MULTI-NEEDLE STITCHED COMPOSITES FOR IMPROVED DAMAGE TOLERANCE

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SUMMARY

A novel multi-needle orthogonal and bias stitch-bonding machine has been developed for hard/rigid close-cellular foam core sandwich composites. The structural performance of impregnated sandwich panels with epoxy resin has been explored. Quasi-static indentation and three-point bending tests were conducted on unstitched and stitch-bonded samples.

Keywords: *stitch-bonding; sandwich panels; hard/rigid closed-cellular foam core, through-the-thickness reinforcement, damage tolerance*

1. INTRODUCTION

Lighter and stronger materials can be achieved by the use of composite materials, and for many years, manufacturing of composites has been continually evolving for many applications. Sandwich composites are one of the examples of composite structures which have been tailored for specific areas. They consist of a lightweight core material and two thin skins. The major advantage of the sandwich structure is its high flexural stiffness to weight ratio. Their low-weight combined with high stiffness and strength has attracted a lot of interest from researchers and engineers in the aerospace, marine, automotive, and wind turbine industries. The most important benefit of a reduction in weight is less fuel consumption which is highly desirable especially in aircraft and spacecraft applications. However, sandwich structures suffer from skin debonding/delamination between the core and skins during manufacturing and their lifetime due to impact damage from dropped tools, fastening, drilling etc. Honeycomb and foam core sandwiches are widely used in structural applications. Both these core types struggle with susceptibility to in-plane shear, core compression failure, buckling instability and face sheet-to-core debonding respectively [1]. Also, the impact damage from dropped objects may result in invisible internal damage and crack propagation which cause a reduction in the strength and stability of the structure.

Through-the-thickness (TT) reinforcement of sandwich structures is a promising attempt to overcome the problems mentioned above. Delamination is reduced because of the existence of transverse reinforcement, and hence the impact resistance and the damage tolerance are increased. TT reinforcement can be achieved by 3D weaving, z-pinning, and stitching/tufting techniques. The limitations for 3D weaving are a slow production rate due to many fibre bundles interlacing several layers, limited capacity of the textile machine [2], the formation of a relatively soft open-cell foam core and the problem of keeping the faces apart in order to keep the z-fibres in tension. Z-pinning is a relatively expensive process and z-pins do not have anchors to the top and bottom skins and hence are less effective in preventing skin debonding [3]. Also, it is a very slow and expensive process and suitable only for the aerospace market [4].

2. STITCH BONDING OF COMPOSITES

Stitching is a promising through-the-thickness reinforcement technique for composite fabrication, which basically involves high-tensile strength sewing yarn, usually made from carbon, glass, or Kevlar, through the layers of composites using an industrial sewing machine. It is a low-cost technique for improving the stiffness and damage tolerance of composites. Stitched composite materials and the use of stitching as a through-the-thickness reinforcement have been studied for many years for structural applications.

Over the past few years there have been a number of developments in stitching. A large, high-speed and multi-needle Advanced Stitching Machine (ASM) was designed and built under the ACT programme by NASA to stitch large, thick, complex wing structures [5]. Altin-Nähtechnik used tufting by inserting the thread under an angle of 45° and 90°, and developed the one-sided stitching ($OSS^{®}$) technique, which is similar to the one-thread chain stitch method, by using two needles penetrating from one side of the preform [6, 7, 11]. The KSL (tufting) technique and the ITA technique which is based on the formation of a two-thread chain pass with two needles penetrating from only one side were developed [8]. QinetiQ also developed a 3D stitching robot using tufting, blind stitching, and two needle single-sided stitching techniques for creating dry fibre preforms [9]. Partridge et. al. developed single-needle robotic tufting by using a robotic arm [10]. Potluri et. al. developed a single-needle stitching process for rigid and close-cellular foam core sandwich composites [3, 4]. In this study, a multi-needle orthogonal and bias stitch-bonding machine has been developed by the authors to reinforce the close-cellular foam core sandwich panels with bias and orthogonal stitches. Stitch-bonded sandwich panels were impregnated in a vacuum bagging process and subjected to indentation and three-point bending tests to evaluate their structural performance.

