Understanding the Lamination Process

M Elkington*, D Bloom, C Ward, A P Chatzimichali, K D Potter
ACCIS, Queens Building, University Walk, University of Bristol, Bristol BS8 1TR
* michael.elkington@bristol.ac.uk

Keywords: Prepreg, Hand Layup, Drape, Ergonomics, Observation, Shear, Technique

1. Abstract

Composites manufacturing is potentially facing an order of magnitude increase in the number of parts to be produced in the next ten years and beyond. Despite the introduction of alternative and automated processes, manual layup remains a crucial and widely used process in the composites industry. However it remains a relatively unknown and certainly undocumented process, which has changed little in the last 30 years. In order to meet increasing demand, composite manufacturing needs to evolve into an optimised, leaner process. To begin this change it is first necessary to build a greater understanding of the existing process. A study is conducted of a variety of operators draping prepreg sheets over a number of representative tasks. Frame by frame analysis of recorded video footage has revealed a set of common techniques used by those laminators. In this paper studies of three representative tasks are demonstrated as examples to highlight the links between layup techniques and specific layup features. This work reveals a systematic approach to layup and is the first step towards building up a knowledge based system to understand lamination.

2. Introduction

2.1 Composite manufacturing

Composites are seeing increased use in a variety of large scale applications, the most high profile being the new Boeing 787 and Airbus A350. The next generation of commercial aircraft are likely to have a much greater composite content. The automotive industry has also shown increased interest in composites for high production volume projects such as the BMW i3 [1]. As a result, both composite production rates and costs will be required to improve by up to an order of magnitude [2].

2.2 What is manual layup?

A large number of composite parts are still made using traditional manual layup. This involves sheets of primarily woven carbon or glass fibres being manipulated into shape over a tool. This is done by highly skilled manual operators using their hands and a collection of simple tools, relying on skills which have changed little over the past three decades. They generally receive a stack of the templated plies for a specific tool, and a manufacturing instruction sheet (MIS). These can contain information on datums start points and orientation, while some give little more than the ply order. From there the correct layup of plies can be left entirely up to the laminators, leading to part variability. This process can be a common source of defects such as wrinkles, bridging and misalignment [3]. Defects such as wrinkles have a significant effect on the strength of finished composite parts, [4] leading to either scrapping or costly and time consuming reworking.

2.3 Why is it so difficult?

The details of the manual layup process have received limited coverage in the traditional literature. To begin to build up an understanding of the process, it is beneficial to briefly look at the basic principles. Surfaces that are flat or have curvature in only one direction, such as a cylinder or flat plate are ‘developable’. These can be formed from a flat sheet with no in-plane deformation. However, to form a flat sheet on a doubly curved surface there does need to be some in-plane deformation [4]. Materials such as thin plastic or metal sheets can be deformed into doubly curved shapes in a vacuum or stamp former. This is possible because they are isotropic and can exhibit significant plastic deformation. However the carbon and glass fibres used in composites provide a more complex problem as their inherent high stiffness and low strain to failure prevent them from deforming in such a manner [5]. Adding cuts known as ‘darts’, or folds into the material can introduce significant structural weaknesses [6]. Fortunately, when the fibres are arranged in a
woven cloth structure, the material as a whole can undergo scissor type in-plane shear. This allows the cloth to deform and ‘stretch’ or ‘contract’ in opposite directions. There are other deformation methods present such as tow slippage, but the majority of deformation is of this scissor type shear [5, 7].

2.4 The material

The woven material used during manual layup is generally pre-impregnated with resin to create ‘prepreg’. The main purpose of prepreg is to closely control the resin content and distribution during the autoclave cure process, ensuring a high fibre volume fraction in the finished part. The added resin also enables prepreg to stick or ‘tack’ onto the tools, holding its shape. However, it adds significant in-plane shear stiffness, requiring the operators to often apply significant forces to create in plane deformation. In addition, the epoxy increases the mass of the woven cloth, causing it to bend more easily under its own weight than dry fabric [8]. Once a section of a woven structure has that tows run through in both warp and weft directions stuck to the tool at any point, it then becomes ‘constrained’. Thus it now only has a single unique pattern of shear deformation that will allow it to fully deform to the tool surface [9]. Predicting the location and severity of this deformation by eye is non-intuitive and can be very difficult for complex shapes. This combination of complex deformation patterns, in-plane shear stiffness and the flexible and tacky material make manual layup a difficult task.

