A COMPARISON OF THROUGH-THICKNESS REINFORCEMENT METHODS: Z-PINNING AND STITCHING

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Abstract

The work presented extends previous work [1] on carbon fibre/epoxy prepreg, where the effects of z-pinning and stitching using PBO poly(p-phenylene benzobisoxazole) thread were investigated. In the current study, a continuous Tenax carbon thread has been used on the same prepreg material, and its effect on the physical and mechanical properties evaluated. In addition, the tufting and stitching of dry carbon fibre fabrics has been performed.

Significant difficulties were encountered during the stitching of the prepreg laminates using the carbon thread due to the tackiness of the resin. Tension and compression tests on the prepreg laminates showed only a small reduction in properties due to the stitching. In general, stitching appeared to result in less fibre distortion compared to z-pinning. Studies on dry fibre fabrics showed that high density tufting is beneficial to compression after impact (CAI) properties.

1 Introduction

Although laminated composites offer significant advantages over many monolithic materials, their tendency to delaminate under the action of through-thickness stresses, and after impact, has placed a significant limitation on their wider exploitation. The need to allow for such damage has resulted in a conservative approach to design; meaning that the full potential of these materials has not yet been realized. In the past, a variety of solutions for improving the damage tolerance and damage resistance of laminates have been explored. Most of these have focused on the use of tougher resins, or the introduction of toughened particulates within the resin. An alternative approach has been the use of through-thickness reinforcements, such as z-pinning, stitching and tufting, and it is this approach to improving delamination resistance with which this paper is concerned.

The effect of different types of through-thickness reinforcement (TTR), particularly the application of z-pinning on composites, has been studied by a number of researchers [2, 3]. The majority of these investigations have been concerned with the effect of TTR on interlaminar properties; the findings of which tend to show that there is a substantial improvement in the mode I (opening) and mode II (shear) delamination resistance of laminates. Fewer studies have been made on the effect of TTR on in-plane properties, and there is no clear consensus, particularly where stitching or tufting has been used, as to whether in-plane properties are degraded or enhanced.

In the work presented here, a carbon stitching thread has been used on the same prepreg material used in a previous study [1] and the effect of the thread on in-plane and interlaminar properties has been investigated. The same carbon thread has also been employed in stitching and tufting experiments, performed using QinetiQ’s robotic stitching facility. The effect of different stitching methods on the compression properties of resin infused laminates was evaluated.

For the prepreg phase of the work, quasi-isotropic test panels were manufactured from unidirectional (tape) prepreg and stitched using a Tenax twisted carbon fibre thread. Stitching was performed using a stitch spacing and areal density (2%) similar to that used on the z-pinned panels. Specimens were cut from the cured panels and the effect of the stitching thread on the interlaminar and in-plane properties evaluated. The results were then compared against equivalent unreinforced specimens and data previously obtained for laminates stitched with PBO [1].

Recent advances in stitching techniques for composite materials has included the design and development of special stitching heads, where the head is carried by a multi-axial robot over a static composite fabric to allow large components to be easily stitched. Restricted access to the fibre part has been overcome by the development of a one-sided stitching technique. Since the work piece has to be accessed from one side only, stitching of complicated structures is no longer limited by the design or size of the stitching machine. QinetiQ's stitching facility consists of a fully computerised automated robotic 6-axis stitching machine, which can also move on a powered 3m long rail, providing a 7th axis of freedom. Three methods of stitching were investigated; two-needle one-sided stitching, single needle blind stitching, and tufting.

2 Experimental Procedure

2.1 Stitching of Carbon/Epoxy Prepreg

Thirty two ply, (4mm thick) carbon/epoxy laminates were laid up using IM7/8552 prepreg with an [(+45,0, -45, 90)4]S lay-up. A proportion of the laminates were then stitched using a Tenax HTA 5641 carbon sewing thread. Figure 1 shows an electron micrograph of the thread, which consisted of two individual carbon fibre tows twisted together. The width of the thread was nominally 0.5mm at its widest, with cross over points every 2.3 – 2.5mm.

