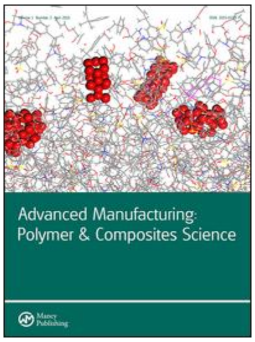

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AMPCS Advanced Manufacturing: Polymer & Composites Science

Original Research Paper

Studying effects of preshearing on hand layup

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Abstract Advanced composites are used extensively in many high performance applications. As they are taken up in a wider range of applications, the volume of demand is pushing manufacturing methods, especially hand layup of woven prepreg cloth, to their limits. An alternative approach to hand layup over complex geometries is proposed. The regular method of layup involves generating shear using grasps and pressures in the prepreg as and when it is needed during layup, leading to a sometimes complex and time consuming process. In the method proposed, all the shear deformation is created in the ply prior to any contact between the prepreg and the mold surface. Guidelines were drawn onto the prepreg surface to enable the correct shear distribution to be presheared by hand. These were created by processing the outputs from a simple kinematic drape simulation within MATLAB. Once preshearing was completed, the ply is laid up onto the mold using regular hand layup techniques. The process was tested alongside regular manual lamination across three example parts and using video analysis effects of the process were investigated via a variety of metrics. This revealed that significant time savings and reduced likelihood of manufacturing variations are possible with this approach. There was also a significant simplification of the layup process, leading participants to comment that a previously difficult layup had become easy. An improved bespoke system for communicating the required preshearing was subsequently developed, and successfully trialed on a fourth example part. Preshearing has the potential to make hand layup more economically viable for years to come. As well as the productivity and cost benefits, preshearing shows promise as a training aid, especially for beginner laminators. Concepts for integrating preshearing into existing industrial practice and its further potential in the field of automation are also discussed.

Keywords Prepreg, Lamination, Ergonomics, Automation, Deskilling

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Introduction

Hand layup

Advanced composites offer a desirable combination of high strength and stiffness alongside low density which makes them very attractive for many engineering applications. Many composite components are constructed or 'laminated' by hand, using sheets of woven carbon, glass, or aramid fibers. These are pre-impregnated with mostly epoxy resin to create 'prepreg'. The layup process generally starts with flat undeformed plies of prepreg which have been cut to shape from a continuous roll of material. A human operator or 'laminator' then takes each ply in turn and manipulates it into a generally doubly curved complex shape whilst using the inherent tack of the resin to secure the ply onto the mold surface or a previous ply. This process will be known as 'Regular layup' from here on in, but is sometimes referred to as 'lamination' or 'drape' in other works. At the hands of a human, the stiff carbon fibers cannot be stretched to any significant strain, but the woven material structure as a whole can be deformed in a number of ways (such as tow slippage), but by far the most dominant is in-plane 'scissor' shear.[1] This allows flat prepreg sheets to be formed over doubly curved surfaces, which by definition will always require in-plane deformation in the prepreg to avoid the use of cuts or folds.[2]

Hand layup is a key part of the composites manufacturing industry due to its ability to create complex shapes, reasonably low start-up costs, adaptability, and potentially short lead times. It forms an important part of many companies' composites manufacturing efforts,[3–5] but it is far from perfect. Historically it has been used extensively in high value applications such as Formula (1) and high performance

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aircraft. Composite materials are now seeing greatly increased use in the higher volume civilian aerospace sector and automotive sector.[1,6] The order of magnitude increase in volume in these sectors, especially automotive, alongside concerns about the low production speed, variability and hence high costs of existing technologies has driven the industrial and academic research towards alternative, often automated solutions. While there has been a significant volume of papers recently on multiple aspects of automated solutions such as automated tape laying[7] there has been very limited work targeted at understanding or optimizing the hand layup process.

Existing work

While there have been numerous studies into the properties of prepreg materials,[8,9] work on the actual process of hand lamination itself is limited to just a handful of papers. The significance of the order in which parts were draped and the different deformation patterns that result have been investigated.[1] As part of the study a drape simulation program called 'virtual fiber placement' (VFP), was developed, and has formed the basis for future works on hand layup. Virtual fiber placement uses a simple kinematic model to predict the required deformations in a sheet of prepreg based on a user inputted drape path. A series of inextensible beams, act as 'virtual' warp and weft tows. Each tow has a first contact with the mold defined by the user. From here the unique shear deformation pattern that allows all the fibers to conform to the surface is calculated. At present this can provide a visual display of deformation, step by step animations of how the ply is laid down over the mold (as seen in Fig. 1), and a numerical data output. Further work by Ward *et al.*[10] showed that different drape orders can significantly affect the manufacture of complex panels.

An example of looking into hand lamination in even greater detail is given in Ref. 11, which examined the exact methods used by laminators to manipulate the woven cloth into shape. The viscoelastic properties of epoxy resin give the prepreg significant in-plane shear stiffness, which has to be overcome by in-plane tension. Trying to shear the material via in plane compression will generally only result in out of plane folding. The study focused on how tension is achieved either by using grasps to directly pull on the prepreg, or by pressing the material into recesses in the mold. It also showed that a

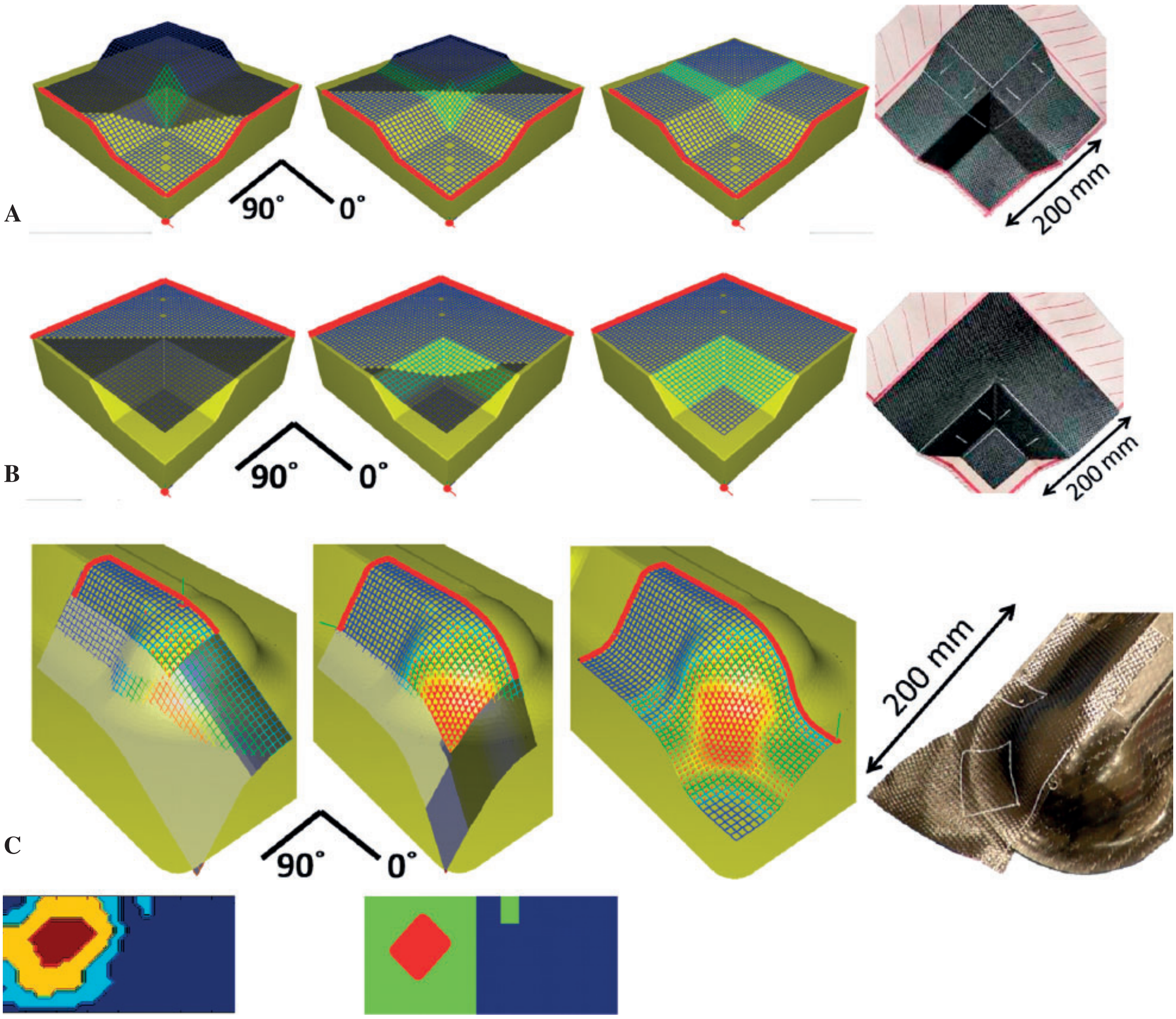


Figure 1 Virtual fiber placement Animations and final ply pictures featuring preshearing markings for Tasks A, B and C (not to scale): (Bottom) example of flat shear map and then simplified shear map for task C

significant number of actions were required to fold or support the cloth during layup. Coordinating all the actions in layup to create a high quality part is complex but given the right experience and understanding of the material, it is within the capabilities of a human. However, with such a complex process comes inherent variability in the operator's actions that can result in variations such as wrinkles, misalignments, or bridging. Such features can adversely affect part strength.[12] How the plies are stuck to the mold surface have been looked at in detail and a series of alternative hand tools proposed to assist in the process.[13] There has also been work to understand the wet layup process in detail using motion capture to understand the techniques and part quality of operators of different experience.[14] However this was only targeted at the use of a roller to distribute resin, which is seen as a much less complex process than prepreg layup.

