitching threads were experimentally evaluated. Finally, optical microscope and scanning electron microscope were used for fractographic analysis.

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II. Experimental Procedure

A. Materials

The composite laminates in this research were fabricated using dry TORAY T-700-300gsm-12K-unidirectional (UD) carbon fibers, CE-R3501 vacuum infusion epoxy and CE-H5000-01 curing agent, all supplied from Composite Envisions-USA. Two types of stitching materials were used in this study, namely, Kevlar10 thread with 10 kg maximum tensile load and 0.3 mm diameter and Nylon with 4 kg maximum tensile load and 0.2-0.25 mm diameter.

B. Laminate Fabrication and Specimen Preparation

Three carbon fiber-epoxy laminates were produced in this research, one was unstitched and two were stitched using Kevlar and Nylon. To produce the stitched composite laminates, 10 layers of UD carbon fibers $[0°]_{10}$ were stitched together in their dry form using both Kevlar and nylon threads through the thickness. The fabrics were stitched in a lock stitch pattern with 5 mm stitch space and approximately 3.6 mm stitch pitch in a direction perpendicular to the UD fibers as shown in Fig. 1.

A 12.7-μm thick non-adhesive Kapton film was inserted between the 5^{th} and 6^{th} fabric layers in their dry form to act as a crack initiator in the delamination test. The vacuum assisted resin transfer molding (VARTM) process shown in Fig. 2 was used to infuse the dry laminates with epoxy mixture. First, the epoxy was heated at 45 °C, then it was mixed with the curing agent at a weight ratio 100:29. After that, the epoxy mixture was infused into the fabrics under vacuum, and the curing process was conducted under vacuum and at room temperature for 20 hours until the composite laminate hardens.

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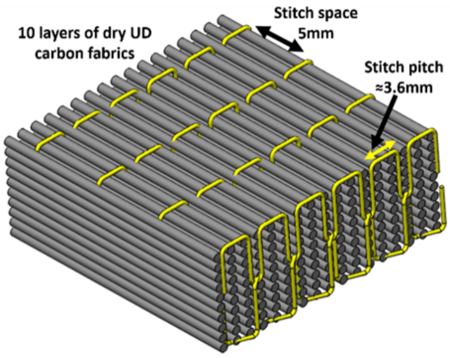

Fig. 1 Schematic illustration of UD-carbon fiber composite with stitching pattern and parameters

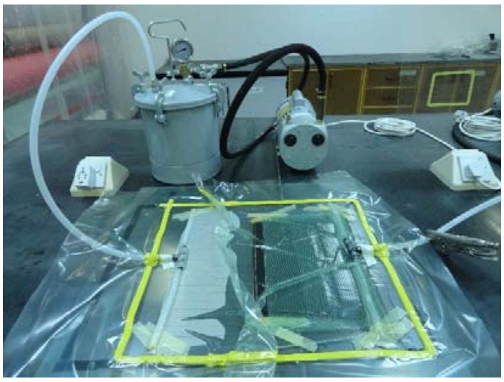

Fig. 2 Vacuum assisted resin transfer molding (VARTM) process

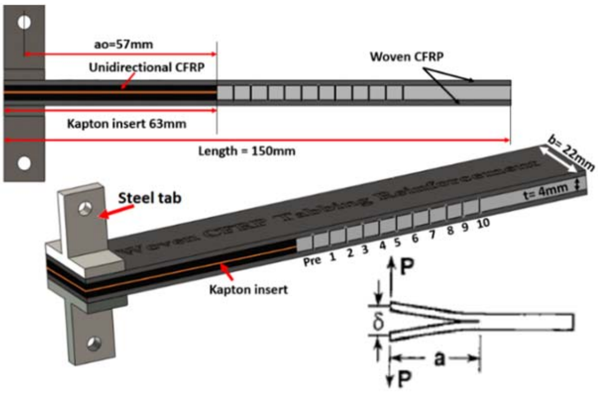

Fig. 3 Side view and 3D view of the DCB- Mode I test specimen showing the dimensions, the tabbing reinforcement and the propagation marks

DCB specimens were cut using a wet diamond saw according to the ASTM standard D5528 [15] with the dimensions shown in Fig. 3. Laminates made of four layers of woven carbon fiber reinforced polymer (CFRP) were secondarily bonded to both sides of the Mode I specimens as shown in Fig. 3 to overcome the high flexural force generated at the specimen's arms due to stitching [7], [16]. These reinforcing laminates were bonded to the Mode I specimen using HYSOL adhesive mixture of Part A-HYSOL EA-9394/C-3NA and part B-HYSOL EA-9394/C-3NA. Small glass beads with 0.1 mm maximum diameter were mixed with the HYSOL adhesive at 1% weight ratio to maintain a uniform adhesive thickness. Steel T-tabs were attached to the DCB specimens using the two parts HYSOL adhesive and following the procedure described earlier.