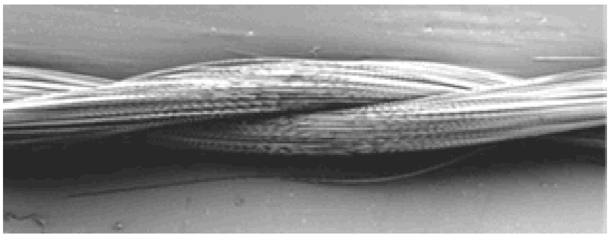

Fig. 1. Cross-sections through z-pinned and stitched laminates

Attempts were made to stitch a number of un-cured laminates, typically 300mm x 300mm, using the Tenax fibre. Stitching was performed using a locking stitch, where a loop of thread is pushed through the laminate and a locking stitch passed though the loop to prevent the loop from being drawn back though the laminate (as the needle retreats). To allow a comparison with existing data obtained for z-pinned and PBO stitched materials, all stitching was performed using an architecture (stitch density/diameter & pattern) similar to that used on previously tested z-pinned laminate. The stitches were spaced approximately 3.2mm apart (i.e. to mimic a 0.51mm diameter/2% z-pin density).

In Figure 2, the front and back face of one of the stitched prepreg panels is shown.

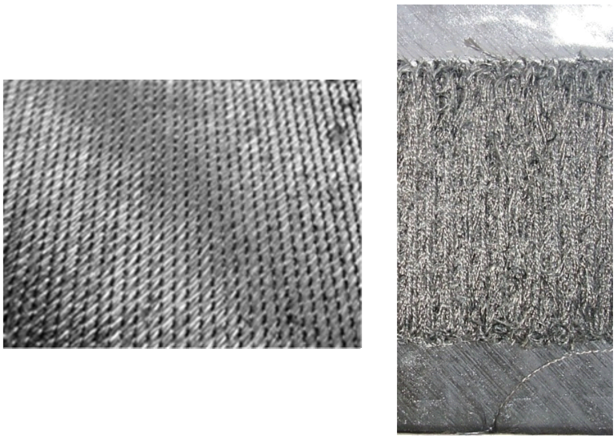

Fig. 2. Front (left) and back face (right) of carbon stitched laminate

Whilst the front of the panel was of a satisfactory quality, the back face of the laminate suffered from severe 'flocking' and 'birdsnesting'; where loose fibres from the carbon thread, and extended loops of overlocking thread, accumulated on the surface of the laminate. Due to the tackiness of the resin, and high penetration resistance of the laminates, both the carbon thread and sewing needles were found to break frequently. Considerable effort was directed at trying to prevent this accumulation of material by warming or cooling the laminate during stitching, the use of different needle sizes and the application of a lubricant to the needle. However, this could not be eliminated completely.

After stitching, the carbon-epoxy laminates were cured in an autoclave and test specimens cut from the panel for evaluation. Prior to autoclaving it was necessary to cut away some of the surplus fibre on the back of the panel. This was necessary to prevent the fibres drawing excess resin out of the panel during curing, which could have resulted in resin starvation within the panel. Once cured, both the plain (non-stitched) and stitched laminates were C-scanned to assess their quality. Good consolidation of both sets of laminates was achieved, with good resin flow into the material between the stitches.

2.2 Stitching of Dry Fibre Preforms

Stitching was carried out on lay-ups consisting of Tenax HTS carbon fibre fabric of 267gsm areal weight, and a quasi-isotropic fibre architecture, as detailed below:

$[+45, -45, 0, 90, -45, +45, 90, 0]_{2S}$
i.e. 8 layers of fabric 16 plies of carbon fibre

Stitching of the fabric was performed using QinetiQ's robotic stitching facility as shown in Figure 3.