There are systems currently available on the market which help the laminators to correctly position a ply by projecting the outline of the finished ply into the mold with a laser, but these give little if any further detail on how to proceed with layup.[15] The concept of giving the laminator additional information was explored by Such *et al.*,[16] using a projector to display the order of layup based on data from VFP and expert knowledge capture. Previous works have added accessories or aids to the prepreg layup process, while this work looked to draw together the existing work and radically modify the core process itself.

Lamination styles

One of the main conclusions from Ref. 11 was that approaches to lamination can vary, depending on whether the prepreg is being sheared 'locally' or 'globally'. Figure 2 (top) is a flowchart of the layup process of a section of prepreg using both methods. It must be stressed that these approaches are opposite ends of a variable scale rather than two distinct separate approaches, and often laminators use a hybrid of both methods. It begins with a section of prepreg which has yet to be stuck down, but all the tows involved have been consolidated elsewhere. Before consolidating the prepreg, the laminator has to determine if the region requires any shear (the 'shearing decision' stage). If it does need shear it is at this point where the laminator can proceeded with either local or global forming. This choice is likely influenced by geometry, shear angle, ply size and to a large degree personal preference and skill.

Local shearing

The lighter (blue) arrows in Fig. 2 represent local forming. Here only small areas of prepreg close to the already consolidated region are sheared at any one time, as is shown in the bottom right image. In order to identify the correct amount of shear (the Local Prediction stage) the laminator only needs to know the location and direction of the required shear. Because the sheared area is adjacent to already consolidated prepreg, it is in close proximity to the mold surface. This allows prepreg to interact with the mold surface during shearing such that the appearance or removal of folds or bridging gives real time feedback to the laminator as to whether the correct shear angle has been obtained. Once the correct shear is created, the layup can proceed straight to the 'consolidating' stage of lamination. The downsides of local shearing are that by only deforming small sections of prepreg at a time, the process has to be repeated many times to form a large area of shear, hence it may be very time consuming. Also the close proximity of the sheared region to the mold can make it difficult for the operator to access some areas of prepreg, especially in internal corners.

Global shearing

The dark arrows in Fig. 2 follow global forming. Instead of only forming small sections of prepreg, large areas are sheared in advance of the consolidated region as is seen in the bottom left image. A key advantage of global forming is that by forming large areas of shear in single action, fewer separate actions are required, potentially making the whole layup process simpler and faster. Because the area being sheared is larger and generally ahead of other consolidated regions, there is often a larger gap between the mold and prepreg than during local shearing. Thus is it often easier to access the ply with two hands, potentially enabling fast shearing of large areas of prepreg, and potentially time savings. Additionally by shearing large sections of prepreg, the ply begins to form the shape of the finished part, which often makes the consolidation of surrounding prepreg an easier task.[11] The downside of global shearing is that the area being sheared is away from the mold surface, so signs of incorrect shear such as wrinkling and bridging are not as immediately apparent. Therefore the laminator needs to predict both the area and amount of shear needed in addition to the location and direction (in the Global Prediction stage). This requires a large degree of intuition and experience, and is potentially the hardest part of lamination. However once an area has been sheared, it must be put back through the 'shearing decision' stage and be offered up to the mold surface to check if any more shear is required.

Introduction to 'preshearing'

A new layup method was proposed that goes a step further than 'global' forming. Instead of creating shear during layup on a feature by feature basis, all off the required shear deformation would be put into the prepreg prior to any contact between the prepreg and the mold. This would cause the ply to take on, and hold, the approximate shape of the finished layup. This preshaped ply can then be applied to the mold and consolidated using the same techniques as regular layup. Minor shear corrections can still be made, to ensure a high quality layup is achievable. Known from here as 'preshearing' this method aims to take the advantages of global layup further dramatically reducing the number of actions and hence time taken to complete a layup. The advantages and disadvantages of this process will be discussed at length in the section on 'Results'. Because the ply was completely separate from the mold during the shearing process it is very difficult for an operator to predict the required shear just from inspecting the mold shape. Thus the challenge was to calculate and communicate to the operator what shear deformation is required.

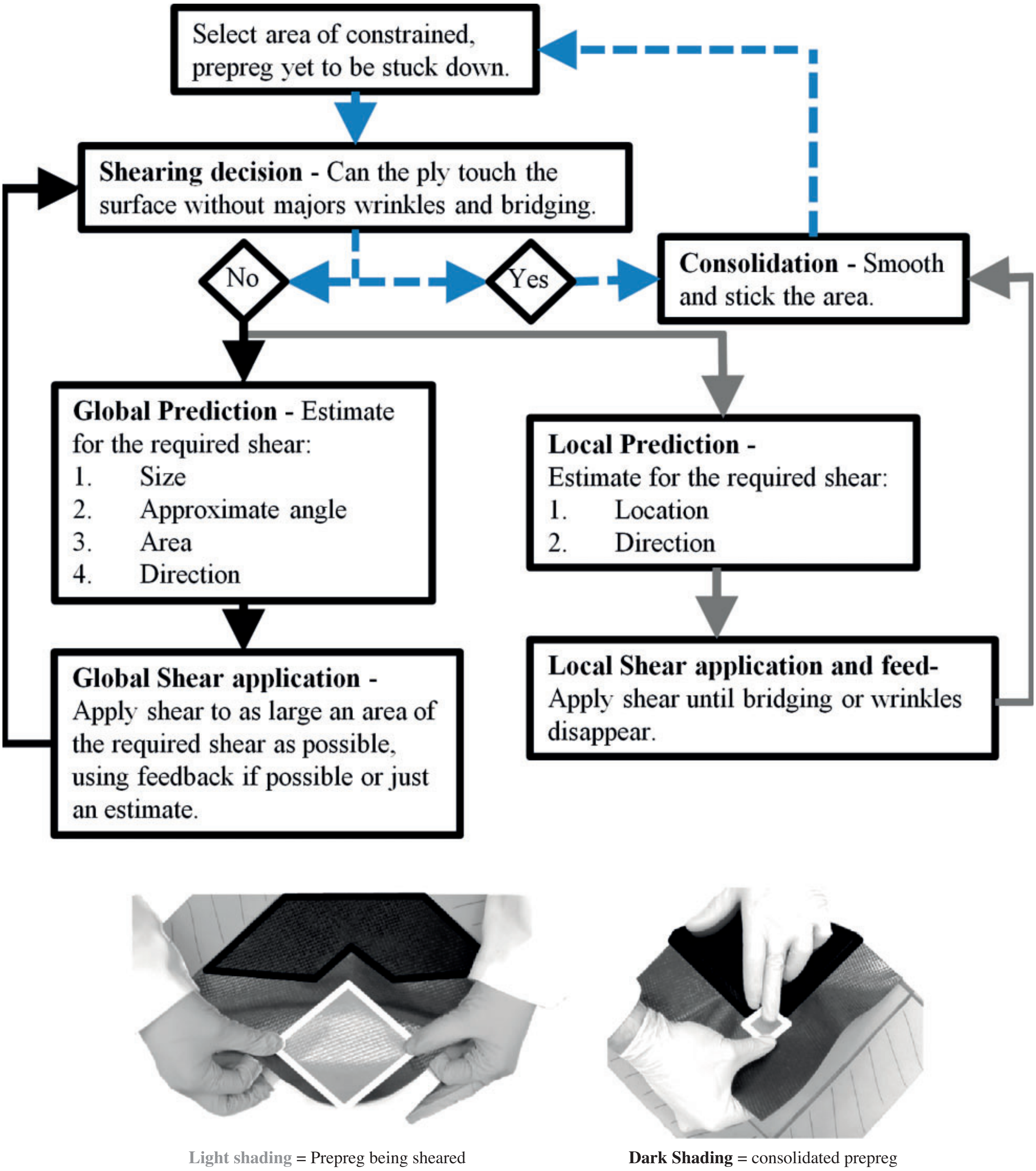


Figure 2 (Top) Flow chart of shearing process: (Bottom left) example of global shearing; (Bottom right) example of local shearing: dark arrows = global shearing, light arrows = local shearing, dashed arrows = both