Both edges of the DCB specimen were painted using a thin layer of water based white paint, and marked every 5 mm from the end of the Kapton insert with vertical lines to ease tracking the crack initiation and propagation visually. The first mark, which was 5mm from the end of the Kaptop insert, was used for pre-cracking the sample, whereas the remaining 10 divisions of total 55 mm length were used for crack propagation. It should be mentioned that the stitches were aligned with each crack propagation division/vertical mark.

C. Tensile Properties of Stitching Threads and Mode I – DCB Test

Tensile tests of the stitching threads (Kevlar and nylon) were conducted using a computer-controlled screw-driven testing machine, Jinan 20WDW with the 2 kN load cell. Five samples from each thread type were tested in a displacement control mode at 5 mm/min rate. The load and elongation were recorded using the data acquisition system, and the fracture energy of each sample was calculated as the area under the load-elongation curve. These tests were done to relate the interlaminar fracture behavior of the Mode I specimens with the stitch thread properties.

DCB tests were conducted following the ASTM D5528 standard using Jinan-WDW20 machine equipped with a 2KN load cell capacity, at 2 mm/min displacement rate. The mode I tests were conducted on ten specimens from each composite laminate, namely, unstitched, stitched with Kevlar and stitched with nylon to calculate mode I interlaminar fracture toughness G_{IC} at several crack lengths (a). The mode I test was carried out in two stages, the precracking and the crack propagation. Each specimen was first precracked, and the location of the precrack was determined precisely using LED illuminated digital microscope and digital caliper. After that, the crack propagation stage was conducted by recording the load (P), opening displacement (δ), and with continuous monitoring of crack propagation using the LED illuminated digital microscope as shown in Fig. 4. A mark was left on the (P-δ) curve when the crack reached a new vertical mark (new crack length a).

The interlaminar fracture toughness (G_{IC}) was calculated using the modified beam theory with the Δ correction factor using the equation shown below:

$$G_{IC} = \frac{3P\delta}{2b(a + |\Delta|)}$$

where P is the load, δ is the opening displacement, b is the sample's width, a is the crack length, and Δ is a correction for crack tip rotation.

D. Fractographic Analysis

Representative mode I fractured specimens from the three laminates were analyzed using Quanta 450 FEG Scanning electron microscope (SEM) and LED illuminated digital microscope. This was done to explore the role of stitching in enhancing the interlaminar fracture toughness, in particular to relate the observed fracture morphology with the mechanical test results.

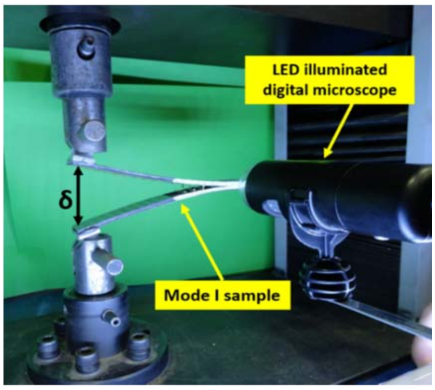

Fig. 4 Mode I – DCB test setup

III. Results and Discussions

A. Stitching Thread Tensile Properties

Fig. 5 shows the tensile properties of the stitching threads (Kevlar and nylon) in their dry form. Each bar is an average value of the five tested specimens' results. It is clear that the maximum load to break is higher for Kevlar, whereas the maximum elongation to break is much higher for nylon. This is because Kevlar is a brittle material in nature, whereas nylon is a very ductile material. In addition, the fracture energy, which was calculated as the total area under the load-displacement curve of each thread sample, is much higher for nylon than Kevlar, which correlates more closely to the maximum elongation to break trend. This stitch thread behavior will have a direct relationship with the interlaminar fracture toughness of the stitched composite as will be discussed later.