2.5 Meeting the challenge

Fortunately, humans have the dextrous and problem solving capabilities to tackle craftsman like tasks such as composite lamination [10-11]. They can successfully adapt their skills to be able to form a wide variety of complex shapes. However, if the composites industry’s dependence on sheet prepreg layup is to continue, production rates and quality need to increase while simultaneously reducing the cost. Despite the complexity and challenges of manual layup, as far as the authors are aware there is little published work moving towards understanding or optimising this process. There are three potential avenues to improve on the current prepreg layup process; automation, an evolution of the current approach and improvements in training.

2.5.1 Automation

The adaptability and ability to form complex shapes of hand layup has not yet been matched by automated processes. For example, using ‘Automatic fibre placement’ (AFP), which involves laying down individual tapes or fibres there was some success with large geometrically simple parts such as aircraft fuselages. However, AFP cannot be used for the more complex secondary structures such as seats, luggage holders and other interior panels, which make up a large proportion of the cost of an aircraft. Current issues with such systems are highlighted in [12]. For many parts with complex geometry, manual layup remains the most viable and commonly used technique [2].

There have been attempts to build automated processes that involve sheet prepreg. Buckingham and Newell [10] present a robot which could pick up, place and consolidate sheets of prepreg onto a very limited selection of singly curved tool shapes. However, despite being very complementary of the skill and achievements of manual operators, there was very little evidence that during the design process any direct observations were made or inspiration taken from real human operators at work. Another approach was developed using compressed air jets to manipulate the prepreg [16]. To aid the shearing, tension was applied to the prepreg. This is a technique used by manual operators, although they were not directly cited as the inspiration for doing so. Additionally a study by Skordos [17] claims to capture the ‘mechanics of draping’ yet again, no direct reference is made to the specific techniques used by laminators in industrial practice.

2.5.2 Evolution of the current process

The process has remained relatively unchanged for the past few decades, so there may be potential to modify the process to make it quicker to both learn and implement without going to an automated solution. An example of the process evolving is the introduction of simulation programs which can predict the required deformation over any shape. One such program, ‘Virtual Fabric Placement’ (VFP) was developed at Bristol University [9]. It
allows the users to specify both the starting point and how the layup should progress over a tool.  Using kinematics it then calculates the required deformation, which is represented graphically on what will be known as ‘VPF diagrams’, examples of which can be seen in figs. 2-4. Designers can then compare shear deformation angles from the simulation to the maximum capabilities of a material, to gauge if a design is achievable [13].

The deformation prediction provided by VFP was used to enhance the lamination process by defining the order in which features should be laid up [2]. Information from similar programs is put to use in ply projection systems such as [15]. These can import ply deformation data from simulation programs and project the outline of the ply onto the tool surface to assist in lamination.

2.5.3 Improved training

At present there is little documented information about the layup process. As a consequence, experience is generally only being passed down directly from one operator to the next or gained through individual experience. A more informed and systematic training program could go towards producing a greater number of efficient and reliable laminators.

2.7 Studying operators at work.

There are discussions in the literature regarding the need to fully understand how humans approach a task before attempts can be made to optimise or automate it [18-19]. At present, as far the authors are aware sufficient documented knowledge around lamination is not available. An earlier study designed for general tasks used observation of human subjects to construct a taxonomy of grasp choice for common hand tools. Observation of a number of subjects showed strong links between the size, shape and purpose of the tools and the use of specific grasp types, [20]. The present study is working towards doing the same for composite manual layup, in this case replacing the tools with individual layup features.

3 Experimental Method

The aim of this work is to identify the techniques used by operators and establish where and why they are used. To achieve this, a series of lamination tasks were designed to cover the most common features tackled during a regular lamination process. The starting points for each task were defined against a datum line on the tool and the required deformation was predefined and presented to the operators using VFP. The aim was to record how the laminators created a specific deformation pattern in isolation. There were nineteen tasks in total, covering a range of different types and severity of features. But due to space limits in this paper, only results from the three representative tasks, shown in figs. 1-3, will be discussed at length.

