INNOVATIVE PREFORM DESIGN EXPLOITING AUTOMATED FIBRE PLACEMENT

Petar Zivkovic [1], Carwyn Ward [2], and Giovanni Marengo [3]

[1, 2] Bristol Composites Institute (ACCIS), University of Bristol, Queens Building, University Walk, Bristol BS8 1TR, UK
[3] Rolls-Royce plc, London, SW1E 6AT, UK
Email: [1] P.Zivkovic@bristol.ac.uk, [2] C.Ward@bristol.ac.uk, [3] Giovanni.Marengo@Rolls-Royce.com;
Web Pages: [1] https://cimcomp.ac.uk/idc/, [2] http://www.bristol.ac.uk/composites/, [3] https://www.rolls-royce.com/

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Abstract

Advanced composite materials generally have good in-plane mechanical properties; but they struggle to perform well in the through thickness direction as this is a resin dominated loading direction. In recent years this issue has been challenged by the use of through thickness reinforcement, in the form of tufting, Z-pining, or 3D weaving; to create a laminate with superior through thickness performance. Despite these methods being effective in increasing the through thickness performance, they are not without drawbacks, such as a decrease in the in-plane performance or requiring additional manufacturing steps. This paper seeks to resolve these issues, by exploring a novel preforming method that creates a pseudo woven structure in a single preforming step using the capabilities of Automated Fibre Placement, such that in-plane properties are retained and through thickness properties are enhanced; and validated by mechanical testing of samples to the appropriate ASTM standards.

1. Introduction

Historically advanced composite manufacturing has been a very intricate process, resulting in it being very labour intensive and as a consequence, expensive. Being a predominantly manual skill, there was in recent times a need to develop automation solutions for better productivity and repeatability. The automation approaches of Automated Tape Laying (ATL) and Automated Fibre Placement (AFP) have largely developed from that need, and are increasingly being adopted by the composites industry. These modern systems use a robotic mechanism to transfer a deposition head over a mould tool and deposits the composite material onto the moulded surface. ATL utilises a large roll of composite material in the form of carbon fibre/epoxy preimpregnated material (pre-preg), ranging from 50mm to 300mm wide. This roll is 'laid' onto the mould tool in the required orientations and stacking sequence in an additive process to produce a composite laminate. In cases where the wide roll of material may make conforming to the mould surface difficult to achieve, or some steering is required, another process is needed. This is where AFP is more applicable, as the roll of incoming carbon fibre epoxy is 'slit' into multiple 'slit-tapes' also known as 'tapes'. The tape width can range from 3.5mm to 10mm, and an AFP deposition head can feed between 4 and 32 tapes side by side, depending on the specific AFP mechanism. As these discretised tapes allow for more scope in terms of fibre steering, more complex geometries (including those of double curvature) can be used [1].

By exploiting the nature of the discretised tapes in an AFP system it is possible to select which tapes are being fed at any one point, providing the ability to create more intricate fibre architectures; which would have been impossible to do with an ATL system, and much too difficult and/or labour intense to do with hand lamination [2-3]. The following work will examine the in-plane mechanical properties of carbon fibre laminates where specific tapes have been placed to create a 'pseudo weave' and comparing the advantages and drawbacks to a conventional monolithic baseline laminate.

2. Methodology

2.1. Laminate Manufacturing

An AFP system at the National Composites Centre (NCC) in Bristol, UK, was used to manufacture two 500mm by 500mm laminates comprised of a $[45°,90°,-45°,0°]_{10}$ stacking sequence; resulting in a laminate with a nominal 7 mm thickness. The material used was a highly toughened aerospace grade unidirectional carbon epoxy system, which had been slit into 6.4 mm wide slit tapes. The first panel manufactured was a conventional monolithic baseline laminate. The second panel was a pseudo-woven laminate and was manufactured by selecting to place all of the odd numbered tapes first for all four ply orientations, and then passing a second time to fill the missing even tapes. Thus, a pseudo weave is created, where the number of plies can be identical to a regular monolithic laminate, although the number of layers required to make that laminate now doubles, as only half the available tapes are placed in a single pass. Therefore, for the 7 mm thick 40 ply laminate, 80 layers are required to create the comparable thickness. The progressive build-up of the first 8 layers required to create the first 4 full plies can be seen in Figure 1.

