NON-SYMMETRIC STACKING SEQUENCES TO AID MANUFACTURE

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Abstract
Achieving high quality, low defect manufacture is essential for modern composite aerospace structures. This reduces expensive scrapping of parts and avoids significant knock-down factors in performance. A demonstrator C-section with tapering thickness has been produced with a novel (non-symmetric) stacking sequence, alongside a baseline with a conventional, symmetric stacking sequence. The resulting quality of manufacture of the two stacking sequences has been analysed, with all other variables equal, in order to determine the potential benefit associated with the novel design. The novel laminate achieved better consolidation, with greater trapped air removal, and reduced the level of warping during manufacture. It also offers greater potential for optimised taper without elastic coupling.

1. Introduction

The manufacture of composite laminates is highly complex and poses many challenges that do not exist when processing other materials. This paper focuses on the complexity introduced where there are significant changes in laminate thickness due to “pad-ups”. These are created by adding layers incrementally, such that the laminate is tapered. During the curing process, laminates de-bulk by a percentage of thickness towards the tool surface assuming good consolidation, as modelled by Min et al. [1]. The action of consolidation over a tapered section under the influence of long fibres is considered. The tendency of a laminate to warp during manufacture is also considered. This is affected by the coupling of laminate stiffness. The sequence in which the layers are stacked can be tailored in order to control stiffness coupling and has been investigated by a number of authors [2-4].

The aim of this paper is to analyse the manufacturing benefit of a new laminate design strategy that has been developed. There are many factors that contribute to the manufacturability of laminates but the scope of the new design strategy is to consider elastic stiffness coupling of the laminate and geometrical effects caused by the thickness change, which are thought to be key aspects determining the level of defects in a tapered laminate. With these in mind, the stacking sequence of a novel laminate is tailored to improve consolidation and minimise warping defects, such as spring-in and twist.

2. Laminate Design Theory

2.1. Consolidation of Tapered Laminates

Consolidation is the removal of bulk, principally trapped air, from a laminate. This de-bulking process causes a thickness reduction, typically 10-15%. The consolidation of laminates with a tapered section is inherently more complex than consolidation of a flat laminate of uniform thickness. Consider the example shown in Fig. 1(a). This shows how the surface (solid line) and a continuous layer (dashed line) move as a result of consolidation. In this case, it is assumed that a layer exists in the same proportionate position through-thickness in both the (thin) far-field and (thick) pad-up laminates. This is representative of the result of scarfing the far-field and pad-up laminates together evenly through their entire thickness, as per a conventional 'diamond' ply drop-off pattern.

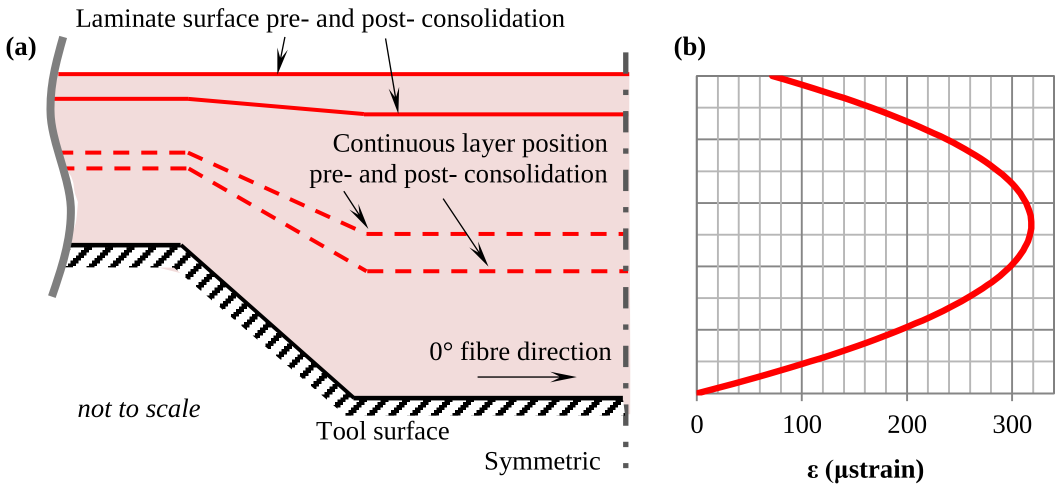

Figure 1. (a) Example laminate pad-up, showing the movement of a layer (dashed line) as the laminate consolidates. The layer has to cover a longer length in the 0° fibre direction post-consolidation compared with when it is first laid down. All other layers are shown as a shaded region for clarity. **(b)** Through-thickness variation of axial strain caused by the length change, assuming 12% consolidation and a 1:10 ramp.