Six operators completed each task three times. Among them were two professional laminators who had at least twenty years’ experience of manual layup, but little or no experience with VFP. There were also two novices, who had very limited experience with both prepreg and VFP. The remaining two operators had some experience with manual layup, but were experienced with the VFP program and its outputs. These will be referred to as the ‘intermediate’ operators.

All tools were made from Rakutool type tooling board, and measure approx. 30cm x 30cm. For task A and B there is a ramp feature which forms a recess in the corner of the tool. Task C uses the exact same deformation pattern as task B, but with an inverse tool shape such that the ramp feature protrudes outwards from the tool surface. Novice and intermediate laminators used tools with 45° ramps, while the professionals used steeper 60° ramps. A typical modern manual layup material (2x2 Twill MTM49, tow width 2mm) was chosen for the trials. All tasks used 23cm x 23cm square plies. All tests were conducted in standard clean room conditions.

Participants were given a brief written introduction to lamination and the principles of how a woven cloth can deform to fit over 3D shapes, based on section 2.2-2.4 of this paper. The laminators were told to focus on quality as the primary driver, but be mindful of time. All laminators wore latex gloves, and the professionals were permitted use of laminators tools, generally known as ‘dibbers’. These are made from hard materials such as...
composites, PTFE or plastic, and feature a selection of varying curvatures, shapes and materials. These were all custom made by the individual laminators. The operators work was recorded on a HD camera which was mounted approx. 0.5m above the tool. This allows repeated analysis of the footage, which is crucial for understanding such a complex process.

Any layup attempts which had defects that could be deemed as serious were identified during layup.

An initial frame by frame analysis of the operators performing the lamination tasks was carried out based on methods described in [21]. This revealed over 40 separate actions such as grasping, smoothing and pressing. To make the analysis more manageable, an approach as used by [22] and [23] was adopted. Thus multiple actions were combined into a more general catalogue of ‘techniques’, an example of which is seen in fig 4. Any given technique can be implemented with a variety of different grasps, but the overall purpose of the technique remains largely the same. In this study, the chosen grasping type is not recorded, with only the technique type of interest. In order to establish the specific purpose of each technique, it was crucial to know which features of the tasks they were being used to form.

To enable this, each task was divided up into multiple areas according to features such as change of shear angle, change of curvature (corner), or any other feature which was observed to be separating areas that required different techniques. These areas will be referred to by the task letter followed by the area number, so area 3 on task B will be ‘B3’. The video footage from each task was then visually analysed frame by frame, using a tally sheet to record every time each technique was used in the different areas. The first two attempts by operators were regarded as ‘training’, a technique also used by [26], and so the analysis is focused on the third and final attempts. The analysis was carried out by a single analyst and the process was validated by a second analyst, showing a repeatable accuracy of approximately 10%.

5 Results

5.1 Universal techniques

The analysis confirms that there are trends for using certain techniques in specific areas of the tasks. Here each technique will be introduced in the context of areas where they are applied, to help explain the reasons for their use. However, there were several techniques which saw use in many similar areas across all of the tools. Figure 5 shows ‘Guiding with two hands’ (G2H) a technique used by all laminators to initially position the ply on the tool.

The G2H technique was used in 70% of areas which feature a starting point such as A1, B1 and C1. This was often followed or replaced by ‘One handed guiding’ (1HG) technique as seen in fig. 6 which was used frequently to align prepreg starting points.

The true complexity of lamination was only revealed when looking at the features in and around areas where the prepreg was to be sheared. Other techniques were only observed as being used frequently in specific features.

5.2 Task A

The segregation of task A into different areas can be seen in fig. 7. The task starts against a datum running along the front edge of the tool and the ply is then draped up the ramp and onto the top tool surface. Figure 7 shows how prepreg was aligned in area A1 using both G2H and 1HG. The laminators then used 1HG again to align A2 and A3, which form the edges of the concave region. As a result of forming a concave section, an in-plane excess of material was created in the area that would eventually become A4. Eventually this excess material was taken up by shear, but during initial forming, it caused the material to starting folding out of plane. Some laminators chose to control and assist this during forming of sections A2 and A3 by actively creating these folds using techniques such as seen in fig. 8.