B. Interlaminar Fracture Toughness of Stitched and Unstitched Composites

Fig. 6 shows G_{IC} versus crack length curves of three representative samples from the unstitched, stitched with Kevlar and stitched with nylon composite laminates. The G_{IC} was calculated at each crack length (a1 to a10) where a1 or point 1 represents the initial point where the crack initiated, and point 10 represents the final point. The initiation interlaminar fracture toughness value ($G_{IC\text{-initiation}}$) is important as it represents the fracture toughness of the composite at crack initiation. It is clear from Fig. 6 that the unstitched composite showed a slight increase of the G_{IC} at the beginning, then stabilization with the increase in the crack length. However, composites stitched with nylon showed similar crack initiation fracture toughness values to the unstitched composite, but with further crack growth, G_{IC} increases tremendously. On the other hand, composite stitched with Kevlar showed an almost steady state value of G_{IC} from crack initiation to full delamination.

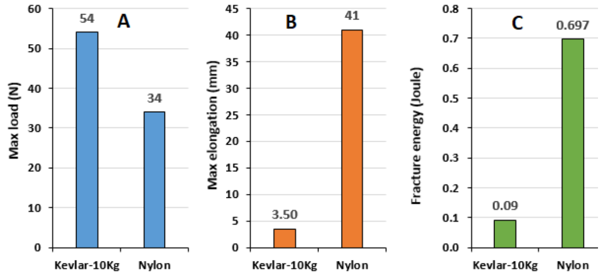

Fig. 5 Tensile properties of the stitching threads: Kevlar and nylon (A) Maximum tensile load (B) Maximum elongation to break (C) Fracture energy

This behavior can be explained as the following: first, the higher G_{IC} values of stitched composites compared to the unstitched composites comes from the fact that stitched composites have higher fiber bridging due to the through the thickness stitches which resist delamination. In addition, the stable behavior of Kevlar stitched composites can be associated to the brittle nature of Kevlar compared to nylon. Kevlar did not significantly stretch before breaking while testing the sample. Instead, when the delamination reached a new row of Kevlar stitches, the entire row of stitches broke suddenly in brittle manner. However, in the case of nylon stitches, the stitches elongated tremendously before breaking leading to higher values of G_{IC}. Moreover, the delamination in the nylon stitched samples propagated without complete breaking of the stitches or even any separation between the upper and lower arms of the specimen. This is considered as a major advantage of using nylon in stitching compared to Kevlar because it provides an early warning sign of crack propagation/delamination without complete damage/failure of the material.

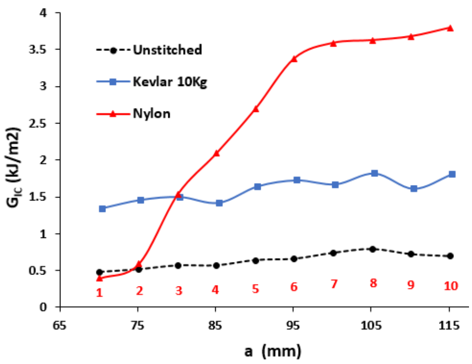

Fig. 6 R curves of representative samples from the unstitched, stitched with Kevlar, and stitched with nylon composites

A full summary of all Mode I test results of unstitched, stitched with Kevlar and stitched with nylon and samples is shown in Fig. 7. For each type of composite, the mean value of all tested samples initial, minimum, maximum, final, and average value of G_{IC} were calculated and plotted as a bar with a standard deviation error bar. Because the minimum and initial G_{IC} values are similar, and the maximum and final G_{IC} values are similar for all types of composites, we will only explain the trend of the initial, maximum and average values of G_{IC}. Fig. 7 shows that $G_{IC\text{-initial}}$ increased from 0.57 kJ/m^2 for unstitched composite to 1.27 kJ/m^2 for the composite stitched with Kevlar, and 0.8 kJ/m^2 for the composite stitched with nylon. These values correspond to 123% increase in the $G_{IC\text{-initial}}$ when stitching with Kevlar and 40% increase when stitching with nylon. The $G_{IC\text{-maximum}}$ of the Kevlar and nylon stitched composite are 156% and 350% higher than the unstitched, respectively. Finally, average G_{IC} shows 146% and 240% increase when stitching with Kevlar and nylon, respectively.