Integrating drape simulation models

The proposed solution utilized the outputs from the VFP program developed by Hancock[1] as it is an in-house piece of software so the outputs can be decoded and manipulated, but any simulation package could be used. The standard visual outputs from VFP are all in the form of the finished part, and so require a large degree of intuition to interpret back into the context of a flat undeformed ply. To help bridge this gap, outputs from VFP were exported into MATLAB for further processing. The VFP model is made up of virtual warp and weft tows, which are numbered sequentially across the part. The points where these cross are referred to as nodes. For each node the output file contains the three-dimensional (3D) coordinates in the finished state, the shear angle and the reference numbers of the virtual warp and weft tows which intersect there. The shear angle for each node was extracted and rearranged into an array with the column and row index referring to the virtual warp and weft numbers respectively. Thus a color plot of the array represents the final shear angle required, but in the format of a rectangular, undeformed ply. These are referred to as 'flat shear maps' herein, and examples can be

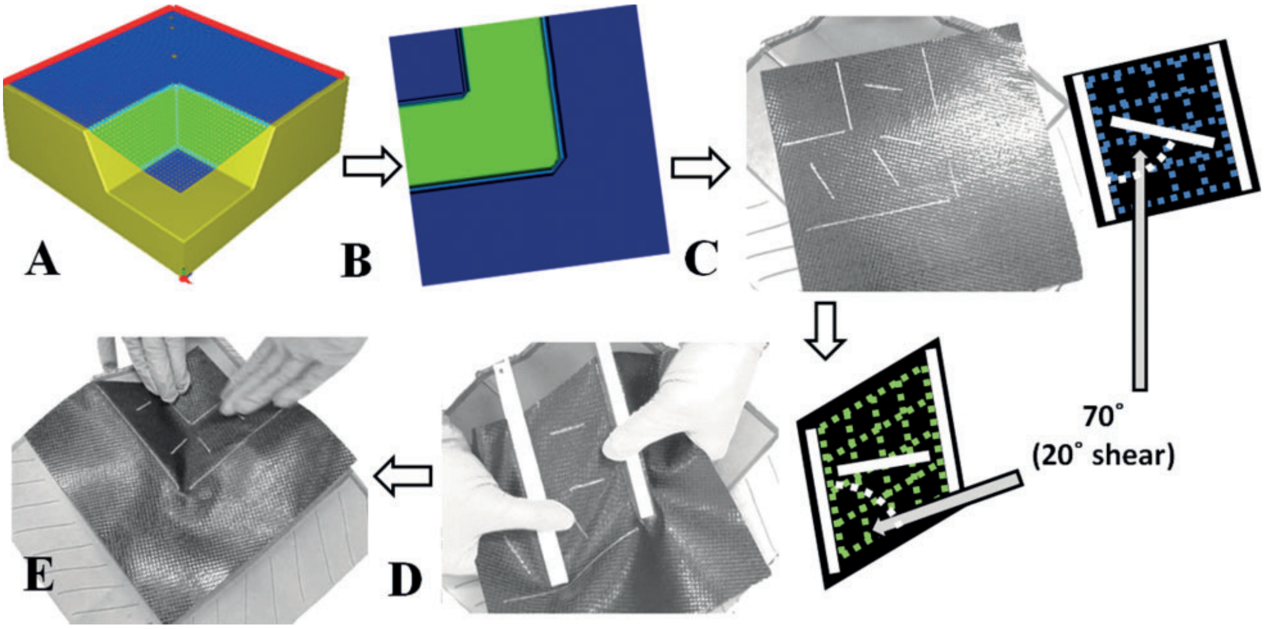


Figure 3 Preshearing process for Task B: (A) virtual fiber placement simulation; (B) two-dimensional shear map; (C) shear pattern on undeformed prepreg with schematic; (D) prepreg being deformed using edge clamping, with schamatic showing formed shear (note white lines are now perpendicular to clamps); (E) preformed ply being placed into tool, approximatly fitting into recess

seen in Figs. 1 and 3. The flat shear map was scaled to size by extracting the 3D coordinates of two adjacent nodes and calculating the distance between them. This length was multiplied by the number of warp and weft tows to obtain the width and length of the graph. Flat shear maps were then utilized in a number of ways to communicate the shear requirements to the laminators. The method for doing so varied between the different tasks trialed as a part of this study, so they are explained in context of each part individually in the section on 'Applying preshear'.

Experimental methods

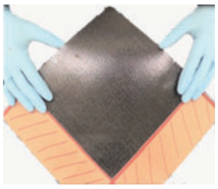
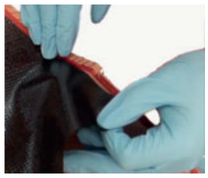
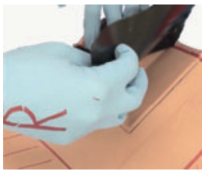
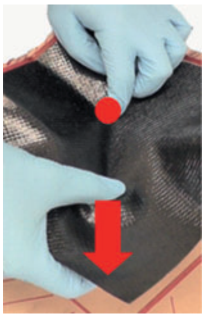
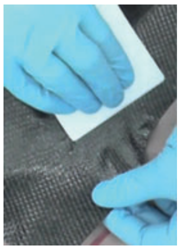
The aim of this paper is to explore how the preshearing concept affects the remaining lamination process, rather than to try and optimize the exact preshearing process itself. To do so, layup with presheared plies was trialed against regular layup across three different tasks. Figure 1 represents each task with three images from a VFP animation and an image of a finished ply. Task A and B shared the same mold, yet had a subtle but important difference in that the ply was initially aligned to the front or back of the mold respectively. This creates two different deformation patterns, which require entirely separate forming techniques.[11] Task C is one quarter of an extended double hemisphere shape, featuring natural curvature that contrasts to the angular form of Tasks A and B. Each task was completed six times by three different participants. Two of these had previous experience of laying up a variety of other typical composite geometries with woven materials and had previously taken part in a previous layup study.[11] This study included exact replicas of Tasks A and B with a similar 2 × 2 twill material. The two participants also went on layup versions of these tasks with steeper 60° ramps, so although they are not as experienced as the professional laminators used in that study, they have a significant experience of these kinds of tasks. The previous study[11] also showed that the techniques and layup times used by the two participants were not remarkably different to the professionals. The third participant was had previously used unidirectional plies to layup parts of a bicycle frame (this cannot be referenced due to anonymity issues), but had not done any doubly curved layup with woven prepreg. Tasks were completed first with three regular plies and then with three plies which had been presheared using the methods described in the section on 'Applying preshear'. All tests were conducted at standard clean room conditions using MTM49-3B 2 × 2 Twill Carbon prepreg manufactured by ACG.[17] This material was chosen because it represented a typical material used to make composite components of this nature, and had previously been used in Refs. 8 and 11 for layup tests. It provides a good compromise between the stability of plain weave, and the formability of 5 harness material. No additional tools or dibbers were allowed during the test. All lamination attempts were filmed using a camera mounted 0.5 m above the tool allowing the process to be revisited and analyzed in detail.

Analyzing layup attempts

The video footage was used to compare regular and presheared layup in terms of time taken, the number of times specialist techniques were used, and also the quality of the final ply. Timings were extracted from the time signature on the video footage, starting with the first time the ply came into contact with the mold until the last contact made by the participant with the ply. Use of the techniques outlined in Table 1 was identified manually, using visual analysis of the video footage. For each layup attempt the number of uses of each technique was recorded in a tally system.