Once the areas A1-3 were formed, the next challenge was to form section A4 which features shear of 20°. Accordingly, extra techniques were required such as ‘Tension Secured Shearing’ (TSS) as described in fig. 9. TSS was used on average over 4 times per ply in these areas, and saw use by all six laminators. Some laminators applied the tension over 5 or more seconds, allowing a large deformation of the prepreg from a single action.
Others applied tension for a much shorter period, requiring many repetitions to achieve the same effect. During this task, there were several occurrences of TSS which caused areas A2, A3, A5 and A9 to come unstuck from the tool surface, requiring them to be realigned using 1HG.

Figure 7 also shows that the intermediate and professional laminators, used an additional technique for areas A4, A6 and A8, involving a combination of applying Smoothing and Tension (S&T) at the same time, as described in fig. 10. This technique appears very similar to TSS but the subtle difference is that the securing hand is mobile, and being used to smooth and stick down new areas of prepreg. The applied tension helps the prepreg to shear rather than to wrinkle as it is stuck down.

Laminators then went on to areas A5 and A9, which have not shear, and, like A1, generally only required the use of 1HG to align them to a starting point. Next up were areas A6 and A8 which both contain shear. These were formed with a similar mix of TSS and S&T techniques as A4. Figure 1 explains why shear occurs in areas such as A4 A6 or A8. In all three areas, each successive tow being consolidated has some excess or length ‘slack’, which needs to ‘pulled’ out. Hence tension is applied to the prepreg via TSS or S&T. The consistency in techniques suggests that if similar ‘excess’ occurs in another task, that TSS and S&T would be the likely technique. One of the novice laminators used both the techniques nearly 20 times in areas A5, A9 and A7. Considering that all professionals and intermediates combined only used the techniques 3 times in total, it could be concluded that the novice was using an inappropriate technique.

5.3 Task B

The segregation of task B can be seen in fig. 12. Task B uses the same tool as task A, but starts from the back of the tool, creating a very different deformation pattern. It only generates two sheared areas, (B3 and B2) which have the same 20° shear angle as areas A4, A6 and A8. However, it was observed that a completely different set of techniques were being used on the different tasks. This is due to a subtle difference in the way the shear forms. Figure 11 shows how in contrast to A8, the prepreg in B2 must now shear away from the edge, making applying tension difficult or impossible. This required a different approach, known as ‘Tool interaction shearing’ (TIS), which can be seen in fig. 13. Figure 12 shows how TIS was the only technique used by the operators in the sheared B3 and B2 areas.

Laminators generally formed these areas in small sections, requiring a large number of repeated actions. Achieving the last few degrees of shear with TIS involves the material contacting the tool, which naturally lead to the process of sticking the prepreg to the tool surface. Unless the prepreg was firmly stuck to the tool after it had been sheared, the viscoelastic nature of the resin caused it to ‘spring back’. This caused prepreg to come unstuck from the tool, and undid some of the applied shear, requiring repeated actions to achieve the correct shear.

TIS relies on the prepreg being securely stuck in the surrounding area so that it can react the tension in the prepreg (see fig. 13). During task B area B1 provides an area of prepreg to secure the tension. However, if this area was particularly small, it might not be able to sufficiently react the force, allowing prepreg to slip across the surface. The professionals paid extra attention to make sure the surrounding areas were firmly stuck to the tool and most used some kind of out of plane pressure to help secure the prepreg during TIS. Some of the other operators did not, and as a result, let the ply slip across the surface, requiring time consuming reworking to restore the correct alignment of the ply.

Both novices and one of the professionals used small amounts of TSS as described in fig. 9. The prepreg needed to be pulled towards, or ‘into’, the tool surface hence there is very limited access to areas where tension would need to be applied, making TSS very difficult to use. One of the professionals used the Tension-Tension Shearing (TTS) which is introduced in fig. 14, and described further in the context of task C, where it was used more frequently.