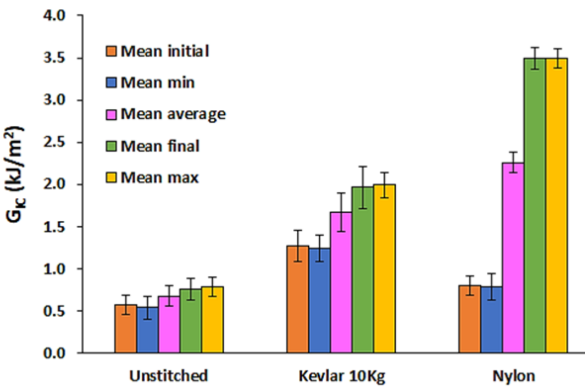

Fig. 7 Summary of the Mode I-DCB results: mean values of the initiation, minimum, maximum, final and average interlaminar fracture toughness ($G_{IC\text{-initiation}}$, $G_{IC\text{-minimum}}$, $G_{IC\text{-final}}$, $G_{IC\text{-maximum}}$, $G_{IC\text{-average}}$)

It can be easily seen that there is a correlation between the fracture energy (and max elongation to break) of the stitching thread as shown in Fig. 5 and the $G_{IC\text{-maximum}}$, $G_{IC\text{-final}}$ and $G_{IC\text{-average}}$ values of the composite as shown in Fig. 7. Clearly, the nylon shows a significant numerical advantage over the Kevlar fiber. On the other hand, there is a correlation between the maximum tensile load of the stitching thread and the $G_{IC\text{-initiation}}$ value, as observed in the comparison between Fig. 5 (A) and Fig. 7, where Kevlar is superior. Nylon has much higher ductility and resulting fracture energy compared to Kevlar, thus the composite stitched with nylon has higher maximum and average interlaminar fracture toughness G_{IC} values. However, Kevlar is much stronger than nylon, thus the composite stitched with Kevlar has higher initiation G_{IC} values, which is a strength-driven property.

C. Fractographic Analysis

The fractographic analysis in this study was done using three methods: digital microscopic images of the Mode I sample while being tested, digital microscopic images of the fractured surfaces, and SEM images of representative fractured specimens. The fractographic analysis was carried out to explore and compare the effect of stitching with nylon and Kevlar on the fracture surface and relate it to the fracture toughness behavior.

Fig. 8 shows two samples, one stitched with Kevlar and the other stitched with nylon, during and after Mode I testing. Fig. 8 (A) shows that, during Mode I test, the crack propagated in the sample stitched with Kevlar without significant stretching in the Kevlar fibers; that is, the threads broke suddenly leading to a complete separation of the two parts of the sample. However, significant elongation can be seen in the nylon threads. In addition, in the sample stitched with nylon, the crack propagated, while the two arms of the sample remain attached via the stretched nylon threads. Fig. 8 (B) shows that, after the test, broken nylon threads exist on both sides of the sample revealing the ductile nature of nylon, whereas Kevlar broke in a brittle nature and exists on only one side of the delaminated sample, with corresponding stitches holes on the other side.

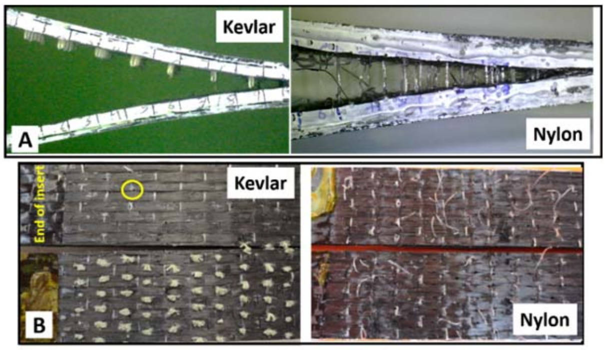

Fig. 8 Optical microscopic images of (A) Side view of samples stitched with Kevlar and nylon during the DCB test (B) Fractured surfaces of the same stitched samples