As evident, the laminate layup was not symmetric, with the previously stated stacking sequence repeated ten times throughout the laminate. This design was purposely used so as to create a spiral type stacking sequence, with a 45° ply on the tool surface and a 0° ply on the top surface, so that the effects of this novel preform could be fully understood. Had the layup been symmetric then at the mid plane it was probable that the laminates would have included a simple full 0° ply, and any progressive crack propagation would behave the same as it would in the baseline laminate. Furthermore a 500 mm x 70 mm strip of 13 µm release film was placed at the top edge in the mid plane of the laminates to create a pre-crack suitable for use in Mode I and II testing. It was placed between plies 20 and 21 for the baseline, and layers 40 and 41 for the pseudo woven panel. As there was no symmetry, this meant that the release film was placed between a 0° ply and a 45° ply, as shown in Figure 2.

After completing AFP layup, a heated debulking cycle was performed that also incorporated the use of a Romer arm to measure the bulk factor before and after the debulk cycle was performed (to better understand any effects the novel architecture would have on bulk). Prior to debulking the baseline panel had an 8.09 mm thickness, and the pseudo-woven panel had an 8.69 mm thickness. Post heated debulk, the thicknesses were 7.68 mm and 7.56 mm respectively, suggesting that even with the addition of novel in-plane architecture of the pseudo-woven panel the thicknesses were nominally similar. Both laminates were then placed on the same tool plate and cured together using the appropriate autoclave curing cycle for the material in use. Once cured thickness measurements, by taking three repeating measurements from nine individual locations on the laminates, were made and it was concluded that the two laminates had very similar average thicknesses of approximately 7 mm. Ultrasonic C-scanning was performed on both laminates for non-destructive testing. It was identified that other than the pre-cracked region (which was deliberately placed) both panels passed inspection to typical aerospace acceptability standards, deeming them acceptable for mechanical characterisation.

2.2 Sample Preparation

Both panels were edge datumed and then machined into 14 off 30mm wide x 500mm long strips. The width of the samples was heavily constrained by the width of the slit-tape, and therefore the effective unit cell of the pseudo weave. This was calculated to be 25.6 sqmm and so the minimum allowed width of the specimens was 30mm to attempt to allow for at least one whole unit cell in each sample. All machining was achieved using an operator controlled diamond saw.

Once machining of the panels into strips was complete, a Zeiss microscope was used to determine the exact location of the pre-crack edge, so that it could be marked as a further datum prior to machining of the strips into into individual specimens for a variety of mechanical charactierisation tests, as shown in Figure 3. From the first seven strips Mode I fracture toughness, tensile, and combined compression-shear specimens were acquired; and from the remaining seven Mode II fracture toughness, compression, and flexural specimens were acquired. Specimens were further ground to a tolerance of ± 0.1 mm, although compression specimens were further ground to a square edge tolerance of ± 0.01 mm.

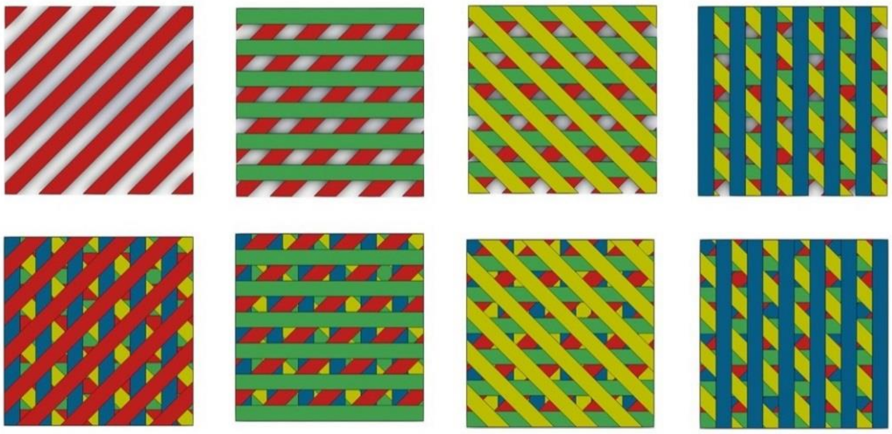

Figure 1. Schematic representation of the pseudo-weaving process used in AFP manufacture.