5.4 Task C
The ply is exactly the same shape and deformation as task B, but with an inverted tool shape, so the feature now protrudes outwards from the tool datum surface. Figure 15 shows how it is segregated. Because the VFP deformation prediction for is the same as in task B, it was expected that the techniques would also the same. But this did not prove to be the case. Figure 15 shows how in contrast to task 2, a variety of alternative shearing techniques were used in addition to TIS.

This diversification of techniques is caused by the inverse tool shape. Because the sheared areas in task B (B2 and B3) are recessed into the tool, the entirety of area B1 can be firmly stuck down prior to any shear being formed. This can provide a secure anchor region for using TIS to form B2 and B3. However, on task C, this cannot be achieved. Because the features over which the shear forms protrude upwards from the tool surface, areas C2 and C3 cannot be stuck down without areas C4 and C5 already being sheared. However C4 and C5 cannot be sheared using TIS without C2 and C3 acting as anchor regions, necessitating the use of alternative techniques.

Some operators overcame this by using an incremental approach, sequentially securing small sections of areas C2 and C3, then using TIS to form small sections of C4 and C5. Another approach was to initially use TTS (fig. 14) to create some of the required shear. The inverse shape of the tool in task C makes areas C4 and C5 much more accessible than the respective areas B2 and B3, enabling easier use of TTS. Once some of the required shear had been formed, it allowed larger portions of A2 and A3 to be stuck down, and form an anchor for using TIS. Others used TSS to apply the shear near the edge of the cloth. There is no identifiable trend in the approach taken the different experience laminators.

6 Global and Local approaches

One notable anomaly on task C which can be seen in fig. 15 is that area C6 received a number of uses of TSS and TTS despite there being no required shear in that region. The usage was much more frequent than similar areas such as B4 and A6 which, if the likely erroneous work of the novice operator is ignored, only received two applications of any technique. This is likely to be a consequence of using TTS. During its use the area of prepreg being sheared has no direct contact with the tool. This means it is hard to relate the current state of shear to that which is required to fit onto the tool. As a result, both the shear angle and the exact area being sheared are hard to control and some shear was inevitably formed in sections such as C6. The TSS used in C6 was therefore used to correct or “unshear” the deformation that was accidentally applied during the earlier application of TTS.

In contrast, the S&T technique is carried out close to, or on the tool surface, thus the deformed shape of the prepreg can be directly compared to the tool surface, allowing the operators to better judge when the required shear has been achieved. TSS is a compromise of the two, allowing some feedback, as the tows often become taut when the material is correctly sheared. The only significant difference between laminators was that novice laminators did not use the closely controlled S&T technique.

The use of techniques such as TTS and TSS may be encouraged by having the deformation clearly mapped out by VFP reports. On these particularly geometric tools, the areas of shear are clearly defined. Hence it is possible to identify and then shear areas such as A4, A6 and A8 well ahead of the stuck material, promoting a ‘global’ type approach. On a more naturally shaped or complex tool, or in the absence of a VFP report the global approaches may not be quite as applicable. Operators will have to use more ‘local’ techniques, relying more heavily on intuition and feedback methods to ensure the correct shear.

7 Smoothing and the use of ‘Dibbers’

For all techniques other than T&S and TIS, once the correct shear has been formed, the prepreg still needed to be stuck to the tool surface. This was achieved mostly by using the pad of the thumbs and fingers to press the prepreg onto the tool surface. These pads are soft, and can deform around shapes such as the external corners of the tools. Some of the laminators, especially the novices, struggled with the prepreg sticking more effectively to their gloves than to the tool. Epoxy from the prepreg was visibly transferred onto the gloves making them too tacky to work with, prompting operators to make regular glove changes.
The tools used for Task A and B feature a concave corner of radius 3mm on the internal corners. Novice and intermediate operators used a combination of the tip and nails of the fingers or thumbs to push prepreg into the tight radii as seen in fig. 16. This frequently caused gloves to break as the fingers nails cut through the latex material.