Fig. 3. QinetiQ stitching robot on 3m rail

The 6-axis robot has approximately a 3m working envelope in its static position, which is increased several fold by movement along a 3m rail. Restricted access to the fibre part (as in conventional stitching) has been overcome by the development of the one-sided stitching techniques. The development of one-sided stitching heads, where the head is carried by a multi-axial robot over a static composite fabric, has been motivated by the need to stitch large composite preforms, and allows large components to be stitched easily.

A comparison of carbon stitching threads was included as part of the investigation, and compared a twisted yarn and stretch broken threads. Two different tuft densities were also compared: 5mm x 5mm and 10mm x 10mm stitch length and stitch row spacing, respectively. Figure 4 shows a close-up view of the tufting process (5mm x5mm) in progress. The one-sided two-needle stitching method produces two rows of stitching simultaneously, which are joined together by thread links [4].

For the parameters used here, the separation of these two rows was 36mm, with a 5mm stitch length.

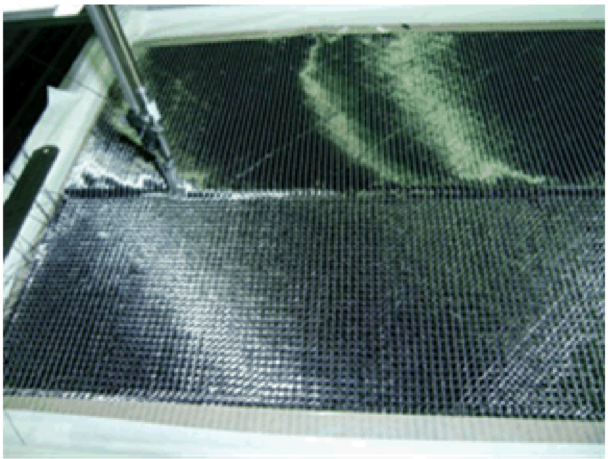

Fig. 4. Tufting of panels

The dry fibre lay-ups were resin infused with a one-part liquid epoxy resin system at 80°C in a large oven. Following infusion, the oven temperature was raised to 180ºC for 2 hours to cure the resin. In common with the prepreg laminates the panels, were C-scanned prior to use to assess their quality.

3 Mechanical testing and Physical Assessment

3.1 Stitched Carbon/Epoxy Prepreg

Prior to evaluating the laminate properties, before and after stitching, the strength of the continuous carbon thread was determined for comparison with existing data on PBO and stretch broken carbon fibre threads. Testing of the thread was performed in tension by wrapping and clamping the ends of a section of the thread around two 25mm diameter cylindrical rollers. The distance between the rollers was nominally 50mm at the centre; the gauge length of the tested section of thread (which formed a tangent with rollers) also being 50mm.

In-plane tension and compression tests were performed and a comparison made between the plain and stitched laminates. Tension tests were performed on 250mm x 25mm specimens with a 150mm gauge length. Compression tests were performed on 125mm x 25mm specimens with a 25mm gauge length. In all cases, the specimens were stitched across the entire gauge length. Short beam shear tests were also performed on samples of both material. Specimens measuring 10mm wide and 25mm long were loaded in three point bending until failure occurred.

3.2 Stitched Carbon Fabric

The stitched laminates were tested in compression before and after impact, using the CRAG compression test method [5]. The compression after impact (CAI) specimens were 200mm long x 50mm wide, with a 100mm gauge length. These dimensions allowed the full impact damage associated with a 15 Joule impact to be comfortably accommodated within the specimen test area. To prevent buckling, the specimens were supported during testing by the use of an anti-buckling guide. The specimen details are summarised below, and five replicate specimens were tested in each case.

