Preshearing: The evolution of manual layup

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Abstract

Hand layup is still widely used in the composites industry, yet it has changed little over the past few decades. This is the first attempt to study in detail the effects of modifying the layup process. An alternative two stage approach to layup is proposed, where the majority of the shear deformation is applied prior to plies contacting the tool. The new process is trialled by three participants on three separate layup tasks. Using video analysis to study the process, it was shown that the key tasks of manipulating the prepreg sheets around doubly curved features and creating in plane shear during layup were dramatically ‘simplified’. This resulted in a large reduction in the use of specialist techniques, a significant time saving and a reduction in the likelihood of defect generation.

1. Introduction to hand layup

Hand layup of woven prepreg combines the dexterity and creativeness of humans with a material that is robust and highly deformable [1]. The result is a very adaptable process capable of forming the most complex composite products. The process begins with a kit of plies cut to shape for the specific part. A human operator then in turn manipulates each ply into shape while sticking them firstly to the tool and then layering up onto the previous plies. This process is often referred to as ‘lamination’, ‘lay up’ or ‘drape’. By geometric definition, forming flat sheets over a doubly curved shape requires in-plane deformation of the prepreg, which is achieved via in plane shear of the woven structure [2]. The inclusion of epoxy resin in the woven fibres means the in-plane shear stiffness of prepreg material is relatively large compared to the out of plane bending stiffness. As a consequence, if a length of prepreg is placed under in-plane *compression*, it will generally buckle, hence *tension* is usually required to create in plane shear. The downside of this combination is that the process can be labour intensive, time consuming, and can also suffer from inconsistencies in the quality and fibre orientation produced by different laminators.

As composites are adopted by the civilian aerospace sector and other high volume industries, there have been efforts to develop more automated manufacturing processes. By doing so, many of the advantages of hand layup are lost. While processes such as Automated Fibre placement (AFP) and Automatic Tape Laying (ATL) can provide reasonably fast and accurate placement of fibres, they are capital intensive to set up and are limited to producing flat or simple single curvature components [3]. Thus hand layup remains the only viable process for many complex components. The details of the manual process have been studied by [4], showing that methods for applying this tension can vary dramatically, depending on the tool shape and the order in which features are laid up. While there have been efforts to improve the hand layup process via the addition of laser guidance or integration of motion sensing equipment, this work looks to build on the study by [4] and dramatically modify the core of the process to tackle some of it key disadvantages.

1.1 Lamination styles

The study in [4] identified seven techniques which form the basis of the lamination process. These are used to align, shear or manipulate the prepreg, and are summarised in Fig 1. It was also proposed that there are different approaches to lamination, the extremes of which can be classified as 'Local' and 'Global', as illustrated in Fig 2.

Ply manipulation techniques	**Shear deformation techniques**	
Two handed guiding. (2HG) Two hands are used to guide and support the prepreg into position	*Tension Secured Shearing (TSS)* One hand secures the prepreg, while the other applies tension, causing the prepreg to shear	*Tool interaction shear forming (TIS)* The prepreg is pushed into a recess on the tool, creating tension which causes the prepreg to shear
Manual Folding (MF) Folds are manually created in the material to assist layup		
One Handed Guiding (1HG) One hand secures the prepreg to the tool while the other grasps and aligns the ply to a datum.	*Smoothing with tension (S&T)* The same as TSS, but the securing hand is this time actively smoothing the prepreg	*Tension-Tension shearing (TTS)* Both hands grasp the prepreg and apply tension in opposing s, directions causing the prepreg to shear

Figure 1: Table of lamination techniques adapted from [4].

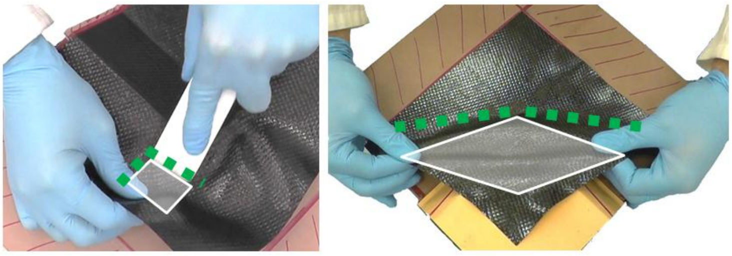

Figure 2: Lamination styles. **(***Left***)** ***Local***: Shearing an area just ahead of the prepreg which is already stuck to the tool. (*Right*) ***Global*****:** Applying shear to a larger area further ahead of the stuck down prepreg. Key: *Light shading – Prepreg being sheared, Dotted line – Edge of stuck prepreg.*