Professional operators avoided this problem by using dibber tools, such as can be seen in fig. 16. For these mostly geometric shapes, the dibber of choice for both operators was a rectangular shape made of PTFE, which can be seen in use in fig. 16. The use of dibbers, especially those made from PTFE is controversial, with some workplaces banning or limiting their use [25]. The tips of these tools can have a tip much narrower than a finger, allowing both increased pressure, and better access to tight internal corners. Hard materials such as plastics and especially Teflon offer a much lower coefficient of friction than the latex gloves worn by laminators, and more importantly the tool surface itself. This allows operators to put significant through thickness force into the prepreg while sliding the dibber across the prepreg without risking the prepreg slipping off the tool surface. This appears to allow more effective sticking of the prepreg to the tool surface, resulting in reduced slippage of the plies.

A more subtle technique which is no doubt brought in from previous experience is how the smoothing progresses across the entire tool. Consider sticking a long strip of sticky tape, most would always start at one end and then along to the other. Starting in two separate places would lead to the tape being either too loose, producing wrinkles, or being too tight, not allowing it to reach into corners or recesses. The operators instinctively treated prepreg in same way, starting from the edges aligned to a starting point and working across the prepreg to avoid sticking the same tow in two places.

8 Conclusions

In this paper three potential avenues for developing the existing manufacturing process were identified, and the current work has laid the foundations to start work in these areas. Whilst these three tools cover the basic techniques of lamination, there are features on the remaining unreported tools such as the variation of corner radii or shear angle which are not covered in this paper. The remaining video footage will be further utilised to analyse the remaining tools and move towards building up a more complete picture of lamination.

8.1 Improve training

Once the study has been extended is will be possible to predict which techniques should be used for the majority of features on any tool. This could be used to give a step by step method for any given layup, specifying the location and order in which techniques should be used. This could allow less experienced operators to produce parts which would currently require many years of practise and embedded knowledge to be able to tackle in an efficient manner. This could help to reduce production time and defect production on early parts. It cause allow improved repeatability between laminators, potentially allowing multiple laminators to work on a single part.

8.2 Automation

This catalogue of techniques may provide designers with a starting point to inform the detailed requirements for any attempt at automating aspects of broadsheet prepreg layup. Once suitable hardware has been developed the step by step instructions could also be used as the basis for controlling and programming an automated system.

8.3 Evolution of the current process

It can also begin to provide a new level of detail for the ‘Design for Manufacture’ process. The work has shown how different features require specific techniques, and it is likely that the associated difficulty also differs between features. The collected video footage could be further analysed to investigate the relative difficulty of different layup features. This knowledge could be made into guidelines which, when combined with deformation simulation software would allow designers to avoid creating particularly difficult features, resulting in parts that are faster and cheaper to make.

The work has begun to build up an understanding of the lamination process. Firstly it is has shown that the majority of lamination can be completed with a ‘tool kit’ of just seven techniques, most of which may have been developed from existing skills, and
are used by novices and professionals alike. Secondly it has then been shown that there are consistent links between specific layup features and the techniques used to form them. Features which had similar techniques applied to them generally had similar shear deformations and shapes. In doing so it has been shown that the ‘skill’ of the laminator can be understood and rationalised to some degree, leading to the possibility of being able to ‘predict’ techniques based on a feature’s properties. However, for some features, it was observed that a variety of techniques were used, sometimes sequentially, showing that there is also scope for using a number of alternative approaches.

Acknowledgements

The authors gratefully acknowledge the support of the EPSRC through the ACCIS Doctoral Training Centre (Grant: EP/G036772/1) and the EPSRC Centre for Innovative Manufacturing in Composites (CIMComp) (Grant: EP/IO33513/1).

References

1. BMW, “BMW i3 Concept”. Available at (http://www.bmw-i.co.uk/en_gb/bmw-i3) Accessed 26/04/2013 2013
25. Correspondence with professional laminators, On 16/10/1987

Fig 1: VFP diagram of Task A. (from left to right) Starting from a datum at the front of the tool and moving up out of the lower region.

Fig 2: VFP diagram of Task B. (from left to right) Starting at the back of the tool and moving down into the lower region of the tool.

Fig 3: VFP diagram of Task C. (from left to right) The shape and deformation as in task B Error! Reference source not found., but with an inverted tool shape, giving a raised, rather than lowered feature.