Table 1. Summary of plain and impacted test specimen configurations

	Compression	CAI
Specimen length	200mm	200mm
Specimen width	25mm	50mm
Gauge length between tabs	100mm	100mm
Length of end tabs	50mm	50mm
Test speed	2mm/min	2mm/min
Impact tup diameter		10mm
Impact clamp ring ID/OD		100mm/120 mm
Impact energy		15J
Strain Measurement	Yes	Yes

The impact damage was introduced into the CAI specimens according to CRAG method 401 [5]. The latter specifies test conditions for the determination of the compression properties of multidirectional fibre-reinforced plastic laminates after impact. The test consisted of two parts (i) impact trials and (ii) the determination of residual compression strength. Impact trials were performed in order to identify a suitable impact energy level, which resulted in significant delamination, but did not cause penetration of the laminate. An instrumented drop weight impact test machine, fitted with a steel hemispherical indenter (tup), was used to impact the laminates. The centre of the test laminate was securely clamped underneath a steel annulus of 100mm internal diameter and the tup dropped onto the centre of the composite.

4 Experimental Results

4.1 Stitched Carbon/Epoxy Prepreg

Prior to mechanically testing the stitched laminates, the tensile strength of the carbon thread was evaluated. The results of these tests showed the continuous carbon thread had a strength of 2029MPa. When compared against similar in-house data obtained for Schappe stretch broken thread and Zylon PBO thread, which had strengths of 1429MPa and 2269MPa, respectively, the Tenax fibre appeared to be only marginally weaker than the PBO and substantially stronger than the stretch broken materials.

Tables 2 and 3 show the results of the plain tensile and compressive tests. The tests showed that stitching the prepreg with the carbon thread reduced the strength of the laminates by approximately 5%.

Table 2. Summary of tensile test results for plain and stitched specimens

	Tensile Properties – Plain Laminates		Tensile Properties - Stitched Laminates	
Sample	Failure Stress (MPa)	Modulus (GPa)	Failure Stress (MPa)	Modulus (GPa)
1	713.4	59.8	671.7	61.4
2	649.0	56.1	594.1	58.6
3	747.3	-	630.8	58.0
4	648.8	60.8	671.0	-
5	675.6	-	687.4	-
Mean	**686.8**	**58.9**	**651.0**	**59.3**
S.D	42.92	2.49	38.05	1.85
CoV (%)	6.25	4.22	5.84	3.11

The tensile moduli of the plain and stitched materials were broadly similar at 59GPa. In compression, the stitching appeared have little effect on in-plane properties; the plain laminates and stitched laminates have strengths of 494MPa and 506MPa, respectively.

Table 3. Summary of compression test results for plain and stitched specimens

Sample	Compression Properties – Plain Laminates		Compression Properties – Stitched Laminates	
	Failure Stress (MPa)	Modulus (GPa)	Failure Stress (MPa)	Modulus (GPa)
1	531.3	55.8	503.8	56.2
2	518.5	55.7	520.3	56.4
3	442.8	-	500.3	-
4	483.1	-	497.9	-
Mean	**493.9**	**55.8**	**505.6**	**56.3**
S.D	39.8	0.09	10.09	0.17
CoV (%)	8.04	0.16	2.00	0.30

The results of the interlaminar shear tests showed that the use of carbon stitching reduced the interlaminar shear strength of the composite; the plain specimens and stitched panels having strengths of 78.6MPa and 70.2MPa, respectively. This was considered unusual, as previous tests on z-pinned and PBO stitched laminates showed an increase in interlaminar properties. To understand the effect of the carbon stitching on the laminate architecture, cross-sections were taken through the stitched panels.