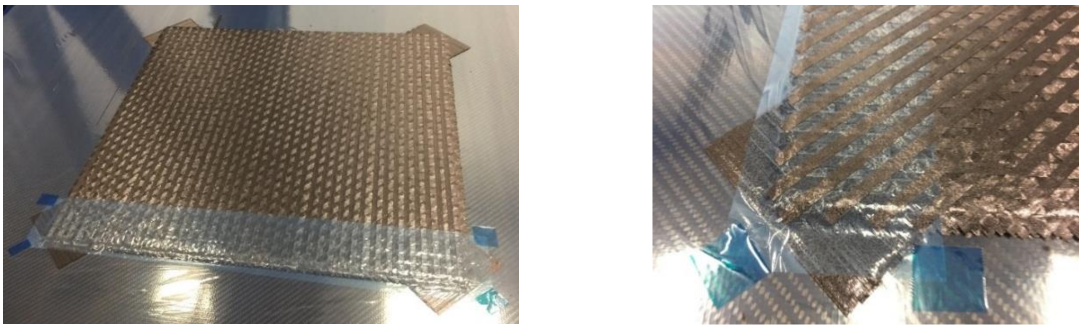

Figure 2. Release film placement for Mode I and Mode II testing (left), and 45° layer 41 placement using the AFP process (right). Both images are not to scale.

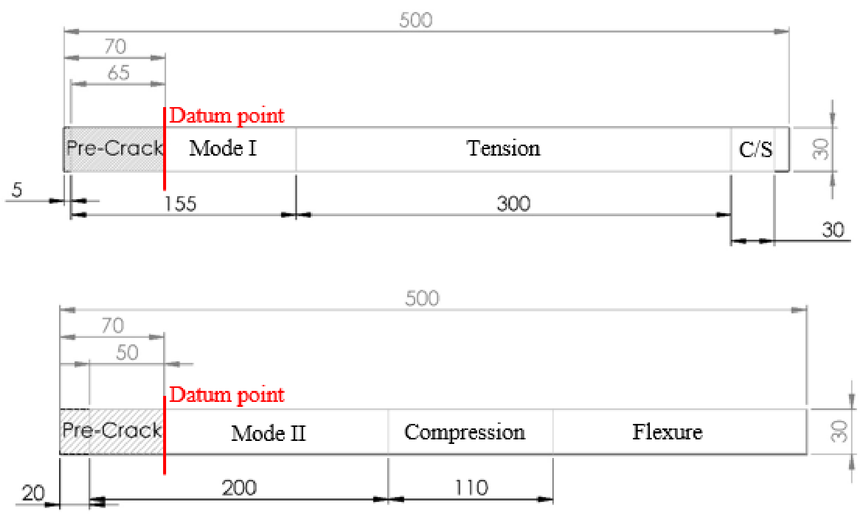

Figure 3. Cutting instructions for acquiring individual test specimens from strips machined from the AFP panels.

2.3. Mechanical Characterisation

In-plane mechanical testing was performed in accordance to the adapted ASTM standards. Six of the seven specimens, (where one remained as a spare sample), were tested to failure for each characterisation test, from each of the two panels. The first characterisation test performed was a tensile test following ASTM 3039/3039M-17 [4]. As the machined specimen width was set to 30 mm, the total length was selected to be 300 mm, so keeping the advised 10:1 ratio of width to length. Along with 100 mm end tabs on either end this provided a test gauge length of 100 mm. Testing was performed on an Instron 250 kN universal testing machine, at a 2 mm/min crosshead displacement. In addition, an LA Vision 16 MP 3D dual camera Digital Image Correlation (DIC) [5] was used in order to capture the full out-of-plane strain mapping.