The lack of experience of some of the participants resulted in them generally producing parts of a lower quality than

Table 1 List of specialist layup techniques identified during layup, for more details description see Ref. 14 (images also adapted from Ref. 14)

Two handed guiding (2HG) Prepreg initially guided into position using two hands.	
One handed guiding (1HG) One hand grasps and aligns the ply to a datum while the other secures the prepreg to the tool.	
Manual folding (MF) Manually creating folds in the material to manage excess material.	
Tool interaction shear (TIS) The prepreg is pushed into a recess on the tool, creating tension, causing the prepreg to shear.	
Tension–tension shearing (TTS) Both hands used to shear the prepreg by grasping it and applying tension in opposing, directions	
Smoothing and tension (S&T) Similar to TSS, but the securing hand is also actively smoothing the prepreg	
Tension secured shearing (TSS) One hand applies tension, causing the prepreg to shear, while the other secures the prepreg.	

would be assumed to be produced by a professional, or would be accepted for use on primary aerospace components. Therefore, the quality of layup was inspected visually, rating the overall severity and seriousness of variations such as bridging, wrinkling, and placement accuracy from 1 to 5, with 5 being the worst case. This coding is used only as a counter to the time based observations, in that it is easy to do an activity quickly at the expense of quality, and vice versa. The quality rating system used does not reflect the relative seriousness of such defects. Results proved that time and quality both improved significantly, so a more rigorous quality analysis was not required at this stage. All analysis was carried out by the same operator.

Applying preshear

In order to supply consistently presheared plies to the participants during the trials, a defined preshearing process was developed. For Tasks A and B, the flat shear map is a well defined L shaped region of consistent 20° shear angle (as seen in Fig. 3). The flat shear map provides information about shear location, direction, angle and area. Figure 3 shows a method of communicating this information during the preshearing stage using a series of guidelines marked on the prepreg surface. Full scale flat shear maps were printed out and the sheared region cut out to make a template. To communicate the shear angle, additional lines were cut into the template at +20 or −20° to the edges of the template depending on the shear direction. Next, a paint pen is used to draw the outline of the template and the 20° lines onto the prepreg.

Figure 3 shows how the correct shear being achieved is signified by the 20° lines becoming perpendicular to the adjacent template outlines. According to Ref. 11 the usual process for shearing a section like this would be tension–tension shearing (TTS) see Table 1. However, the maximum width this technique can be applied across is always limited to the size of the operator's thumb being used to grasp the prepreg. The width of the sheared area is distinctly larger than a thumb, so many repeat actions were required, resulting in a slow process and inconsistent shearing. To counter this, a technique known as 'edge clamping' was developed, based on a material test by Bloom *et al.*[8] Two pairs of metal strips were used to extend the gripping area of the hand, allowing all of the shear area to be created in just two actions, as can be seen in Fig. 3.

For Task C the edge clamping method was not directly applicable because the shear varies continuously across regions of the ply and does not run out to the ply edge, so an alternative method was therefore developed to allow preshear to be applied by hand. Figure 1 shows the flat shear map, with the shear angle rounded to the nearest 10°. To test the robustness of the preshearing process, this was approximated to just three areas of shear as can be seen in the template. The central red area is sheared to approximately 40° which can be judged by hand as this is typically the locking angle of woven prepreg materials so the in-plane shear stiffness increases significantly at this angle.[8] The surrounding areas of shear and a third region on the edge of the ply, marked in green, represent approximately 20° of shear, which is left to the operator to judge. Although this method may appear basic in comparison to the system used for Task A and B, results show it was still effective for shaping plies for these tasks.

An issue that affected the preshearing process is 'spring back' where the viscoelastic nature of the epoxy means some of the shear deformation could be lost once the applied tension is removed. Based on the findings of Refs. 18 and 19, efforts were made to minimize spring back using a combination of a slow deformation rate and holding the deformed prepreg under load to allow stress relaxation in the epoxy resin. To ensure consistency in the spring back effects, all preshearing was done by the same operator to achieve an approximately consistent deformation rate, and then left for approximately one minute until they were handed on to the participants. A subsequent investigation has shown that increasing the temperature of the prepreg during preshearing can almost totally eliminate spring back.

Results

Before results are presented, the issue of learning curve effects must be addressed. The three attempts with presheared plies were made after those with regular plies so it could be argued that learning curve effects will be present, as the presheared attempts have the benefit of the experience gained from the regular layup. For a more experienced laminator, the learning curve effects would be expected to be greatly reduced. For the less experienced participants in this study, the effect was counteracted by comparing the average scores and times for presheared layup with the minimum or best case for the regular layup.

It is intuitive that by completing some of the required manipulations to the prepreg prior to layup, the remaining processes will be both shorter and require fewer manipulations. This was confirmed by the data in Fig. 4 which shows the time taken to layup the presheared plies on the mold was reduced by an average of 59%. Figure 5 shows that total technique usage was reduced by 77%. Considering only those techniques directly associated with creating shear,[11] the reduction is even greater at 86%. While the physical application of a technique may only take a second or two, the operator has to complete a full loop of the system outlined in Fig. 2, which includes multiple checks and decisions that take up time, accounting for the dramatic time saving. Further investigation into the time taken to form specific areas of the Tasks revealed the time spent on areas with no shear was actually reduced by a similar proportion to those where there was shear. There was also a corresponding reduction in the use of techniques not directly associated with shear such as 'One handed guiding' (1HG). These observations suggest there are secondary effects of preshearing beyond helping to form highly sheared areas, and these will be explored further on a Task by Task basis.

The total quality score for all three tasks as presented in Fig. 6, showed an improvement of 50% for the presheared plies. It must be stressed that this does not mean preshearing will make parts '50% better'. The operators were not of professional standard and hence could be argued to be more prone to creating variations than those experienced in layup. The 50% improvement in quality shows that preshearing plies can reduce the likelihood of variations and that the increased layup speed did not come at the cost of reduced quality. Combining results from the three analyses proved that preshearing changed the layup process dramatically.

Task A

From Fig. 5 it can be seen that there was a significant drop in the use of 'Tension secured shearing' (TSS), a technique strongly associated with applying shear.[11] The drop in the use of the remaining techniques also shows the importance of preshearing on other areas of layup. To understand the reduction in techniques and defects during presheared layup it is necessary to first explore why they occur so frequently in the regular process. The left hand image in Fig. 7 shows a ply during regular layup of task A. Fitting the ply against the datum running around the concave recess created 'excess' material.[2] This results in folds in the material

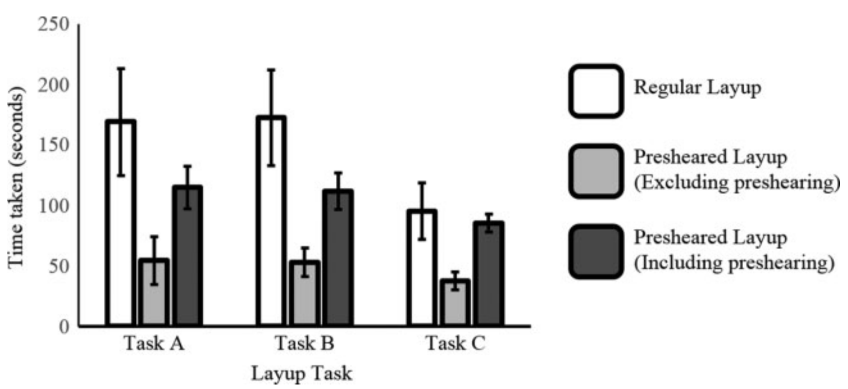


Figure 4 Time taken to lay up using regular and presheared layup. Times for Presheared layup are shown with and without time taken to apply preshearing added in. Error bars show one standard deviation each way