By trigonometry, the dashed line in Fig. 1(a) is longer in the 0° fibre direction post-consolidation. If the layer represented by this dashed line resists this length change, it will in turn hold back consolidation. The length increase can either be accommodated by the layer stretching, drawing in length from the far-field (slipping), or by some combination of these. If the length is assumed to be accommodated entirely by the layer stretching in the tapered section, the strain can be calculated from three dimensionless parameters: ramp rate, consolidation percentage and through-thickness position as a percentage of overall thickness. Fig. 1(b) shows how the strain varies through-thickness assuming a 1:10 ramp rate and 12% consolidation. 0° fibres will offer most resistance, since they have the greatest stiffness in the direction of required length increase. They also run the full length of the component and so drawing in length will also not be easy as that would require the slipping of a large amount of material along the length of the component, assuming the component is longest in the 0° fibre direction.

Consider now however, if the dashed line remained equidistant from the tool surface throughout the pad-up ramp, as illustrated in Fig. 2(a). Since there is an equal thickness of material between the layer and the tool in both the far-field and pad-up sections, the layer will move down equally in both cases. In contrast to Fig. 1(a), the dashed line in Fig. 2(a) will not have to span a greater length in the 0° fibre direction post-consolidation. In this more novel design, there is no scarfing in the bottom half of the (thin) far-field laminate, i.e. no layers are added or removed between the dashed line and the tool surface in Fig. 2(a).

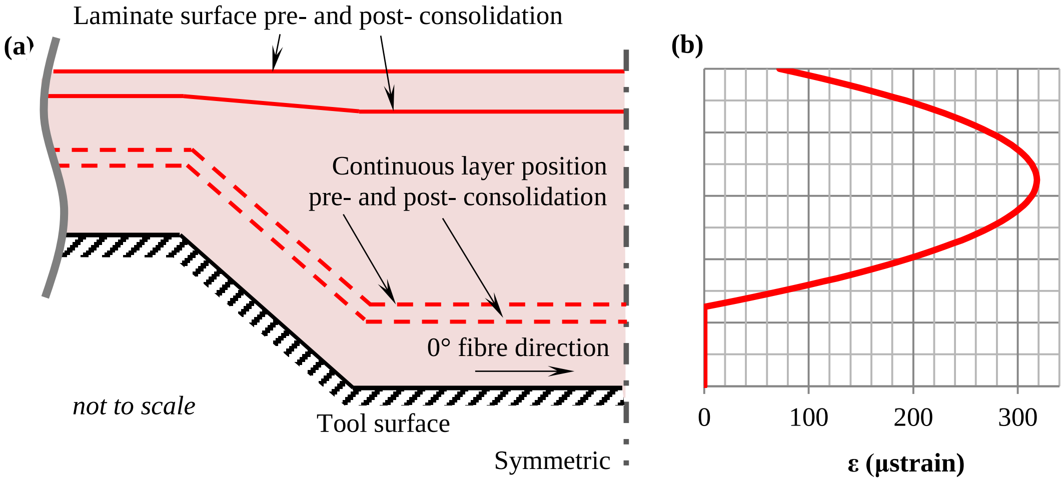

Figure 2. **(a)** Novel laminate pad-up. In this case, the dashed line remains equidistance from the tool surface throughout the pad-up ramp. As a result, it will not have to cover a longer length in the 0° fibre direction post-consolidation. **(b)** Through-thickness variation of axial strain, assuming 12% consolidation, a 1:10 ramp and that the layers in the bottom half of the far-field laminate remain equidistant from the tool surface.

Fig. 2(b) shows the benefit of the novel design, with the layers in the lower half of the far-field laminate (and lower quarter of the pad-up laminate) not required to accommodate any length change. The peak strain is the same as in Fig. 1(b), showing that in creating a zone of zero strain, it has not increased the maximum strain required elsewhere in the laminate.