The second characterisation test was a compression test following the adapted Imperial College method. The machined width was again fixed at 30 mm, with a total length of 110 mm, of which 40 mm were end tabbed leaving a test gauge length of 30 mm. The compression fixture was used in an Instron 250 kN universal testing machine, at a 2 mm/min crosshead displacement. An LA Vision 16 MP single camera DIC was used to examine the 2D strain field in the edgewise orientation. On the opposite side of the testing machine a Photron Fastcam SA-Z high speed camera [6] was set up to capture the failure initiation at 20,000 frames per second.

The third characterisation test was Mode I fracture toughness following ASTM D5528-13 [7]. The specimens were a total size of 155 mm length x 30 mm width, with a pre-cracked length of 65 mm, leading to a test gauge length of 90 mm. Testing was performed on a Shimadzu AGS-X precision universal tensile tester with a 1kN load cell, at a 1 mm/min crosshead displacement. An Imetrum universal video extensometer video gauge [8] was used to track the crosshead displacement, although this specific equipment had been upgraded to also be able to track the cracks propagation.

The fourth characterisation test was Mode II fracture toughness following ASTM D7905/7905M-14 [9]. The specimens were a total size of 200 mm length x 30 mm width, with a pre-cracked length of 50 mm, leading to a 100 mm span with a 25 mm of pre-cracked length and a 25 mm of gauge length for each crack propagation. Crack propagation was repeated three times for each specimen. Testing was performed on a Shimadzu AGS-X precision universal tensile tester with a 10 kN load cell, at a 0.5 mm/min crosshead displacement. A Nikon D5300 DSLR camera with a 60mm macro lens was used to record the test and crack propagation.

The fifth characterisation test was a flexure testing following the ASTM D7264/D7264M-15 [10]. The specimens were a total size of 170 mm length x 30 mm width, selected as it was the leftover length from the Mode II and compression specimens. A span to thickness ratio of 16:1 was selected resulting in a span of 112 mm to accommodate the specimen length. A four-point bend test was selected over a three-point bend test to allow for less shear to be induced into the specimen. Testing was performed on an Instron 8801 100 kN universal testing machine, at a 1 mm/min crosshead displacement. An Imetrum universal video extensometer video gauge [8] was used to track the crosshead displacement.

The sixth and final test was a combined through thickness compression and shear test, but was not performed at this time due to difficulties in obtaining the correct specimen holders; and as such is left to be reported as further work. The setups of all of the previous five characterisation tests can be seen in Figure 4.

Figure 4. Characterisation test setups used, showing tensile (top left); compression (top right); Mode I (bottom left); Mode II (bottom middle); and; flexure (bottom right).

3. Results

Figure 5 shows representative tensile and compressive strength curves. From the results of tensile testing it was observed that on average the baseline specimens out-performed the pseudo weaved specimens by +3.7 % for the average load and +3.4 % for the average displacement. This was a somewhat expected result, as the pseudo weave results in fibre crimp to create the woven like structure, resulting in wavy tapes [11]. The microscopy images of Figure 6 demonstrate this, but also show non-uniformity of the pseudo weave through the thickness, despite using a fairly regular preforming pattern and an NC automated manufacturing process. In contrast to the tensile results, it was observed from the compression testing that the pseudo weaved specimens out-performed the baseline specimens by +3.2 % for the average load and +1.0 % for the average displacement. This was somewhat contrary to the expectations of the authors, given the decrease in performance seen in tensile testing, and other published works on compression testing with fibre misalignment [12]. It is thought that due to the relative regularity of the crimping and waviness within the pseudo woven specimens, in-plane and through thickness, a resistance to the larger specimen geometry bucking is created by the pre-buckling or kinking of tapes/fibres. This results not only in a minor increase in performance but also a more contained and potentially less catastrophic (or mass loss) specimen failure.