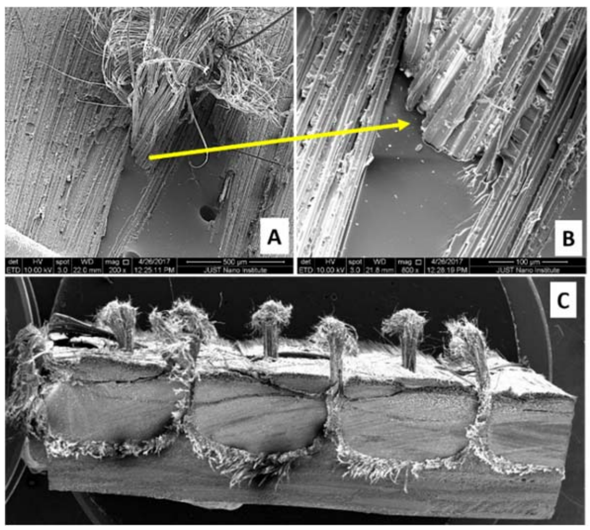

Fig. 9 SEM images of fractured sample stitched with Kevlar showing (A) A single Kevlar stitching thread with the epoxy matrix and carbon fibers (B) The adhesion between the thread's multi filaments and the epoxy (C) 3D view of the fractured sample

Fig. 9 shows SEM images of fractured samples stitched with Kevlar. It is clear that the Kevlar stitches consist of multiple filaments attached together, which results in stronger thread and enhanced bonding with the matrix. The broken carbon filaments in the SEM image are due to the Mode I load (opening mode) which brokes the sample into two halves (upper and lower halves) resulting in damage at the sample's interfacial surface which causes the matrix, the carbon filaments and the stitching threads to break. The broken carbon fibers occur when the crack skips slightly from just below a carbon fiber to just above it, putting the carbon fibers in tension as the specimen opens. Fig. 10 shows SEM images of fractured samples stitched with Nylon. One can observe several features in these images. First, as observed in Fig. 10. (A), it is obvious that the nylon thread (which is under tensile load as the crack opens) experienced significant elongation before breaking in a ductile manner. Note that it failed at the classical ductile 45° with respect to the applied load tensile direction. In addition, nylon shows strong adhesion with the epoxy matrix as observed by the torn nylon thread as in Figs. 10 (A) and (B), by the rough imprints left behind the nylon threads pulled out, as shown in Fig. 10 (D), or by the strong bonding shown in Fig. 10 (C). Fig. 10 (D) shows that resin pockets form around the transverse nylon fibers, as the UD carbon fibers must spread to 'go around' them, and the space created is filled with the liquid resin. This creates a situation at the microscopic level which is quite complex, and worthy of further study. All these features together may explain the improved interlaminar fracture toughness of the composite stitched with nylon compared to Kevlar due to the significant elongation of the nylon threads and the enhanced adhesion between the nylon thread and the epoxy matrix compared to Kevlar.

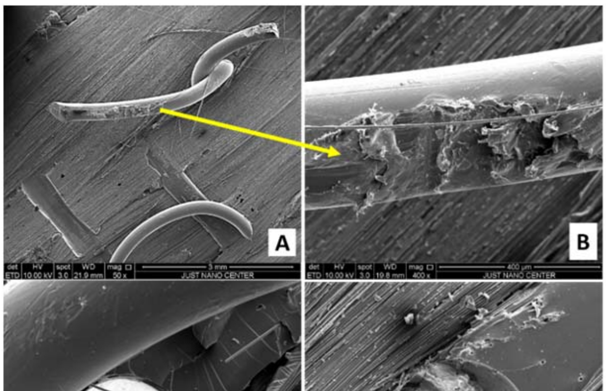

Fig. 10 SEM images of fractured sample stitched with nylon showing (A) Elongated and broken nylon thread in the carbon fiber-epoxy composite (B) the torn nylon thread (C) Adhesion between nylon thread and epoxy (D) Nylon thread pullout imprint in the epoxy matrix

IV. Conclusion

The effect of stitching UD carbon composites with Kevlar and nylon on their Mode I interlaminar fracture toughness was investigated. Two stitched laminates and one unstitched laminate were manufactured using VARTM process and tested using DCB-Mode I delamination test. Results showed that stitched composites have higher initiation and propagation interlaminar fracture toughness G_{IC} compared to the unstitched composite. composite stitched with nylon showed higher crack propagation G_{IC} compared to Kevlar stitched composite, whereas Kevlar stitched composite showed higher crack initiation G_{IC} values. This was due to the ductile nature of nylon thread, which elongated significantly, compared to the stronger yet more brittle Kevlar. stitching with nylon gives the benefit of early warning signs of crack initiation and propagation before complete failure.

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