2.2. Coupling of Laminate Stiffness

As well as considering geometrical effects, it is essential to consider the coupling behaviour of a laminate in order to ensure high quality manufacture. Elastic coupling can lead to undesirable characteristics post-cure. It can give rise to structural instability [5] and bend-twist coupling can have a significant impact on the buckling resistance of laminates [6-7]. For manufacture, it is particularly important that there is no tendency for the laminate to warp. Special cases of laminates exhibit elastic coupling but will not warp during manufacture. These are referred to as hygro-thermally curvature-stable (HTCS) and can be very useful [8]. Laminates exhibiting no elastic coupling do not warp during manufacture; they are always HTCS, although not usually referred to in this manner.

The novel stacking sequence for manufacture was designed to be fully uncoupled. The level of coupling was assessed using the well-known Classical Laminate Theory and ***ABD*** matrix notation. The constituent parts of the ***ABD*** matrix are calculated, according to ESDU 94003 [9], from

$$\boldsymbol{A} = \sum_{k=1}^{N} t_k \boldsymbol{b}_k \,, \quad \boldsymbol{B} = \sum_{k=1}^{N} t_k \overline{z_k} \boldsymbol{b}_k \,, \quad \boldsymbol{D} = \sum_{k=1}^{N} \left(t_k \overline{z_k}^2 + \frac{{t_k}^3}{12} \right) \boldsymbol{b}_k \,, \tag{1}$$

where N is the number of plies in the laminate, t_k the thickness of layer k, $\overline{z_k}$ the distance between the reference plane (usually the mid-plane of the laminate) and the mid-plane of the layer k. $\boldsymbol{b}_k$ is the stiffness matrix of layer k in the global laminate co-ordinate system and is different for different layer orientations, which are commonly limited to 0°, 90° and ±45° within industry. This formulation of the $\boldsymbol{ABD}$ matrix is convenient when developing criteria for fully uncoupled laminates. The current industry standard is to use balanced, symmetric laminates. By definition a balanced, symmetric laminate can only exhibit bend-twist coupling. This will be removed, making the laminate fully uncoupled, if

$$\sum_{k=1}^{N}\left(\bar{z}_k{}^2\right)_+ = \sum_{k=1}^{N}\left(\bar{z}_k{}^2\right)_- \quad , \tag{2}$$

where $\left(\bar{z}_k{}^2\right)_+$ and $\left(\bar{z}_k{}^2\right)_-$ are the square of lever arm terms for positive and negative angle plies respectively. Anti-symmetric laminates are defined as the opposite of symmetric, i.e. where a positive angle-ply exists one side of the mid-plane, it is mirrored by a negative angle-ply on the other side. Anti-symmetric laminates can only exhibit extension-twist coupling (synonymous with shear-bending). This will be removed to produce a fully uncoupled laminate if

$$\sum_{k=1}^{N}(\bar{z}_k)_+ = \sum_{k=1}^{N}(\bar{z}_k)_- \quad . \tag{3}$$

An important observation is that equating the sum of the lever arm terms, Eq. (3), is much more readily achieved than equating the square of the lever arm terms, Eq. (2). The result is that there are many more fully uncoupled anti-symmetric laminates than there are symmetric ones.

Another major advantage of anti-symmetric laminates is that it is possible to drop a single ± angle-ply pair and maintain a balanced, anti-symmetric laminate with the potential that it is fully uncoupled. In contrast, a symmetric laminate requires that a minimum of four angle-plies must be dropped in order to maintain balance and symmetry, which is significantly more limiting for small thickness changes.

A fully uncoupled anti-symmetric laminate will not exhibit bend-twist coupling regardless of the position of the reference plane (about which $\bar{z}_k$ is measured). This is significant where the reference plane shifts, such as in the corner between the web and flange of a C-section.

2.3. Novel Laminate Design Strategy

Using the understanding of consolidation of tapered laminates and the theory of laminate stiffness coupling, covered in the previous two sections, a new design strategy is developed. The first rule of the design strategy is that continuous 0° plies (i.e. those that run the full length of the laminate, not just the pad-up regions) remain equidistant from the tool surface throughout the ramp, as in Fig. 2(a). The second rule is that stiffness coupling is minimised or eliminated throughout all sections of the laminate.

In practice, the first design step is to produce a fully uncoupled (thin) far-field stacking sequence. The fact that continuous 0° plies must remain equidistant from the tool surface implies that all layers between them and the tool are also continuous, forming a "protected zone". This protected zone would exist between the dashed line and the tool surface in Fig. 2(a).