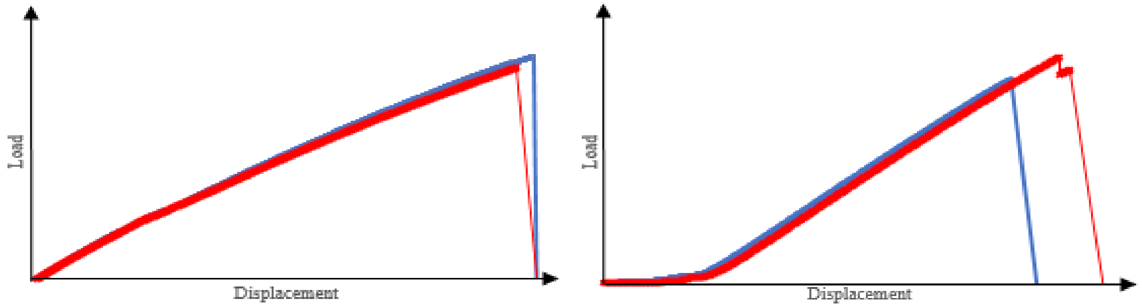

Figure 5. Representative tensile (left) and compression (right) curves of the baseline laminate (blue) and pseudo woven laminate (red).

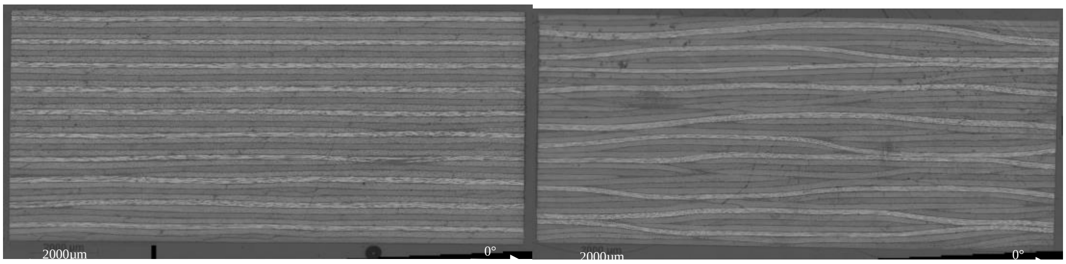

Figure 6. Microscopy images of the baseline laminate (left) and pseudo woven laminate (right).

Figure 7 shows representative Mode I and Mode II fracture toughness curves. For the Mode I fracture toughness tests the equations provided by ASTM D5528-13 [7] could not be used, as these calculations are for laminates that contain 0° plies at the interface where the pre-cracked film has been placed, and in this paper both laminates used an interface of a 45° ply and 0° ply. Thus, to comparatively examine the performance of the two laminates, all specimens were tested to absolute failure, with both halves of each specimen delaminating to separation. As all specimens had the same length to ±0.1 mm, the energy dissipated during failure was calculated by determining the available area under the load-displacement curve. From the results of Mode I testing it was observed that the pseudo woven specimens energy absorbing capability decreased by an average of 15.1% compared to the baseline specimens. During testing a large amount of fibre bridging took place at the 45° ply in the interface for both specimen types; although for the pseudo woven specimens the relative discontinuous nature of these plies meant that every time bridging would take place the tape path would end, and so the crack would jump to the next available 45° tape. This phenomenon is suggested to be the most likely the cause for the large decrease in performance. From the results of Mode II testing it was observed that the pseudo woven specimens outperformed the baseline specimens by an average of 9.9 %. This is a result of the same phenomenon of Mode I testing, although such bridging and jumping now contributes additional friction in the testing and so a relative increase in performance is gained.