The majority forming carried out by laminators is '*local',* where forming is that the deformation is happening very close to the tool surface. This makes it possible to identify and fix developing wrinkles and bridging which might indicate incorrect deformation. The downside is that access is always required to the area of prepreg being worked on. Geometries with deep recesses or requiring large plies can make it difficult for operator's hands to comfortably get into the right position to manipulate the prepreg. In contrast, *global* shearing has the inverse characteristics; the material is sheared *away* from the tool, making it much easier to access, allowing application of high forces. The result is that larger areas can be sheared in a short space of time. Another advantage is that forming the appropriate in-plane shear gives the ply the associated out of plane deformation, making it 'fit' the tool. The combination of these effects has the potential to dramatically reduce the number of actions needed during layup. Unfortunately shearing material away from the tool means that the signs of incorrect shearing such as bridging and wrinkles are not immediately apparent; making gauging the state of the shear while it is developing becomes more difficult.

Using deformation simulations

The work presented looks to counter the disadvantages of global shearing by utilising the outputs from kinematic deformation prediction tools such as 'Virtual Fabric Placement' (VFP) [1],[5]. The output from VFP will be used to assist the creation of accurate deformation by providing guidance during the shearing phase to compensate for the lack of feedback. Potentially this would enable more of the benefits of a global approach to be put to greater use. In order to integrate the deformation predictions into layup, the process was split into two distinct stages. Firstly, the required deformation is created in the prepreg before any contact with the tool, during a 'preshearing' phase. In the second 'final layup' stage, the already deformed or 'presheared' ply is applied to the tool using the same techniques and methodology as regular hand layup.

2. Experimental method

For a rigorous investigation of the detailed effects of preshearing on the layup process, three tasks producing different example parts were compared side by side with regular lamination. The three parts are shown complete with VFP deformation diagrams in Fig 3. Tasks A and B share the same tool of approx 30cm x 30cm which features a flat top surface and recessed corner section, linked by a 30˚ ramp. This creates vertexes of both concave and saddle type curvature. The difference between A and B is that the ply is aligned with the front or back of the tool respectively, creating two entirely different deformation patterns requiring entirely separate forming techniques [4]. Task C is one quarter of an extended double hemisphere shape, featuring natural curvatures which contrast to the angular form of Tasks A and B.

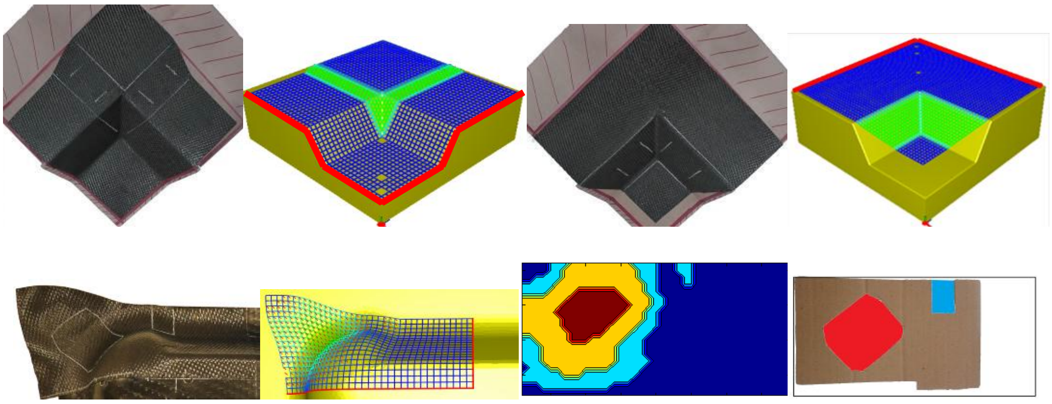

Figure 3: (*Top row*) (*Left*) Finished Task A ply and (*Left middle*) a VFP simulation, (*Right middle*), Finished Task B ply and (*Right*) VFP simulation. *(Key: Blue areas - unsheared, light green - 20˚ shear and Dark red - starting point)*, (*Bottom row*) (*Left*) Task C: Finished ply, (Left middle) VFP diagram showing fibre deformation, (*Right middle*) Shear translated to flat ply with 10˚ contours, (*Right*) an approximate template for drawing shear onto plies.