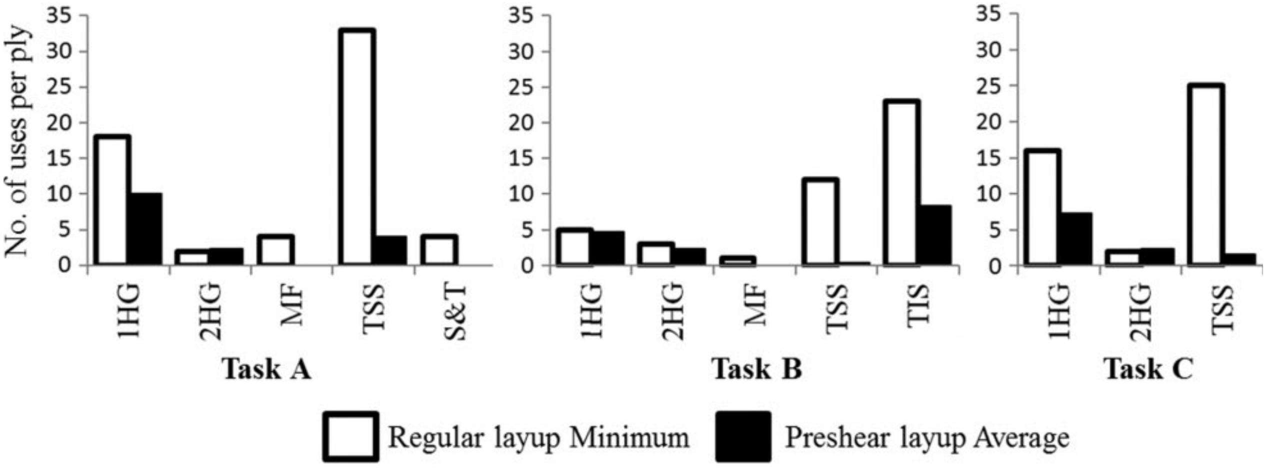


Figure 5 Comparison of minimum recorded techniques usage for regular layup verses average recorded during Presheared layup

which have to be dealt with, accounting for the frequent use of 'Manual folding' (MF).[11] The folds also make aligning the edge of the ply difficult, so multiple uses of 1HG are required for regular layup. This potentially accounted for the poor alignment standards highlighted by Fig. 6. By preshearing the ply, it is 'preshaped', such that it fits into the mold. Thus there was no excess material created so there were no folds when the edge was aligned to the datum, as can be seen in the right hand image in Fig. 7. This drastically reduced the number of corrective or managing actions required and enables the ply to be aligned more quickly and more accurately. Use of 'Two handed guiding' (2HG) remained consistent, generally being only used once per layup to initially locate the ply, and was therefore regarded as an action which did not appear to be effected by preshearing.

Task B

As Task A before, Task B sees a reduction in the use of the primary shearing technique used in regular layup ('tool interaction shearing' TIS), as would be expected with the shear already created in the ply. It also sees a reduction in the use of 1HG, but for different reasons to Task A. Again it is necessary to look closely at why these techniques are present in regular layup in order to understand why they are not needed in presheared layup. Layup starts by aligning the ply to the rear edge of the mold, and ply consolidation can reach all the way to the edge of the recess before any double curvature starts to take effect. At this point participants using regular layup made extensive use of the TIS technique to form the shear, as seen in Fig. 8. Using TIS generates tension in the prepreg, which has to be reacted against by a mixture of frictional forces and adhesion between the already consolidated prepreg and the mold surface. These forces are dependent on the 'tack' between a material and the mold surface, which can vary greatly.[8] For this material–mold combination, it was common for the tension to be high enough to overcome these forces, causing the prepreg to slip across the mold surface and wrinkle near the recess as is shown in the left image in Fig. 8. The middle image in Fig. 8 shows an example of such a slippage being repaired using 1HG, which accounts for its high usage during regular layup and also poor datum alignment. Some of the wrinkles were not dealt with and remained in the final layup, accounting for the poor quality score. By preshearing the ply, there was a much reduced need to use TIS to create shear in situ. This helped reduce ply slippage, therefore reducing the use of 1HG to repair alignment errors. This also reduced any associated wrinkling,

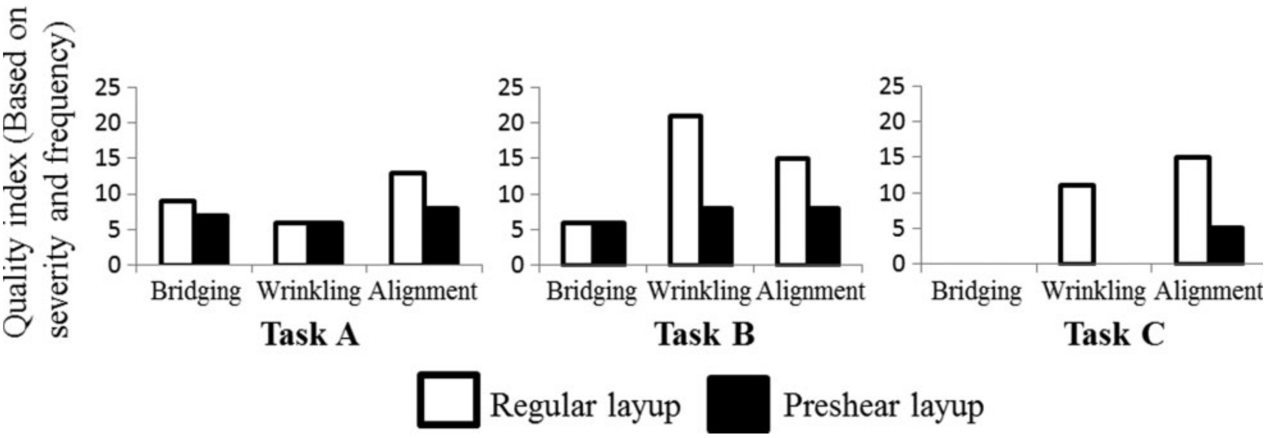


Figure 6 Totals quality scores for each task in layup trials. Each ply was graded from 1–5 in each category, with higher scores represent lower quality layups

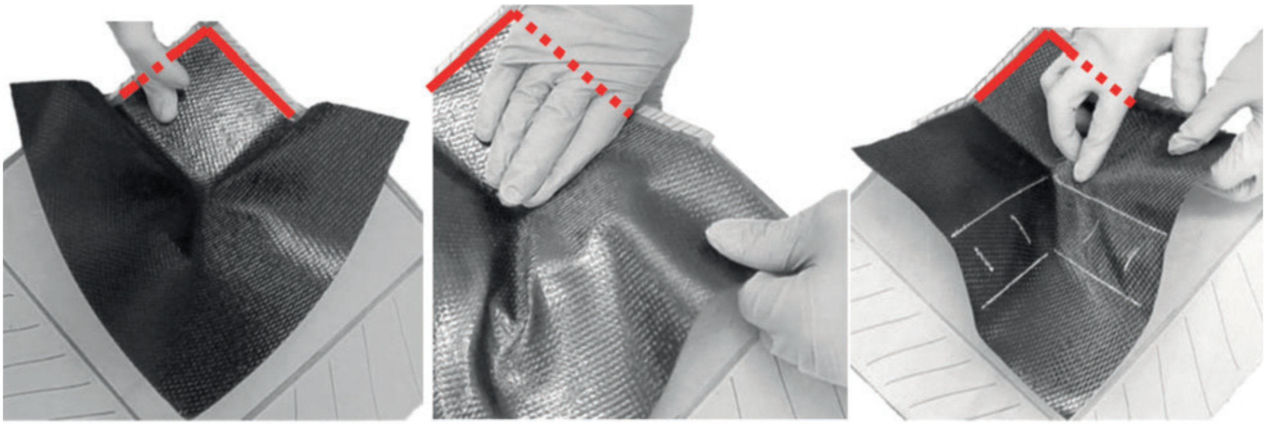


Figure 7 Task A lamination (datums shown as red lines, dotted where obscured by hands): (Left) regular ply folding as it is placed into concave region; (Middle) example of type of 1HG action used much more frequently during regular lamination; (Right) presheared ply fitting into tool recess without folding being generated

accounting for the much improved wrinkle performance of the presheared plies. These effects in combination account for the much reduced time to layup.

Task C

Task C was a very different geometry to the other two tasks, featuring curved surfaces and convex sheared regions. But as Fig. 5 shows, the trend of seeing large reductions in the use of the primary shearing techniques continued, with the use of TSS reducing dramatically. Again this is acompanied by a less intuative reduction in the use of 1HG. The top left image in Fig. 9 shows how as the ply is aligned to the highlighted datum during regular layup it creates double curvature. As during Task A, this creates excess material, leading to folds. These folds are then removed by applying tension with TSS to shear the prepreg (as can be seen in the top right image of Fig. 9). When a global shearing approach was used, the required forces were great enough to overcome the prepreg-mold adhesion and the ply was pulled off the surface, and slid away from previously aligned datums (see highlighted circle in Fig. 9). This required multiple uses of 1HG as a corrective action, which can be seen in the bottom right image. An alternative used on some attempts was to use a very local shearing based approach, aligning and shearing only small sections of the prepreg at a time, reducing the force, but requiring a large number of uses of both techniques and therefore increasing the time taken. By using preshearing, the ply is already shaped to fit the mold as can be seen in the bottom right on Fig. 9, and the use of TSS and associated layup variations and defects are largely avoided. Thus issues with fixing slipped plies or working at a very local level are avoided, leading to a quicker and less complex process.

Discussion

Is preshearing effective?