The protected zone dictates much of the pad-up stacking sequence, with the remainder designed to produce a fully uncoupled sequence. The protected zone leads to non-symmetric sequences in the ramp as layers are dropped-off. It is difficult or impossible to ensure all of these are fully uncoupled if the requirement is to drop a single layer at a time. This is also the case for the conventional symmetric intermediate sequences in the ramp. However, minimising the coupling in the ramp for the novel design, such that its effect should be negligible, is readily achievable and a computer code that does this has been created.

3. Manufacture of Example C-sections Laminates

3.1. Demonstrator Designs

In order to experimentally validate the potential benefit of the novel design strategy, two laminates were manufactured; one using the novel design strategy and the other using balanced, symmetric stacking sequences, typical of many industrial applications. The symmetric laminate forms a baseline to compare the novel laminate against. Apart from the stacking sequence, the two laminates are geometrically identical, forming two C-section components with 3 thickness pad-ups along their length. The tool onto which the laminates were laid, using an Automated Fibre Placement (AFP) machine, is illustrated in Fig. 3.

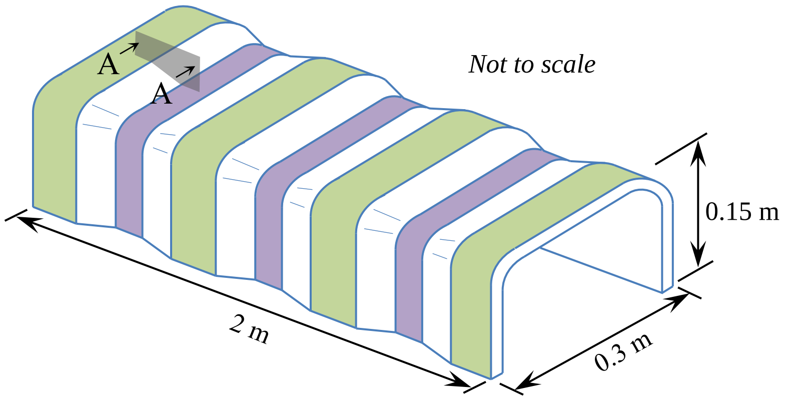

Figure 3. Isometric view of demonstrator C-section tool. The 3 thickness pad-ups are shown. Section A-A highlights one of the 1:10 ramps associated with the pad-ups, in which a thickness change of 4 mm occurs over a length of 40 mm. All 3 pad-ups have identical geometry.

Fig. 3 highlights the 3 pad-up regions. These pad-up regions consist of a total of 44 layers, while the thinner sections consist of a total of 24. Each layer is approximately 0.2 mm thick, resulting in a total pad-up thickness increase of 4 mm from the 20 additional layers. This thickness increase is accommodated by the 3 pad-up ramps in the tool surface (inside the C-section), meaning once the lay-up process was complete, the laminate surface (outside the C-section) was approximately flat. The cross-section A-A from Fig. 3 is illustrated in Fig. 4 and Fig. 5, showing the stacking sequences for the baseline and novel laminates respectively.

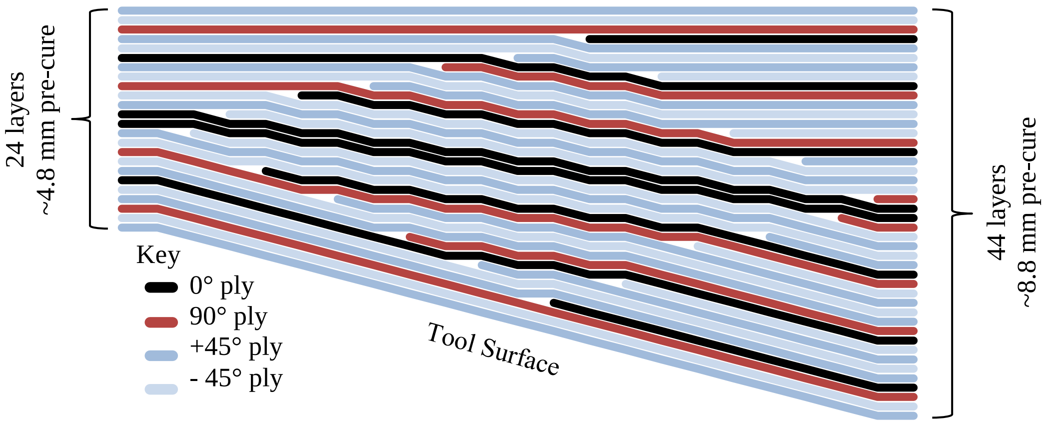

Figure 4. Section A-A from Fig. 3 for the baseline laminate, showing the (thin) far-field and pad-up stacking sequences. Also illustrated is the way in which the 20 additional layers are dropped-off in the ramp to transition between the far-field and pad-up sequences. For the baseline this is done using a conventional 'diamond' drop-off pattern. The stacking sequences are largely balanced and symmetric. Refer to colour version of figure.