Three participants also laid up three flat normal undeformed plies onto the tool as is done during the existing 'regular' layup. Presheared plies were then prepared by a third party (the researcher in this case) and then given to the laminators to laminate onto the same tools. All plies were sheared approximately one minute before they were applied to the tool. Each task was completed three times by three different laminators, first with regular and then the presheared plies. All tests were conducted at standard clean room conditions using 2x2 Twill, tow width 2mm with MTM49 resin. The participants were not allowed to use any additional tools or dibbers during the test. The participants were not professional laminators but had some experience of laying up on similar tools. The plies for task A and B were 23cm x 23cm, and 23cm x 11.5cm for task C. Using a technique similar to that used by [4], the video footage was analysed frame by frame to record both the time taken and the total number of uses of each technique per ply using a tally system. The participants were aware of being recorded but not of the criteria being studied.

2.1 Preshearing the plies

The aim of the study is to assess the effect on the layup process of the preshearing, rather than to optimise the preshearing process itself. Suitable manual preshearing processes used during the study are outlined here, and the scope to improve or potentially automated this is currently being investigated by the authors. The VFP outputs in Fig 3 show how the angular shapes of tasks A and B create well defined uniform areas of shear in the prepreg. A Matlab code was generated which took the text VFP output file and created a 2D plan of the deformation based on the shape of original ply, an example of which was shown in fig 3. From this an outline of the shear area can be defined and in this case transferred onto the ply using a paint pen and a template. Although the rectangular shear areas are geometrically ‘simple’ they are not easy to form with a human hand. The prime method for grasping any thin sheet uses the thumb to oppose one or more fingers [6], thus limiting the width across which tension can be applied to the dimensions of a thumb. Creating large areas of shear therefore required many multiple actions, resulting in an inconsistent shear distribution. Based on a shear stiffness test developed by [7] an ‘edge clamping’ technique was developed to enable consistent tension to be applied across the whole width of the sheared area (see Fig 4). Two pairs of aluminium strips were clamped onto the prepreg by hand, and then shear applied by pulling the clamps in the appropriate direction. Task C features natural curves which produce a field of shear (Fig 3), that is non uniform and does not follow straight lines nor is it at the edge of the ply, thus the edge clamping method cannot be used. Instead the shear was approximated into two distinct areas of shear, marked onto the plies and generated by hand, using the tension-tension shearing (TTS) technique defined in Fig 1.

Figure 4: *(Left to right):* The VFP deformation diagram. Preshearing the material using ‘edge clamping’. showing the marked shear area. Presheared ply being applied to task A and already fitting into the tool recess. Presheared ply being applied to task B and already fitting into the tool recess

Both techniques were complicated by the effects of ‘spring back’. When prepreg is deformed and then released, there is a restoring force which causes spring back or ‘unshearing’ [8]. Using techniques from [9] a combination of deforming the prepreg to a greater shear angle than was required and then holding it at its deformed state before release to allow stress enabled the correct shear levels to be achieved. Successful methods to combat spring back are currently being trialled by the authors and will be reported at a later date.

3. Results

3.1 Time

The grey points on Fig 5 show the time spent laying up plies was significantly lower when the ply had been presheared, giving an average 60% time reduction per ply compared to the white point representing regular layup. It is clear from the average 60% time difference in final layup that the remaining layup process has changed dramatically. It would be intuitive to assume that because shear had already been applied to the prepreg the majority of the overall time saving would be gained during forming of the sheared areas. However, it was discovered that approximately equal proportions of time are saved in both sheared and unsheared regions. The reasons for this are explored by looking at the process in more detail in section 3.3. Once the time taken to preshear the material was included (shown as the black symbols on Fig 5), the saving was significantly reduced. If the average for both lamination types is compared, there is a 25% saving. It is intuitive that some increase in speed would naturally occur due to learning curve effects because the regular layup were the first three attempts at the plies, while the presheared plies are the fourth through to sixth attempts. If the presheared times for each participant are compared to the *fastest* respective time for regular layup to negate these effects, then the saving is further reduced to only 10%. Looking individually at the tasks, the time reduction for preshearing tasks A and B remains significant at 20% and 24% respectively. Task C however was actually marginally *slower*, seeing an 8% increase in time. This is possibly due to tasks A and B featuring a more efficient specialised preshearing process, while task C relied on similar techniques to normal layup, highlighting the need for a more optimised preshearing process.