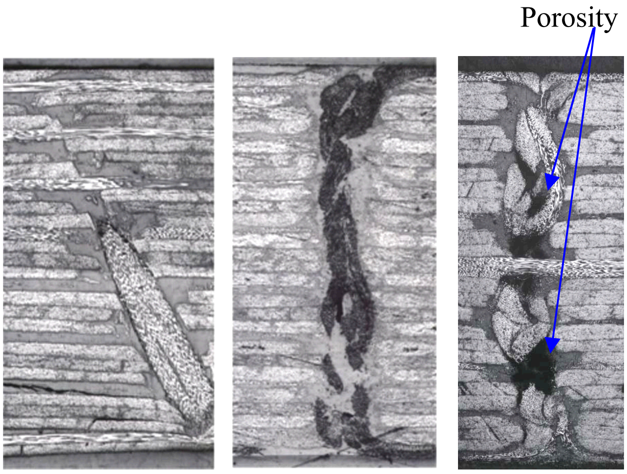

Fig. 5. *Cross sections through z-pinned (L) PBO stitched (M) and carbon stitched (R) laminates*

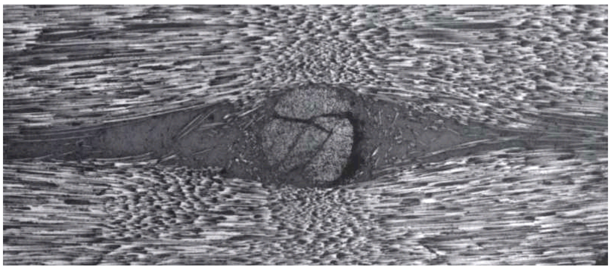

Fig. 6. *Cross section through carbon stitched laminate - plan view showing resin pockets (voids)*

Figures 5 & 6 show two cross-sections, one taken through the thickness of the laminate, the other parallel to the surface of the laminate (plan view). Similar views for the PBO and z-pinned laminates manufactured in an earlier study are also shown.

It was apparent from the cross sections that the reduced interlaminar strength of the carbon stitched laminates could be attributed to the presence of porosity within some of the stitches (see Figure 5 & 6). Although the composite between the stitches was well infused with resin, poor infiltration of the epoxy resin into the stitches was observed.

The effect of stitching the laminates using the Tenax fibre appeared to be broadly similar to that observed in previous laminates stitched with PBO. The most obvious feature was that the stitches were upright, whereas the z-pins were angled. It was also noted that the stitches had often collapsed slightly, due to consolidation of the laminate. The latter observation was significant, since it implied that although the tension in the stitching thread may be high during the stitching process, much of this tension may be lost during laminate consolidation and curing. The width of the carbon stitches appeared to vary through the thickness of the laminate, depending on the extent of laminate consolidation. Although some nesting of the looped carbon thread had occurred, the carbon stitches were typically 0.8-1.0mm in diameter, whereas the z-pins and PBO stitches were typically 0.5-0.6mm in diameter.

4.2 Stitched Carbon Fabric

The compression strengths and compression after impact strengths were compared with a baseline unstitched panel, and the average results for each are shown in the graphs in Figures 7 and 8 for strength and modulus, respectively.

It should be borne in mind that the one-sided two-needle stitch method produced two linked rows of stitches, with a much wider spacing than the tufting method, and so cannot be directly compared with the greater density of the tufted laminates.

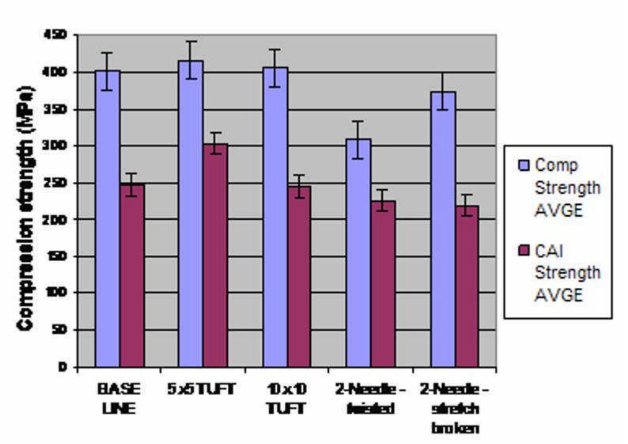

Fig. 7. Comparison of compression strength and CAI in stitched/tufted fabric laminates