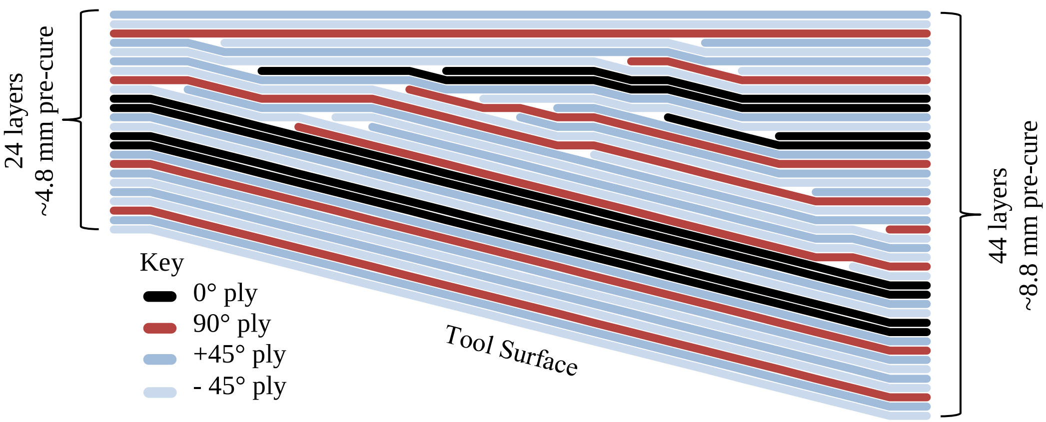

Figure 5. Section A-A from Fig. 3 for the novel laminate. The (thin) far-field and pad-up sequences are anti-symmetric and fully uncoupled. The 20 additional layers are dropped-off in the ramp using the novel design strategy. The continuous 0° plies remain equidistant from the tool surface. Refer to colour version of figure.

4. Comparison of Results for C-section Laminates

4.1. Consolidation

The laminates were measured using a CMM (co-ordinate measuring machine) before and after they were de-bulked and cured in order to assess the overall level of consolidation. The measurements were grouped into a series of lines for different thickness sections in the web and flanges of both the novel and baseline laminates. An example showing the laminate thickness in a pad-up region, pre- and post-cure, for both laminates is shown in Fig. 6. Overall, by averaging the consolidation in each section, the baseline laminate was found to have consolidated by 12.6% and the novel by 13.4%. In order to assess the post-cure thickness in the corner, the laminates were sectioned and micrograph images were taken, Fig. 7. Multiple thickness measurements were taken from these and averaged to smooth out the effect of tow gaps. The novel laminate was found to be thinner, reinforcing the measurements shown in Fig. 6. Moreover, the first 15 layers (protected zone of novel laminate) accounts for two thirds of the total thickness difference between the two laminates.

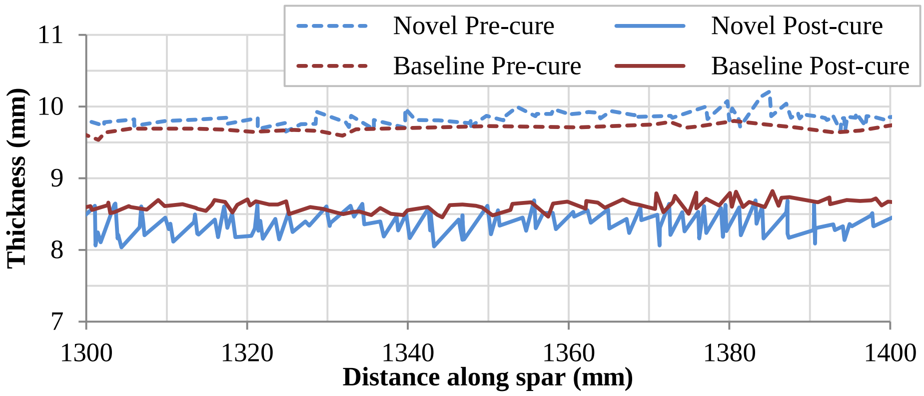

Figure 6. Thickness measurements across one of the flange pad-ups, pre- and post-cure, for both the novel and baseline laminates. In this case the novel laminate consolidated by 14.9% and the baseline by 10.9%.