3. MANUFACTURING OF SANDWICH PANELS

Divinycell H grade (density = 130 kg/m^3, thickness = 12 mm) close-cell foam with one layer of woven carbon skin (area density = 536 g/m^2) on each side of the foam were used in the experimental work. Sandwich panels (30 cm x 30 cm) with stitch spacing of 1 cm were prepared using a set of heavy-duty sewing needles. The placement of stitches can be seen in Figure 1. Because of its high strength and flexibility, Kevlar 49 yarn (158 tex) was used in the experimental work. The panels were impregnated with epoxy resin (Araldite Resin LY 5052, Hardener HY 5052; mixing ratio of 100:38 by weight, respectively) in a vacuum bagging process.

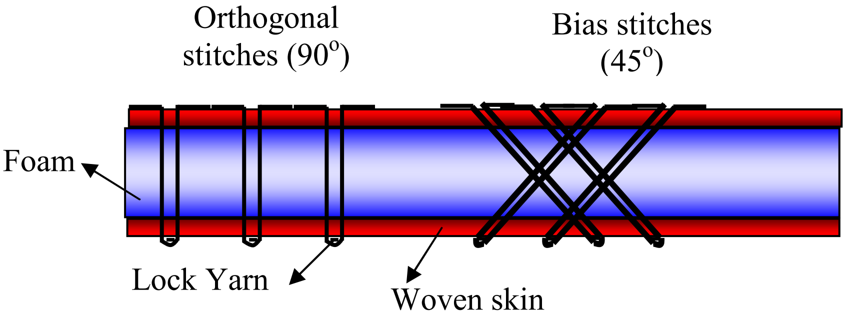

Figure 1: A sandwich panel and orthogonal/bias stitches

In the multi-needle stitch-bonding machine which is based on the modified lock stitching technique shown in Figure 2, each needle inserts a loop of Kevlar 49 yarn in the thickness direction across the width of the panel. Loops are created by partial retraction of the needles. Like the weft insertion in the weaving process, a rapier inserts a locking yarn through the opened loops on the needles. Then, the needles are fully retracted and the lock yarn locks all the stitch yarns on the top. Finally, the sandwich panel is advanced forward for the next stitch row.

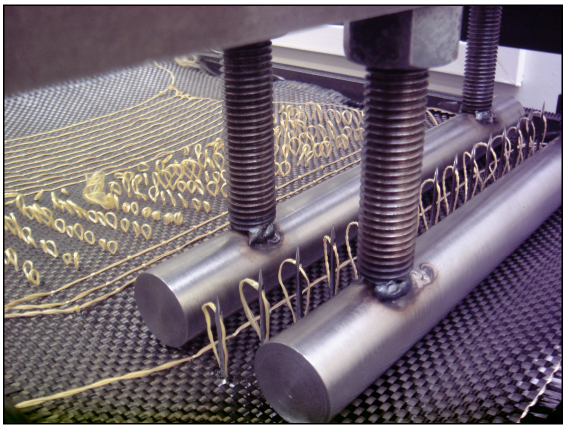

Figure 2: Multi-needle stitch bonding machine

4. OPTIMIZATION OF KEVLAR YARN FOR STITCH-BONDING

During the resin impregnation of the sandwich panels, the resin fills the gaps caused by the sewing needles when they penetrate through the panel and surrounds the stitching yarns. Once it is cured, columns (cured resin involving yarn) are created in the stitch holes. These columns resist the force, reducing the propagation of cracks in the structure and delamination on the bottom skin, and therefore increase the performance of the panel. Therefore, the stiffness and strength of the Kevlar yarns are of interest, because the tensile strength of yarn affects the column properties.