Preshearing has been shown to dramatically reduce the time spent laying up a ply onto a mold, which has the potential to create significant cost savings. However, the time savings identified thus far do not include the time taken to undertake the preshearing. This took between 40 and 60 s, and a further 4 s was added to compensate for the time to draw the guidelines onto the ply. Once these were included in the data, the time saving for Tasks A and B remained very significant but dropped from 64 and 65% to 27 and 36% respectively. A 50% time reduction during Task C became a 2% increase in time. In contrast, this task saw the largest drop in technique usage at 74%, so it would appear that preshearing is having a positive effect during task C. The time was likely

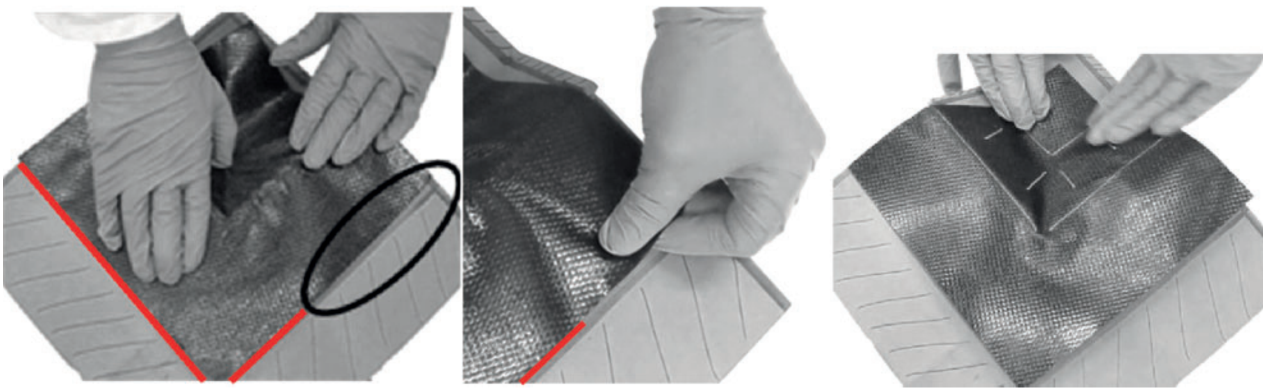


Figure 8 Task blamination: (Left) regular ply forming into recess, causing prepreg to slip from marked datums (circled); (Middle) example of 1HG being used to correct slip; (Right) prehseared ply fitting into tool before any consolidation, avoiding slippage and so negating need for corrective actions

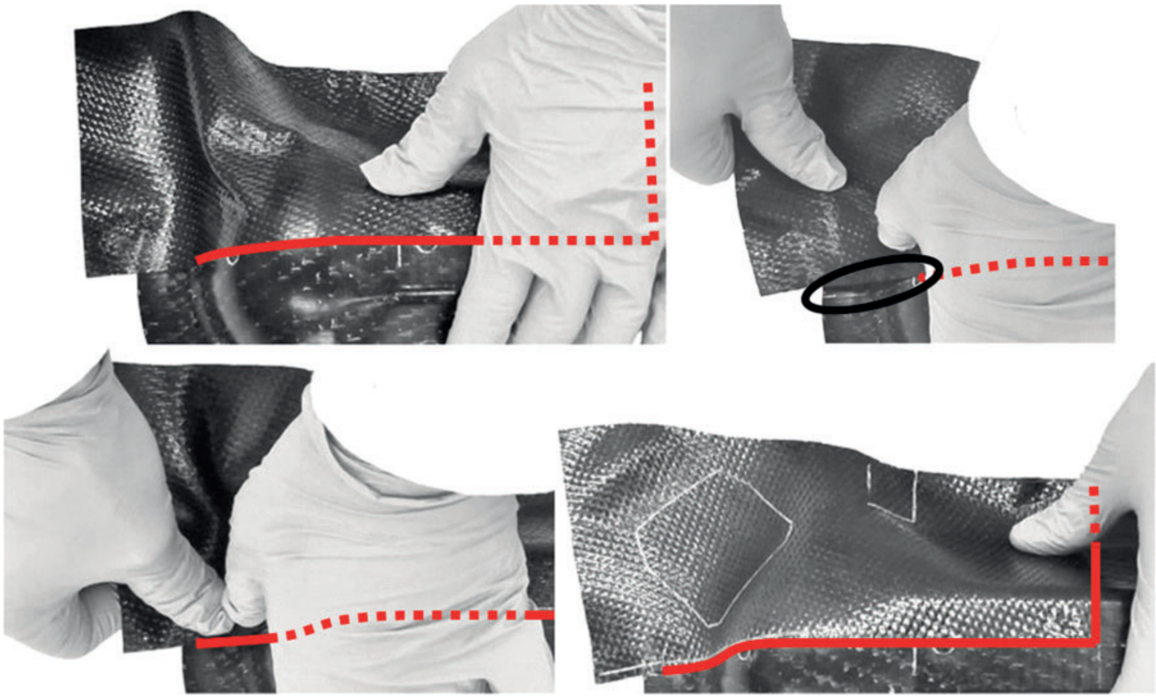


Figure 9 Typical issues arising during regular layup of Task C, and presheared alternative: (Top left) regular ply wrinkling as it is aligned along datums (shown as red lines, dotted where obscured by hands); (Top right) regular ply lifting off edge as TSS is applied (defect circled); (Bottom left) previosuly generated defect being repaired; (Bottom right) presheared ply is shown conforming to tool surface after being aligned to datum, greatly reducing wrinkling, folding and slipping as seen in regular layup

taken up by the preshearing stage, because it requires high shear as well as multiple actions and visual judgments made by the laminator, all of which took up more time than in the other 2 tasks.

How could preshearing be improved?

It can be argued that the large reduction in the number of techniques represents a 'simplification' of the layup process, and this was confirmed by comments from participants that

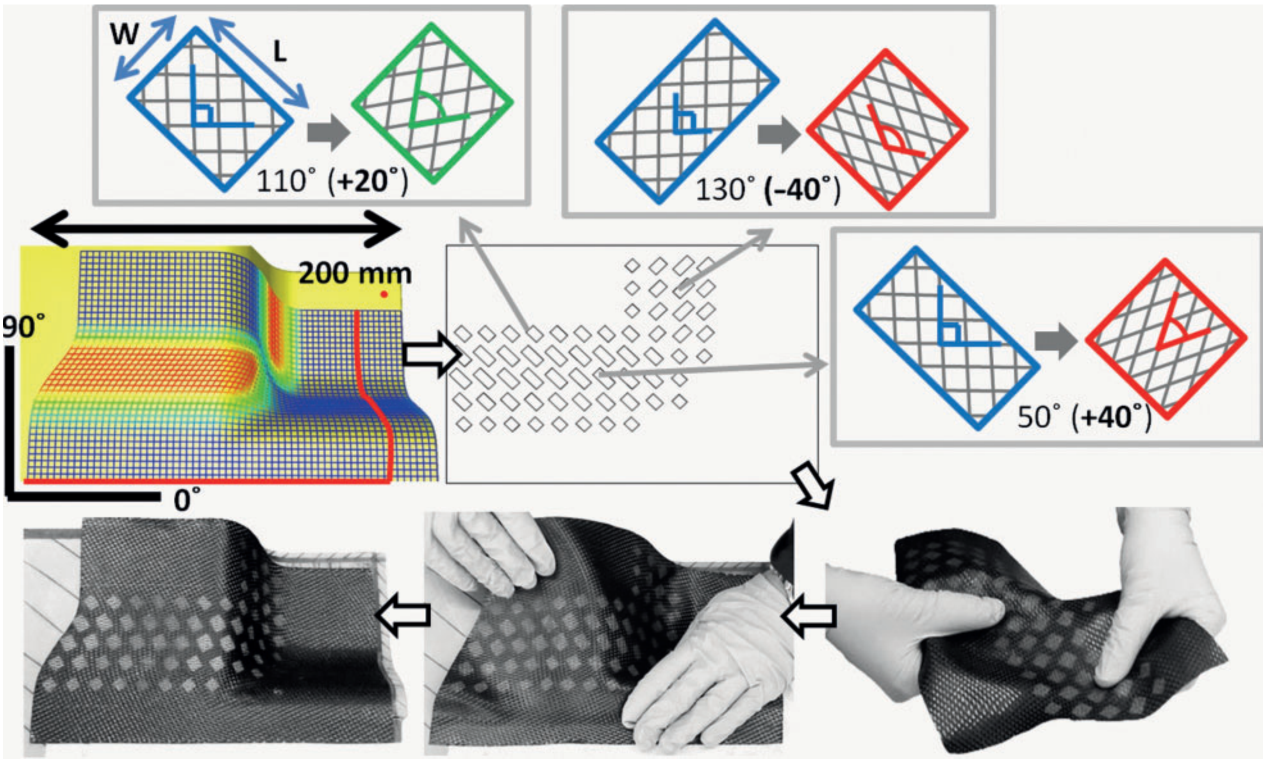


Figure 10 Task D lamination and use of RIF: (A) virtual fiber placement diagram of Task D; (B) RIF pattern with schematics of three example rectangles; (C) ply marked with RIF pattern being presheared; (D) presheared ply being fitted to tool; (E) finished ply