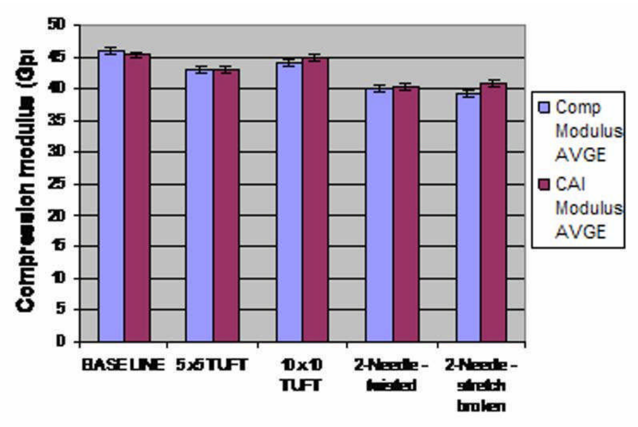

Fig. 8. Comparison of compression modulus in stitched/tufted fabric laminates

In most cases, the various stitching architectures did not result in any significant reduction in compression strength before impact, compared to the baseline unstitched laminate. The only exception was the two-needle stitching with the twisted yarn thread, but this result was somewhat anomalous, as the same method with the stretch broken yarn was within the scatter of the other results. There is probably an effect of higher void content in this panel, which was supported by the C-scan results. This was due to issues relating to the resin infusion of this particular resin system, which required a relatively high infusion temperature.

There is a slight indication that the higher density tufting resulted in a marginal improvement in compression strength but this was well within the standard deviation scatter.

After impact, it can be seen that all stitched architectures gave a broadly similar result, although again the higher density tufted laminate showed a higher result. The CAI result for this laminate represents a 22% increase in CAI strength compared to the unstitched baseline value, and this was supported by C-scan evidence of the impacted panels, which indicated a smaller area of damage for this tufted laminate compared to the unstitched baseline.

The modulus of the tufted panels was also fairly similar to the baseline unstitched panel, with perhaps a slight reduction for the higher density tufting. Comparison between the two different stitching threads showed them to be similar in modulus before and after impact.

5 Discussion

With regards to the performance of the carbon stitched prepreg laminates, it was apparent that stitching resulted in a slight reduction in tensile properties. Such a reduction in properties was not unexpected since this behaviour has also been observed in similar quasi-isotropic laminates after z-pinning (see Figure 9) and stitching with PBO thread [1,6].

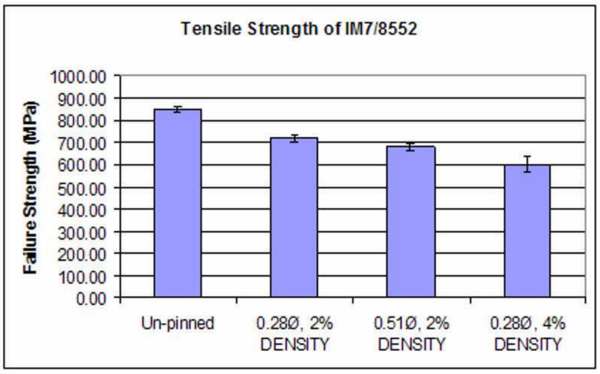

Fig. 9. Tensile strength of plain and z-pinned laminates

The reduction in tensile strength was attributed to fibre fracture caused by insertion of the TTR. This fibre fracture is thought to provide an array of initiation sites from which damage can grow under tensile loads.

Under compression loading, the carbon stitches appeared to have little effect on the failure stress of the prepreg-based material. This behaviour was considered slightly unusual, as previous studies on similar z-pinned laminates (see Figure 10) and stitched laminates [1,6] showed a slight reduction in strength by the incorporation of the TTR.