Lack of cohesion between the filaments in the untwisted Kevlar yarn causes problems during stitching due to filamentation. Hence, an optimized balanced twist was developed and used in the stitches. The balanced twist yarns involved two individual plies of S twisted Kevlar 49 which then twisted together in the Z direction by 70% of the twist level of the single plies. Based on the observations during stitching, 35, 71 and 106 turns/metre Z-balance twisted yarns were studied and compared to each other in terms of tensile strength and the filament behaviour of each yarn was observed in stitch-bonding process. Of these, sample with 71 turns/metre was chosen because it has acceptable stitching performance with minimum reduction in strength. Tensile tests of yarns were carried out in accordance with the ASTM D 2256 standard [12]. Tensile strength and stiffness, Figure 3, reduced while the twist per metre increased as a result of the orientation of the filaments around the yarn axis. The cross section of the columns can be seen in Figure 4.

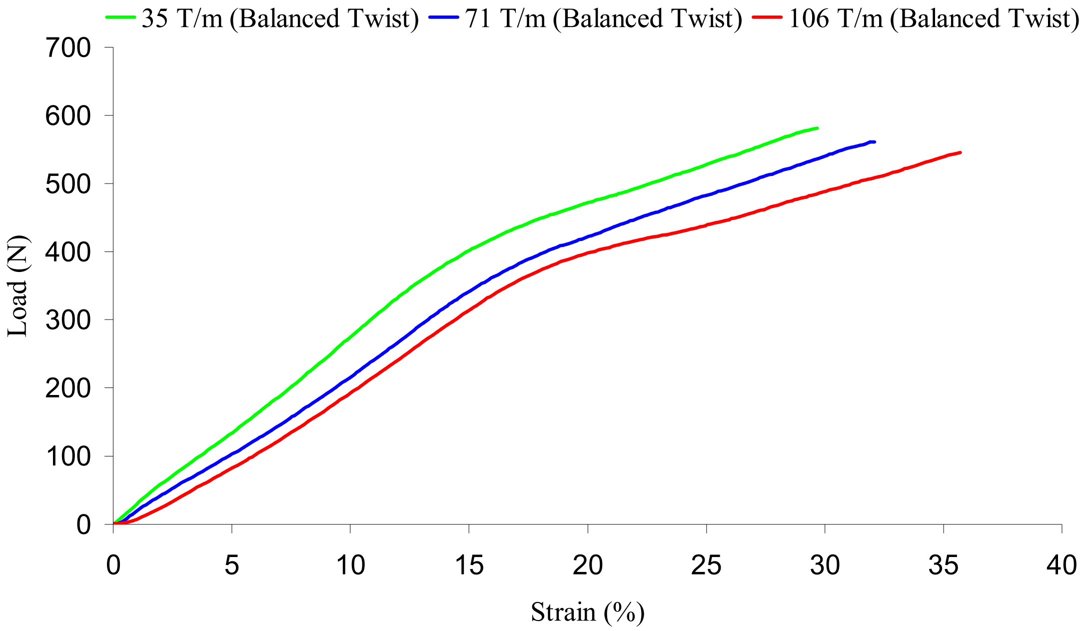

Figure 3: Tensile strength curves of balance twisted yarns

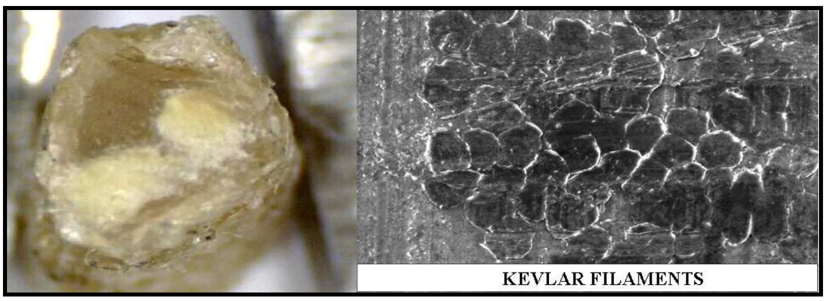

Figure 4: Cross section of a column

5. QUASI-STATIC INDENTATION TESTS

The sandwich panels were placed in a square frame (Figure 5) with an exposed area of 20 cm x 20 cm. The lateral displacement of the material was restrained. A 25 mm diameter cylindrical flat-faced indenter was forced into the sandwich panel with a crosshead speed of 5 mm/min by means of an INSTRON 5569 machine. The load and crosshead displacement were recorded