lamination of the presheared plies was 'easy' compared to regular layup. However, it could be argued that preshearing should ideally eliminate dedicated shearing techniques altogether. Some of the attempts at Task C achieved this, while others still required a number of shearing actions. This suggests variations in the preshearing process, which in these cases resulted in a discrepancy between the shear created in preshearing, and the shear required for final layup. To add or remove shear from the prepreg would require the laminators to temporarily revert back to using the regular layup process outlined in Fig. 2. As stated previously, the preshearing techniques used so far were entirely manual and required judgements from the operator so will always be a source of variation. Additionally the problem of spring back as discussed in the section on 'Applying preshear' had not been fully addressed, so some of the shear was being lost between preshearing and layup phases. The 'ideal' final layup process would contain no corrective or adjusting actions, leaving only a constant forward stream of work resulting in a more economical process. To try and achieve this, a more detailed and robust method for communicating the required shear was developed.

Developing new preshearing system

A system was needed for communicating shear that would facilitate the operator in preforming the right amount of shear, in the correct direction and only in the required regions. Also whilst the methods described in the section on 'Applying preshear' enabled preshear instructions for some specific patterns, a more adaptable method was required for others. A new system known as a rectangular indicator field (RIF) was designed to achieve this. Figure 10 shows how this system uses a pattern of rectangles to communicate the shear. A section of woven material being sheared can be visualized and modeled as a pin jointed net.[9] If it is stretched in the $+45°$ direction, it will contract in the opposite $-45°$ direction and vice versa. Consider the rectangle drawn onto the surface of the prepreg in Fig. 10 with the shorter sides aligned in the $+45°$ direction. If tension is then applied in the $+45°$ direction, the shorter side of the rectangle will elongate while the longer side will contract until eventually all four sides are the same length, forming a square. By adjusting the proportions of the initial rectangle, both the shear direction and angle at which a square is achieved can be predefined. The process for creating the RIF pattern is outlined:

(i) starting with a flat shear map, the shear deformation angle was averaged (α) over an $N \times N$ set of nodes, where N is defined by the user. The greater the value of N, the larger and easier to follow the rectangles will be. However a large value of N means small details in the shear pattern may be lost (much like using a too large node length in finite element analysis). N should be chosen as a trade-off between both effects, taking into consideration the element size used in the drape simulation. For this task it was chosen such that an $N \times N$ grid would represent a 15×15 mm region of the ply, as this would be easy to interpret, but still capture the gradual change in angle across the sheared region

(ii) if the average shear angle (α) was below a defined threshold angle, no rectangle is drawn. This reduces the number of rectangles, allowing the operator to focus on the higher shear areas. The threshold was set to 5°, as shear below this level can from naturally as the ply is stuck down

(iii) the length of the rectangle (L) is calculated by putting the shear angle (α) into equation (1). The width (W) of the rectangle was set at a constant 7 mm for this part so the rectangles will fit inside each 15×15 mm sample area

$$L = W \times \left[1 + \frac{1 + \sin(45 + \alpha/2) - \cos(45 + \alpha/2)}{\sin 45}\right] \quad (1)$$

where L is rectangle initial length, W is rectangle initial width (constant) and α is final shear angle.

(iv) to orientate the rectangle correctly, the direction of the shear was calculated. The 3D coordinates of the four nodes at the corners of the $N \times N$ sample set in their deformed state were extracted from the data. The distance between the nodes on opposing corners of the square were compared, to determine if the elongation was in the $+45$ or $-45°$ direction, and hence which direction to align the short (W) side of the rectangle to. Figure 10 shows examples of an RIF patterns featuring variations in both shear direction and angle

(v) once the whole map had been processed, the rectangular patterns were plotted as a DXF file and

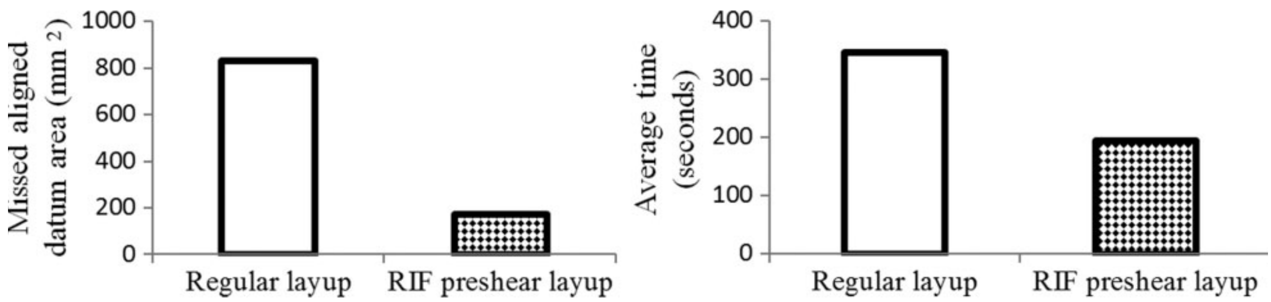


Figure 11 Graphs comparing (left) datum misalignment area; and (right) time taken for layups using regular plies or those with RIF presheared pattern to enable in preshearing

used to cut out a template from stiff plastic film using an automated ply cutting table

(vi) the template is then used to stencil the RIF onto the ply. During this pilot study, spray paint was used, but a more compatible solution would be needed for industrial use. An epoxy resin with UV dye was also successfully trialed for a single ply.

RIF testing

To prove RIF as a feasible method for communicating preshearing information, a comparison was made between regular layup and layup where the participants presheared plies following an RIF pattern. The comparison was made over a fourth task (Task D, Fig. 10), which is a hybrid of the three previously used tasks. It featured a similar corner recess to Task A and B, but with steeper 60° ramps and open (30 mm) radii at all corners similalry to Task C. There was one datum along the flat top surface and another was along the recessed edge. Virtual fiber placement and RIF patterns are also shown in Fig. 10. Four participants were each given two regular plies, while another four participants were each given two RIF plies. One participant in each of the two groups had previous experience with layup of woven prepreg materials onto double curved surfaces, while the remaining six had only used prepreg on flat or singly curved parts. The experimental setup and procedure was the same as the initial preshearing study, apart from using a 913 2 × 2 Twill Woven Carbon material manufactured by Hexcel.[20]

Results

Figure 11 shows that layup of the RIF plies, including the preshearing process, was on average 43% faster than regular layup. This is a very significant time saving, and a similar improvement was found in the overall quality of the parts. The surface area of any datum overlap or shortfall was measured using photographs of the finished plies and using the 'ImageJ' software.[21] Figure 11 shows the total area of the missed datums was 79% smaller for the presheared plies. If the regular plies were laid up to the same positioning standards, it is likely that the time saving will be even greater.

Some of the issues during regular layup of Task D are highlighted in Fig. 12. Firstly in the left image, as the ply is being pressed into the recess it has slid away from the datum. This also generates wrinkles (as can be seen in the enlarged image) as the ply deforms to accommodate it. The same effects can be seen in the right hand image, where the ply has come away from the edges. These defects either remain in the layup or take time to go back and repair them. Another noted problem during regular layup was that some participants tried to shear the material in the wrong direction (stretching in the direction it should be contracting), or in the wrong place (shearing regions that did not need to be sheared), suggesting they were struggling with the 'prediction' stages of lamination that are outlined in Fig. 1. Figure 10 shows an example of a presheared ply being fitted into the mold. As discussed earlier, preshearing greatly reduces the need to generate shear during layup. Thus many of the problems identified during regular shearing can be avoided. It also avoided the confusion suffered by the inexperienced laminators, as the RIF pattern provided a guide as to where and what direction to apply any extra shear. This short study has proven that the RIF pattern is highly effective in communicating shearing instructions to operators, allowing them to preshear plies exclusively by following a pattern on the ply surface.

Discussion

It has been shown that preshearing can dramatically alter the lamination process, offering significant time savings and simplifications. However it must be considered that the amount of time preshearing can potentially save will always depend on mold geometry, ply size, laminator experience and material characteristics.