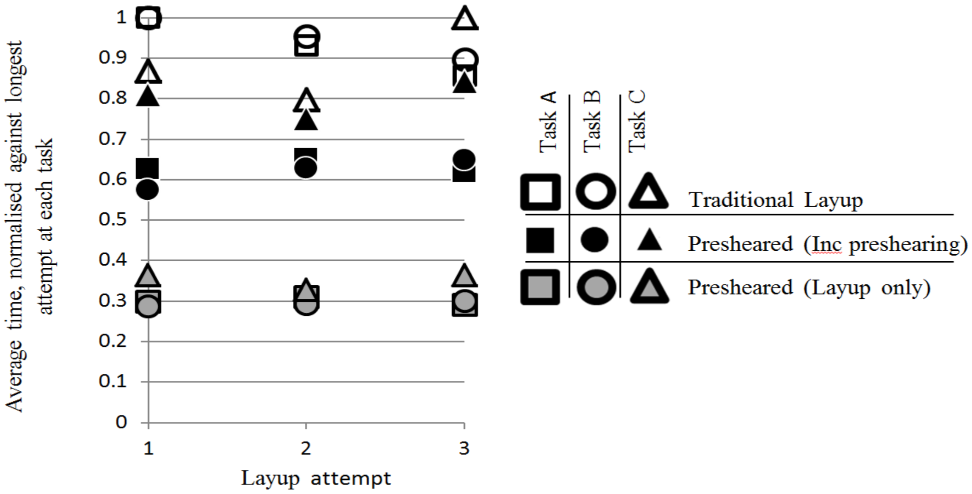

Figure 5: Showing average layup times for each task.

3.2 Quality

Although the time taken for layup is a major factor, the quality of each layup is vitally important [11]. Quality was compared using and approximate visual inspection. The severity and frequency of: missed datum's, wrinkles and bridging were graded from one to five according to their relative severity and frequency. In an industrial application many of the defects even graded as a one would cause the part to be reworked or scrapped [11]. Fig 6 shows that the presheared layups received an average score that was 50% lower than the regular attempts. It must be stressed that it *cannot* be claimed that preshearing will 'increase quality by 50%' because the participants were not professional laminators. Regardless, there is strong evidence that the preshearing of plies helps layup become less prone to defects, especially when using less experienced laminators. To explain the reasons for the decrease in both time taken and defects, the next step was to study the actions of the laminators in detail.

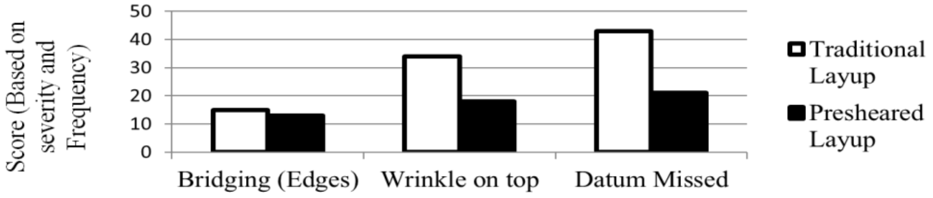

Fig 6: Graph showing the severity and frequency of defects seen in Regular and Presheared layup. A higher scored donates a larger frequency and greater severity of defects.

3.3 Technique usage

There is an average 77% reduction in the use of specialist techniques across all three tools, and when considering only the actions directly associated with generating shear [4] (see fig 1), the reduction is even bigger, at 86%. Looking more closely at the technique usage (fig 7) there are clear differences in the effect of preshear on each task:

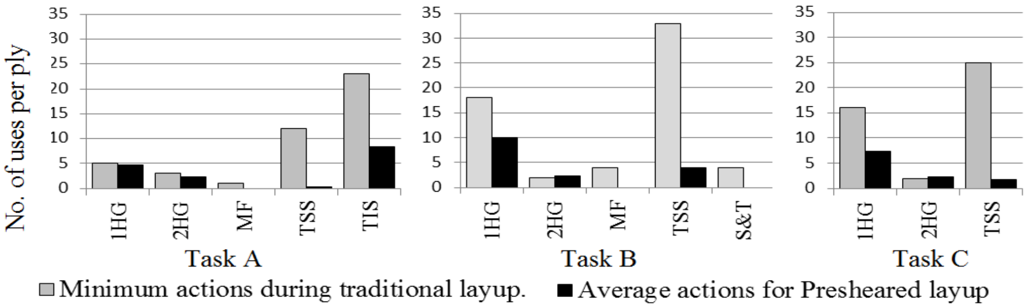

Figure 7: Graph comparing the average number of times special techniques were used during presheared layup against the minimum used during regular layup. (Unused techniques are not shown)

During task A, it is intuitive that if the shear has already been created in the prepreg, then the TSS technique, which is associated by [4] with creating shear mid layup, saw a reduction in use. In addition there was a drop in the use of the ply manipulation techniques such as 'one handed guiding' (1HG) as well as 'manual folding' (MF). This can be explained by looking at the starting points (red lines on fig 3) which are located over a doubly curved concave region. When a flat ply with no shear is placed onto a concave surface, there will be excess material at the edges requiring repeated uses of MF and 1HG to manage and locate the ply. However when a ply a presheared it simultaneously forms the approximate 3D shape of the tool thus it does not need to manipulated or folded, negating the use of many ply manipulation techniques. In contrast G2H is only associated with initially positioning the ply into position, a task which is required regardless of whether the ply is presheared or not, hence its use remains consistent.