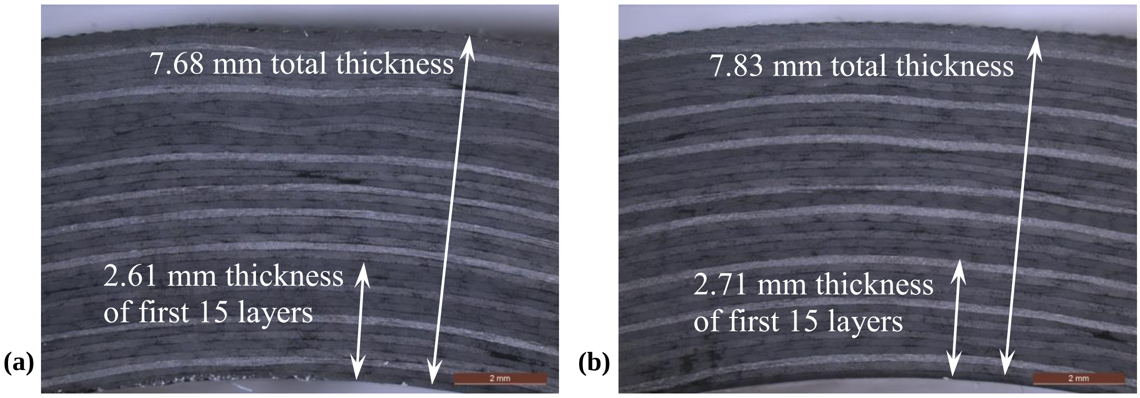

Figure 7. Micrograph images of **(a)** novel and **(b)** baseline laminates, sectioned on the corner between the web and flange. A series of measurements were taken and then averaged. The novel laminate was found to be thinner, especially within the first 15 layers, where the protected zone of layers was positioned.

4.2. Warping and Spring-in Deformation

After the two laminates were cured a series of measurements were taken from their inner faces, again using a CMM. From this large set of co-ordinates, planes were created, representing the inner faces of the web and flanges. The angle between the web and flanges could then be calculated. This was done for each of the sections (divided by the tapered regions) in order to determine the average angle between the web and flanges. Since the inner faces of the C-section were those in contact with the tool during layup, the difference between this average angle and that of the tool (90°) gives the level of spring-in of the laminate. The level of twist of the two laminates was assessed by taking measurements along the web of the C-sections. The rate of change of out-of-plane measurement, with respect to x and y co-ordinates represents the level of warping of the laminates in the form of twist.

Table 1 summarises the results, showing a reduced level of spring-in for the novel laminate. This was as a predicted because the novel stacking sequences exhibited no or significantly reduced coupling as compared with the baseline laminate. It was found that the novel laminate consistently exhibited less spring-in in every like-for-like web-flange pair, compared with the baseline. The novel laminate exhibited almost two-fold less twist when compared with the baseline, which was also expected as a result of eliminating bend-twist coupling.

Stacking Sequence	Average spring-in	Web Twist ($-2\partial^2 z/\partial x \partial y$)
Novel	1.41°	3.4×10^{-6} rad/mm
Baseline	1.53°	6.0×10^{-6} rad/mm

Table 1. Spring-in between the web and flanges and twist of the web, measured from the two demonstrator C-sections. The novel stacking sequence shows a significant improvement as a result of reduced coupling.

Significant force was required to remove the baseline laminate from the tool, post-cure. This was as a result of the spring-in and twist summarised in Table 1. The novel laminate, in contrast, was readily removed having shown minimal warping during the curing process.

5. Conclusions and Future Work

The anti-symmetric laminate showed an improvement of over 6% in consolidation against the baseline (symmetric) laminate. It was also significantly less warped, allowing it to be removed from the tool without the force required to remove the baseline laminate. This is reinforced by a two-fold reduction in twist and a small reduction in spring-in. Further research will investigate the performance of the two laminates by subjecting test coupons to a 4-point bend test. The bend-twist coupling of the baseline laminate, which caused some twisting during manufacture, is also expected to affect the results of this testing. For the novel laminate in contrast, bending and twisting remain uncoupled regardless of where the reference plane is and hence 4 point bending of the corner should not produce any twist.

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