Fig 4: Showing examples of an individual grasp (top left), pressure (top right) and a technique (bottom).

Fig 5: Guiding with two hands (G2H). Two hands are used to guide and support the prepreg into position, and often to apply the pressure for the initial sticking on to the tool. Seen here forming area B1. From left to right: Free prepreg, Aligning the prepreg with both hands while using the thumb to support the remaining prepreg, Stuck prepreg.
**Fig 6: One handed Aligning, (1HG).** Prepreg is placed in an approximate position at one point on the datum and then held in place by one hand via a through-thickness force. The second hand grasps the prepreg and is used to align the edge of Prepreg with a datum, pivoting around where the other hand has secured the prepreg. A slight tension is applied to remove folds in the cloth, but it is low enough to not directly shear the cloth. *Seen here forming area 2 of task 1. From left to right: Free prepreg, securing and aligning the prepreg, Stuck prepreg.*

**Fig 7:** (top) Task A divided up into separate areas, (bottom), Techniques used by professional and intermediate laminators.

**Fig 8: Manually Folding material (MF).** The material is actively folded out of plane, to allow layup in concave regions. *Seen here helping to form areas A1, A2 and A3. From left to right: Prepreg sheet free to move, Initial folding, and Folding using the finger to allow a datum to be aligned.*

**Fig 9: Tension Secured shearing (TSS)** One hand grasps the prepreg and applies tension to stretch the prepreg, causing it to shear. In order to prevent the prepreg coming unstuck from the tool, the second hand is used to apply an out of plane pressure on the prepreg. This generates increased friction against the tool, which reacts against the tension force. The tension is generally applied in the direction along a line running between the two ends of a sheared area that will stretch furthest apart, as shown in the schematic below. *Seen here forming area A4. Clockwise from top left: Unsheared prepreg, Securing and grasping, applying tension and showing the shear deformation, Sheared prepreg.*
**Fig 10: Smoothing with tension (S&T)** One hand is used to apply tension directly to the prepreg, while the other hand has the combined role of securing the prepreg to prevent it slipping while also moving across the material to help smooth and stick it to the tool. *Seen here forming area A6. From left to right: Unsheared prepreg, grasping and pressing on the prepreg. Tension applied while other hand (shown here using a dibber tool) moves along surface, Sheared and stuck region of prepreg.*

**Fig 11: Showing the difference between areas of shear that initially appear very similar. Left:** As task A reaches area A6 the current tow (black) has had a longer path from the datum than the preceding tows (white) because of the recessed region and ramp. Hence the prepreg shears away from the datum. **Right:** As task B reaches area B2, the opposite effect is seen, as the current (black) tow has the shorter path, and the preceding (white) tow has the longer path down through the recessed ramp. Hence the prepreg has to shear back towards the datum to allow for the difference in path length.

**Fig 12:** (top) Task B divided up into separate areas, (bottom), Techniques used by professional and intermediate laminators.
The 19th INTERNATIONAL CONFERENCE ON COMPOSITE MATERIALS

Fig 13: Tool interaction shear forming (TIS) Shear is created pressing the material into recesses in the tool shape. The prepreg is working like a beam fixed at both ends, so the out of plane force creates in plane tension, causing the prepreg to shear, allowing it to deform into the recess. This technique requires the prepreg to be firmly secured in the bordering regions. Seen here forming area 2 and 3 of task 2. Clockwise from top left: Unsheared prepreg, Pressing on the prepreg, contact made with the tool surface, Sheared prepreg.

Fig 14: Tension-Tension Shear forming (TTS). Both hands grasp the material, and pull in opposing directions, causing it to stretch. Seen here in use on areas C4 and C5. Clockwise from top left: Unsheared prepreg, Grasping the prepreg with both hands, Applying tension, Sheared prepreg.

Fig 15: (top) Task C divided up into separate areas, (bottom), Techniques used by professional and intermediate laminators.

Fig 16: Clockwise from top left: Example dibbers, Dibber in use, Using the finger and nail to consolidate an internal corner, Using the pad of a thumb to stick prepreg to the tool surface.