Task C also has starting points which cover a doubly curved region of the part. In this case it is a convex region so folding of the material is needed, but during regular layup participants tended to progress across the tool by repeatedly alternating between the aligning the edges of the ply and applying shear elsewhere, resulting in frequent uses of both 1HG and TSS techniques. In the presheared case the majority of the in plane shear and hence out of plane displacement was already in place, so such an iterative approach was not required, hence a smaller number of both techniques was observed. In fact several of the attempts were completed with no uses of TSS or any shearing technique whatsoever.

Task B contrasts with tasks A and C in that the starting datums are located across a region with no curvature in either direction, so the prepreg is initially not required to fold or deform in any way. While the preshearing reduced the usage of the primary shearing technique, Tool interaction shearing (TIS), it is theoretically of little or no advantage while forming the flat undeformed section of the task. However, there was still a reduction in time taken to form the regular sections as well as a reduction in the use of 1HG. This is potentially linked to a reduction in the number of associated defects that are generated, and subsequently fixed during repeated uses of TIS.

4. Impact and application

The trend across all three tasks was a considerable drop in number of techniques applied and several attempts at task C used no grasping actions at all. This is backed up by comments from the participants that lamination had become ‘easy’ or words to that effect. Using both these facts it could be argued that the presheared layup stage is much ‘simpler’ than regular lamination. This opens up a number of opportunities to evolve the layup process.

4.1 Delegation or automation of Preshearing

The regular lamination process is often considered a ‘craft’ [12] relying on the skills and experience of laminators. The preshearing process, which can be reduced to essentially distorting a ply according to a prescribed pattern is certainly closer to being classified as ‘*unskilled labour’* rather than a ‘*craft*’. Thus, the preshearing stage could be carried out by less skilled workers, who may be lower cost and more readily available than *‘master craftsman’* laminators. The presheard plies could then be passed onto the *‘master craftsman’* laminators for final lamination, maintaining the quality standards and traceability associated with regular hand layup, but in a fraction of the time. Taking task C as an example, there may be a need to automate or adapt the preshearing process to fully see the benefits. There is real potential to use existing methods such as press or pin bed [13] forming to automate the preshearing process.

4.2 Achievable automation of the final layup.

The simplification of the final layup process caused by preshearing makes the task of automating considerably more achievable than trying to emulate regular hand lamination directly. Presheared plies could potentially be applied to technologies such as vacuum or stamping forming. Alternatively a single robot arm with a variety of end effectors may be able to complete final layup of simple parts. Work of automation of both the preshearing and final layup stages is currently being carried out by the authors.

4.3 Deformation control

The fibre orientation in a composite component is critical to its strength and stiffness. The process of preforming the plies to a set pattern can provide designers with greater control over the fibre angles of the final ply develops. It has also been demonstrated that intuitive methods for making parts are sometimes not the most efficient in terms of time or structural properties [5, 6]. Systematically applying the deformation beforehand could help to consistently produce the exact deformation patterns specified by the designers.

5. Conclusions

This work demonstrates that dividing layup into separate Preshearing and Final Layup stages has a dramatic effect on the process. The time taken to layup onto the tool is significantly reduced, and far fewer specialist techniques are used in comparison to regular layup. This approach also reduces layup defects, while participants also commented that the process had become 'easy'. With the basic preshearing process developed here, once the time spent preshearing the material is included, the time saving is reduced, but remains significant. Potential industrial applications for preshearing have been identified, but further work is needed to improve the preshearing process to rapidly produce create consistent and accurate plies. The effectiveness of preshearing is likely to vary with different part geometries. For example, a flat or singly curved plate would not benefit, but as parts become more radically doubly curved and require more shear deformation the pre-shearing may have an even bigger effect. Thus, to the next step would be to test the preshearing process on tools of varying severity and complexity in order establish and estimate the true time and cost savings in more detail.

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