Mold geometry

If a mold has only a small amount of double curvature there will consequently be very little shear, thus the benefits from preshearing are likely to be limited. These types of parts may be better suited to production via other, possibly automated methods such as AFP. Hand layup is ideal for parts with large amounts of shear arising from complex double curvature, and this is where preshearing is likely to be most effective.

Ply size

The preshearing and handling process is likely to be effected by greatly affected by the size of the ply. For small

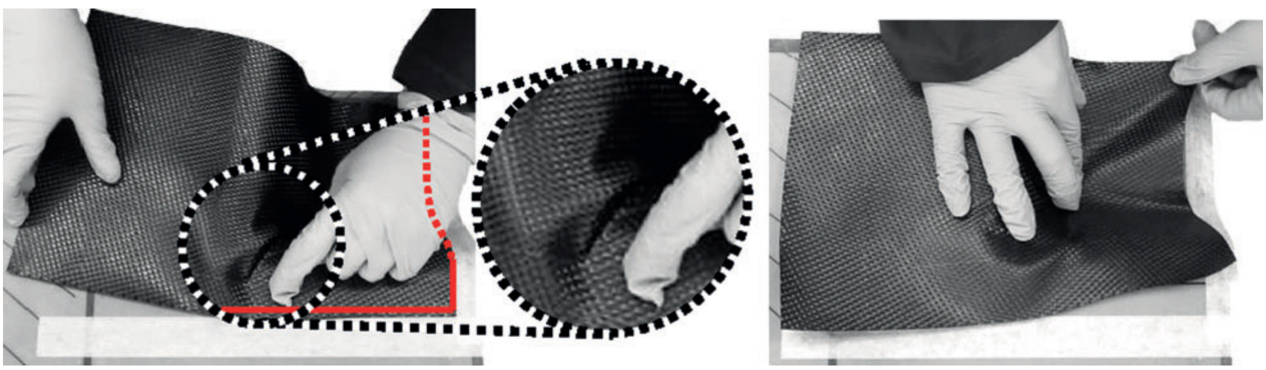


Figure 12 Typical issues during Task D: (Left) ply aligned to datum and then wrinkling (circled); (Right) example of participant shearing wrong region of ply while trying to reach datum

plies (300 × 300 mm or less) the inherent out of plane bending stiffness of the prepreg is enough to prevent the ply buckling or wrinkling under its own weight. In fact the out-of-plane deformation can actually make the ply more resistant to bending, similar to corrugated iron or plastic. However as yet unpublished studies on preshearing very large plies (2 × 1 m) showed that the greatly increased weight of the plies can be great enough to cause it to bend or buckle under its own weight, complicating both the preshearing and handling process. The preshearing of plies is limited by both the size of human hands and the fact it is only possible to contact the play in two places at once, and work is currently being undertaken to use additional tools or a press to assist in preshearing as discussed subsequently in the section on 'Applications of preshearing and future work'.

Material properties

Studies on the differences between materials and their effect of hand layup were carried out at Bristol University,[8] highlighting that increased in-plane shear stiffness has a significant effect on the difficulty of layup, reducing the quality while increasing the time taken. It is expected that as shear stiffness and therefore the difficulty of shearing the fabric in-situ during layup increased, preshearing would likely become more effective.

Laminator experience

The benefits of preshearing in terms of time saving and defect reduction will also depend on the skill level of the laminator. The less experienced a laminator is, the harder they will find regular layup, and so the 'simplified' preshearing process may be more beneficial. Considering the significant previous layup experience of the participants in the main preshearing study, they were suitable test subjects at this early stage in development. The trials with the RIF pattern show preshearing was highly effective when working with novice laminators. However the authors accept that further work testing the process with professional laminators such as those used in Refs. 8 and 11 would be needed to fully validate its potential commercial benefit.

One further issue with the methods presented here is the use of paint or other markers to draw the preshearing pattern onto the plies. This may negatively impact on interlamina properties, and so a more compatible solution will need to be developed for industrial use. A test ply was successfully prepared and laid up using an epoxy resin with a UV dye instead of paint, and this could prove to be a suitable solution.

Applications of preshearing and future work

This work, alongside Refs. 8, 10, 12, 13 and 22, among others is part of a wider vision at Bristol University to update and improve the current layup practice and training methods. Subject to further investigation across a wider range of parts and with more experienced laminators, preshearing has the potential to play an important role in a number of areas of composite manufacturing.

Integrating preshearing into the existing workplace

The simplest method for integrating preshearing into a work force would be train it in using RIF, and apply a pattern to every ply surface. Thus the existing workforce and molds could benefit from some time savings and reduced learning curves for complex parts. It can also provide simple quality assurance because an incorrect layup is identifiable by any remaining rectangular shapes on the finished ply. If the laminator follows the pattern correctly the deformation pattern they achieve can be dictated, giving designers more control of the fiber paths in the final product. Such control is increasingly important as production more frequently becomes separated from design as manufacturing is moved abroad and design intent becomes difficult to translate.

Alternatively, preshearing could be done by a separate operator. The task of preshearing by following a set RIF pattern could be done by less skilled workers and then passed onto the more experienced laminators for final layup. These works could be both more readily available and lower cost than only using experienced laminators, and could increase production speeds. However, resistance to change in the workplace can be problematic if it is not implemented in the correct manner.[23] It must be appreciated that lamination itself is often considered a craft, with laminators taking great pride in their work.[22] Accordingly, any changes to the lamination process would need to be introduced in a way which does not appear to override or undermine the current valuable skill set, or status of the work force.[23] The practice of pre-shaping plies to fit into tight singly curved radii and other personal adaptations of the process are not uncommon,[24] suggesting that adaptations of the existing process may be readily accepted. Further work integrating RIF into existing workforces would be needed to establish both its effectiveness on experienced laminators, and how it is received by the workforce.

Improvements to training

It has been shown that having an RIF pattern on a ply can make lamination 'easier' for inexperienced workers, reducing the steepness of the learning curve associated with the laying up of complex parts. As a result, it may be possible to use RIF to fast track the training process of new laminators, allowing relatively inexperienced workers to make complex parts that are usually only made by an experienced workforce. Potentially the RIF pattern is only needed to train operators on the first few plies of a complex part, and may not be needed on every ply. Further work could be directed towards developing RIF based training systems and comparing them against traditional training methods.

Automated preshearing

This work has only focused on manual preshearing of prepreg which could increase productivity significantly, potentially reducing the need for automated processes. However if presheared layup proved to be insufficient to keep up with ever increasing demand, there is scope for introducing automation into the process. Press type mechanisms and pin bed forming have been shown to be capable of shaping prepreg sheets,[25] and could be utilized to rapidly preshear the plies. These plies could then be passed onto regular laminators to be finished off in layup to the quality and standards expected of the regular layup. Although it has been shown the layup time using a presheared ply is much reduced, it is possible that both the layup speed and availability of workers may still be too low to compete with other manufacturing methods. If this proves to be the case there is potential to use preshearing to bring automation to the whole lamination process. One of the key conclusions from Ref. 14 was that regular lamination is highly complex, requiring multiple contact points and a variety of feedback methods; all characteristics that make it very difficult to automate layup with existing robotic systems. However, it has been shown that preshearing simplifies the layup process meaning plies can be consolidated without the use of any grasping type techniques. As a result, the concept of using a single robot with one or more end effectors to consolidate a presheared ply onto a mold becomes feasible. Work is currently being undertaken by the authors to achieve this.

Conclusions

This work has shown that by preshearing a ply, lamination can become significantly faster and less prone to defects. Simultaneously, the process became much 'simpler', requiring fewer uses of specialist techniques. Two of the three tasks showed significant time savings of over 20%. However, the third task showed a slight time increase. An alternative shearing method was developed and has been shown to be effective in increasing the working speed and quality of operators of limited experience. Further work should look towards trialing preshearing on a wider range of molds and more experienced laminators. If the process can be successfully integrated into the existing manufacturing process, it has the potential to dramatically increase output while reducing costs. Such an achievement would make hand layup a more competitive option in the face of increasing competition from automated solutions. Alternatively there is scope to use preshearing in a fully automated method, which could have the capability of producing parts of equal complexity and quality to hand layup, something which often very difficult or impossible to achieve with existing processes. Future work should be focused on establishing the effectiveness or preshearing considering variables such as laminator experience, material properties, ply size and mold geometry. If the process proves to be effective across these parameters, then work should focus on workplace integration and developing and testing training schemes.

Conflicts of interest

None.

Acknowledgements

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