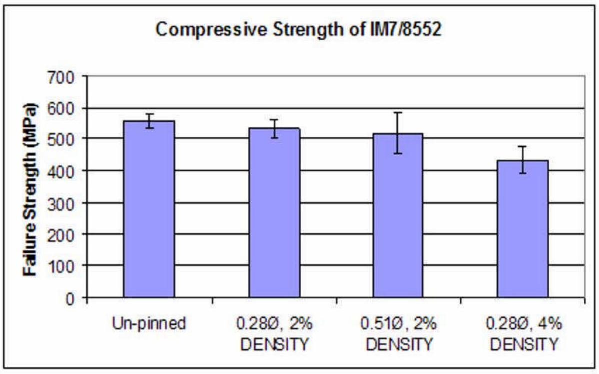

Fig. 10. Compressive strength of plain and z-pinned laminates

This reduction in strength was attributed to distortion of the load bearing fibres around the TTR. This distortion de-stabilises the fibres, making them more prone to fibre microbuckling under the action of compressive stresses. The extent to which the compressive properties are changed by the introduction of a TTR appears to be controlled by a variety of factors including its diameter, density, alignment and architecture. The architecture of the laminate (i.e prepreg, woven fabric) is also important, since woven fabrics already contain an inherent crimp, which in some instances might negate the effect of any fibre waviness introduced by the TTR. It may also be the case that when the TTR is closely spaced, adjacent bundles of fibres are pushed apart over a considerable distance, rather than the fibres undulating in and out between the z-pins or stitches. In this instance, the fibre waviness would be reduced, the fibres being more parallel, and the stability of the fibres under compressive loads may be improved.

With regards to the performance of the stitched fabric laminates, the use of tufting appeared to give the best results, with slight improvements in the plain compression properties being observed. Two needle stitching, using both the twisted carbon thread and the stretch broken thread, had a slightly negative effect on compression strength.

Tufting, particularly using the closer 5mm x 5mm arrangement was seen to give a substantial improvement in CAI properties compared to the baseline laminate. In CAI, the initiation of failure in impacted specimens is controlled by two competing mechanisms; the growth of delaminations, and the collapse of the fibres due to fibre microbuckling. The interaction between these mechanisms is complex but, in this instance, the improved delamination resistance attributable to the tufts appears to have overcome any negative effects caused by disruption of the fibres.

Conclusions

The results of this study have shown that the stitching of prepregnated carbon composite laminates with Tenax carbon thread was difficult. Due to the tackiness of the resin, and high penetration resistance of the laminates, both the carbon thread and sewing needles were found to break frequently and additional problems with ‘birdsnesting’ and ‘flocking’ were encountered. The increased strength and resistance to abrasion of the PBO thread, used in previous stitching work, probably explains why the use of this polymeric thread was more successful than the use of a carbon thread.

A limited comparison between the properties of plain (non-stitched) and carbon stitched laminates was performed, in which the in-plane and interlaminar properties of the laminates were compared. The results showed that stitching reduced the plain tensile strength of the prepreg laminates by approximately 5%; this reduction was lower than that observed in z-pinned materials. The plain compression strength was largely unaffected by the use of carbon stitching.

The interlaminar properties of the stitched prepreg laminates were marginally lower than the unstitched laminates. This reduction was attributed to the presence of some porosity within the stitches.

It has been demonstrated that the stitching and tufting of carbon fabrics, with carbon yarns, is practical and good results can be achieved in terms of impact and CAI for both twisted and stretch broken stitching threads. Qualitative examination of the C-scan images suggests that high density tufting (5mm x 5mm spacing) reduces the amount of impact damage. This is supported by the mechanical test results, which show that tufting does not have a negative effect on the compressive properties measured, and, indeed, the compressive strength is higher for the tufted material. The CAI results are enhanced by high density tufting (5mm x 5mm spacing) by 22%. The compression modulus values are largely unaffected, both before and after impact.

Acknowledgements

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