Figure 5: Quasi-static indentation test

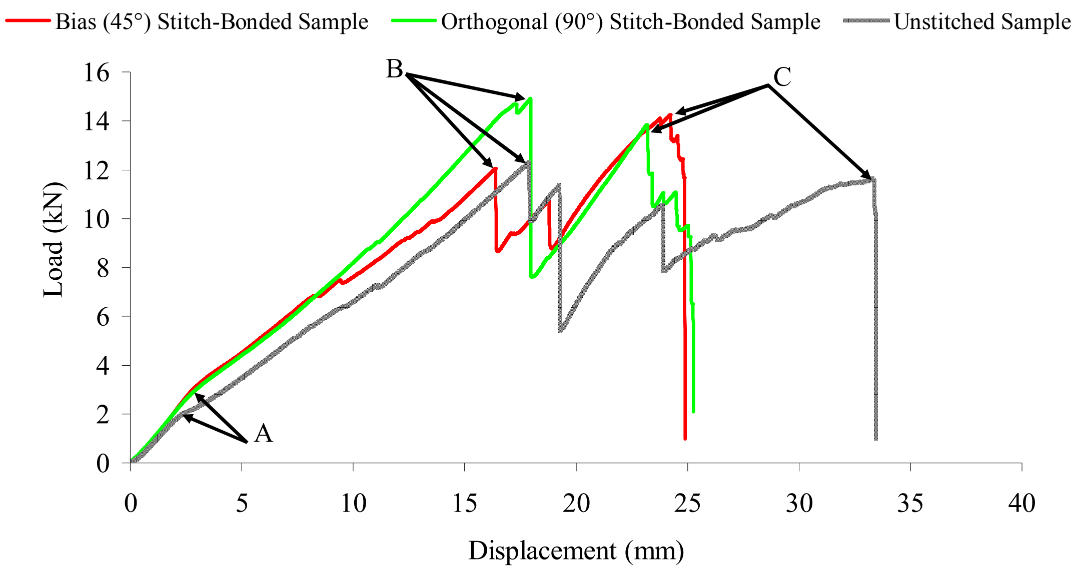

Figure 6: Quasi-static indentation tests on sandwich panels with 1 cm stitch spacing

According to the load versus displacement curves (Figure 6), the deflection increased linearly up to point A (initial damage), and cracking noises were heard. After this point, the inclination dropped slightly but it kept increasing gradually up to point B which is the top skin fracture. At this point the indenter punched a disk out from the top skin of the panel and a very sharp drop in load could be observed. Once the bottom skin fracture/debonding was complete (point C), the load dropped sharply. The indenter displacement, shown in Table 1, was almost the same for the bottom skin debonding failure for both the orthogonal and bias stitch-bonded samples. Also, the debonding area was almost equal to the diameter of the indenter, shown in Figure 7. For the unstitched sample, the completion of the fracture of the bottom skin continued with the indenter displacement up to the clamped edges.

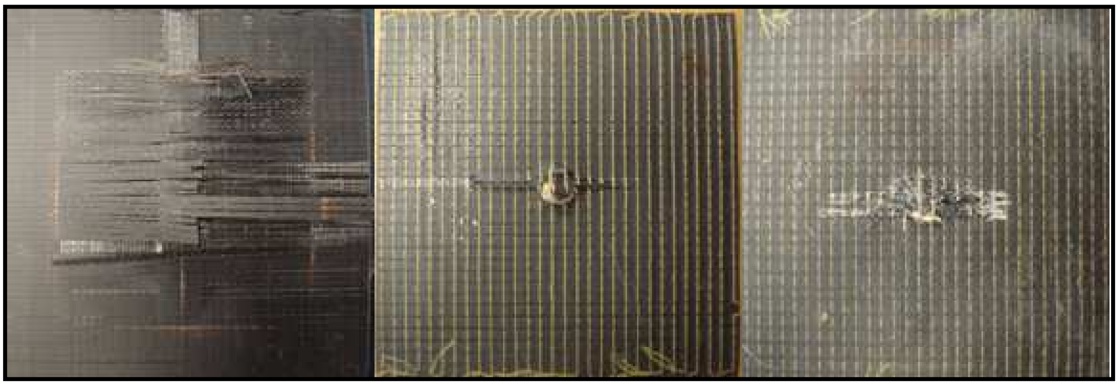

Figure 7: Bottom skin de-bonding of unstitched, orthogonal (90°), and bias (45°) stitch-bonded samples after quasi-static indentation tests