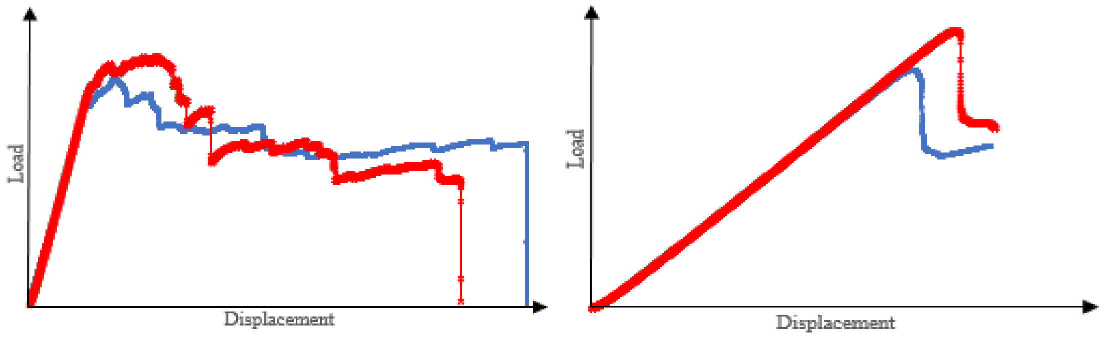

Figure 7. Representative Mode I (left) and Mode II (right) fracture toughness curves of the baseline laminate (blue) and pseudo woven laminate (red).

Figure 8 shows representative flexural strength curves, and it is initially suggested that the testing showed almost identical peak load results. On further examination into the obtained load-displacement curve it was noticeable that the area under the curve was smaller for the pseudo woven specimens compared to that of the baseline specimens. Further analysis showed an average 14.9 % decrease in the energy dissipated during failure by the pseudo woven specimens. When visually reviewing the samples the pseudo woven specimens tended to include more examples of delaminations than the baseline specimens, however this arguably does not agree with the testing results testing as larger numbers of delaminations would imply there was more energy dissipation, which is not the case.

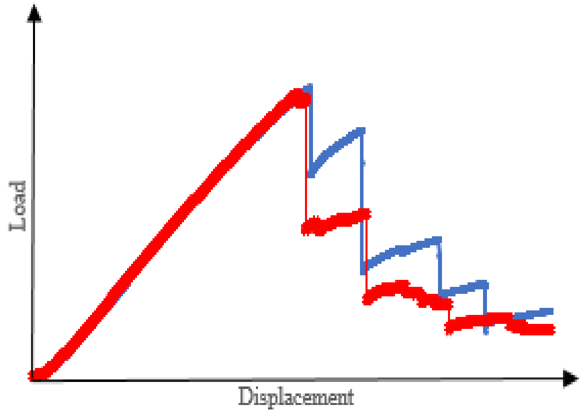

Figure 8. Representative flexural strength curves of baseline laminate (blue) and pseudo woven laminate (red).

From the results it can be seen that the pseudo weave has cause the tensile, Mode I and flexure properties to decrease in mechanical performance, but the compressive and Mode II have increased as summerised in Table 1.

Test Method	*Testing Standard*	*Performance Change*
Tensile Strength	ASTM 3039/3039M-17 [4]	**3.4% ↓**
Compressive Strength	Adapted Imperial Collage Compression Method	**3.2% ↑**
Mode-I Interlaminar Fracture Toughness	ASTM D5528-13 [7]	**15.1% ↓**
Mode-II Interlaminar Fracture Toughness	ASTM D7905/7905M-14 [9]	**9.9% ↑**
Flexural Strength	ASTM D7264/D7264M-15 [10]	**14.9% ↓**

Table 1. Summary of performance changed between the baseline and pseudo woven laminates.

4. Conclusions

A pseudo woven laminate was manufactured using an AFP process along with a baseline laminate of more typical construction for reference. Both laminates were machined in accordance to adapted ASTM standards to evaluate the tensile, compressive, flexural, Mode I, and Mode II fracture toughness properties. It was found that the intricate structure of the pseudo weave had a comparatively negative effect on the tensile, flexural, and Mode I fracture toughness properties; however, a comparatively positive effect on the compressive, and Mode II fracture toughness properties. Further work involves more testing and characterisation, such as combined through thickness compression and shear; as well as further design and manufacturing studies such as developing more intricate pseudo weaves. Such activity should contribute to gaining a better understanding of the cause for the compression strength increasing, the Mode I fracture toughness decreasing, and the large delamination areas in flexure.

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