Regarding the stiffness (k values) and the energy absorption, the following observations were made from Figure 6 and Table 1:

- According to the stiffness values for the bi-linear part (Figure 6) up to the top skin failure, the k_1 value represents the initial damage while k_2 represents the stiffness after the initial damage up to the top skin fracture. These values can be seen in Table 1. k_1 was higher for the bias stitch-bonded samples whereas k_2 was higher for the orthogonal stitch-bonded samples. The unstitched samples exhibited lower stiffness values.
- The stitch-bonded samples showed higher load at bottom skin debonding failure and less total energy values than the unstitched samples. The stitches increased the stiffness of the sandwich panels, and reduced the delamination area on the bottom skin.
- The orthogonal stitch-bonded samples showed the highest load at top skin (point B) failure, and k_2 value. This could be attributed to the initial resistance of the vertical stitches against the applied force up to the top skin failure.
- The bias stitch-bonded samples exhibited the lowest top skin failure load, but their k_1 and the load at bottom skin debonding failure were the highest. Even though the stitch spacing was the same for the orthogonal and bias stitch-bonded samples, the bias stitches resisted the transverse compression better than the orthogonal stitches. This could be the result of the stitch orientation in the sandwich panel.
- Even though the load and energy absorption values at the top skin failure for the unstitched samples were higher in comparison with the bias stitch-bonded samples, their load at bottom skin debonding failure, k_1 and k_2 values were the lowest.

- Energy absorption at the top skin failure was the highest for the orthogonal stitch-bonded samples. The total energy absorption value was the highest for the unstitched samples because the bottom skin debonded until the clamped area.

Table 1: Quasi-static indentation test data

Stitching angle (°)	Load at top skin failure (kN)	Indenter Disp. (mm)	Load at debonding failure (kN)	Indenter Disp. (mm)	k_1,(up to initial damage) (N/mm)	k_2, (up to top skin failure) (N/mm)	Energy at top skin failure (J)	Total Energy (J)
Unstitched	12.32	18.43	11.65	33.83	837.40	652.46	108.17	257.57
90 °	14.91	18.28	13.84	23.52	1042.47	778.20	135.91	212.70
45 °	12.06	16.40	14.26	24.23	1071.94	666.67	105.62	201.50

6. THREE-POINT BENDING TESTS

Three-point bending tests were carried out on an INSTRON 5569 testing machine in accordance with the ASTM C 393 standard [13]. Sample dimensions were 300 mm (length) x 60 mm (width) x 14 mm (thickness), and the span length was 18 cm. The unstitched and stitch-bonded sandwich composite samples were placed on two round supports of diameter 20 mm, and compressed by a 20 mm rod. The load and deflection values were recorded.

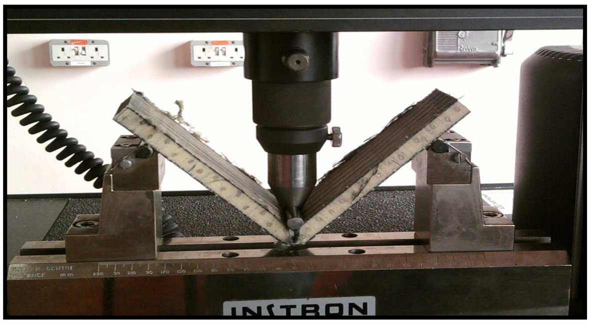

Figure 8: Three-point bending test

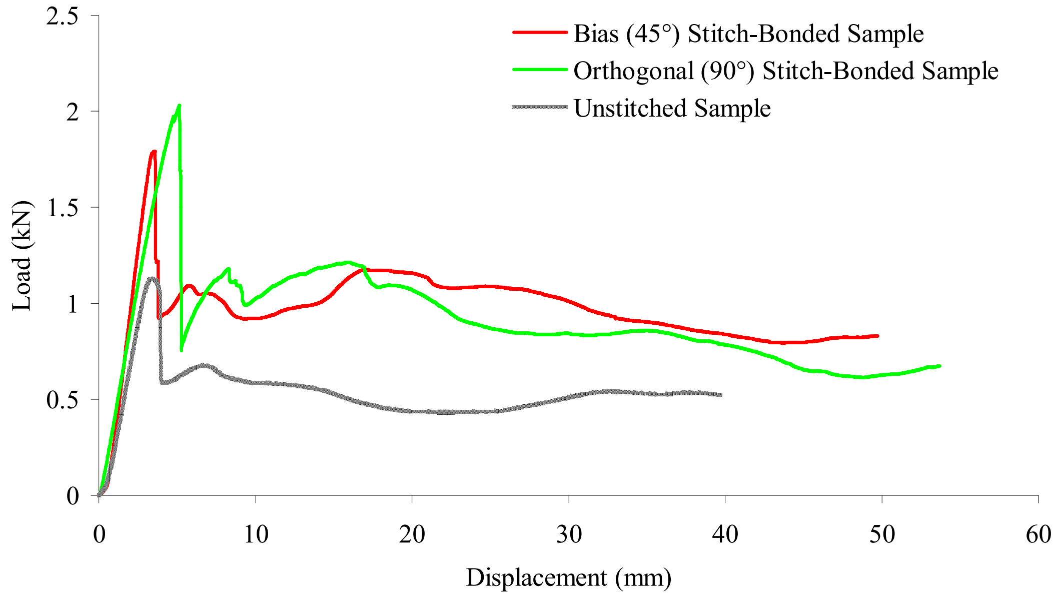

Figure 9: Three-point bending tests on sandwich panels

Similar to the quasi-static indentation test results, stitch-bonded samples showed higher top skin failure load, stiffness and flexural rigidity values after three-point bending tests, as shown in Table 2. Bias samples exhibited higher flexural rigidity and stiffness. Therefore, bias stitches were effective in resisting the bending and transverse shear loads. The orientation of stitch reinforcements played an important role when resisting the applied transverse load.

Table 2: Three-point bending test results

Sample	**Top skin failure**			
	Load at top skin failure [kN]	**Displacement at top skin failure [mm]**	**k values up to top skin failure [N/mm]**	**Flexural rigidity (E.I), [N.mm²]**
Unstitched	1.13	4.06	415.93	$50x10^6$
Orthogonal (10 mm)	2.03	5.16	426.27	$51x10^6$
Bias (10 mm)	1.79	4.76	615.94	$74x10^6$

7. CONCLUSIONS

In the experimental work, sandwich panels were stitch-bonded by means of the developed stitch-bonding machine mentioned above. The stitch-bonded panels were impregnated with epoxy resin in a vacuum bagging process. For the performance evaluation of the sandwich panels produced, quasi-static indentation and three-point bending tests were carried out on unstitched, bias stitch-bonded and orthogonal stitch-bonded samples. Stitch-bonding increased the indentation and bending performance of the panels. Up to the top skin failure, the performance of the orthogonal stitch-bonded samples was better than the bias stitch-bonded samples. However, bottom skin debonding failure was higher for the bias stitch-bonded samples and the total energy to failure up to bottom skin fracture was the least. Hence, bias stitches were superior in terms of minimising the bottom skin debonding with the least total energy absorption. The total energy to failure was lower for the stitch-bonded samples when compared with the unstitched samples. According to the three-point bending test results, the stiffness and the flexural rigidity of stitch-bonded samples were higher than the unstitched samples. Those were higher for the bias stitch-bonded samples. This proves that, similar to the indentation tests, the stitch orientation played an important role and the bias orientation showed better performance. It was proved that the existence of the stitch reinforcements in the sandwich panels was effective in resisting the applied force onto the samples. However, further investigations are needed to explore the effect of varying stitch densities with different stitch orientation for the debonding failure and bending stiffness, thus clarifying the significance of stitch orientation.

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