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AUTOMATED LAYUP OF SHEET PREPREGS ON COMPLEX MOULDS

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Abstract

A new two-stage method for the automated manufacture of high performance composites components is presented which aims to combine the capacity for forming complex shapes of Hand Layup with the speed of existing automated systems. In the first stage of the new process plies are formed into the approximate shape of the mould using a press mechanism. They are then passed onto a layup stage which uses multiple end effectors controlled by a six axis robot to stick the plies down onto the mould. This is the first time an automated process has been capable of forming sheets of woven prepreg onto truly complex moulds while maintaining a high level of fibre alignment. This work represents a condensed version of the second half of the thesis by the author entitled ‘The evolution and automation of sheet prepreg layup’.

1. INTRODUCTION:

The use of composites in engineering is expanding rapidly. Previously only used in small scale, performance driven industries such Formula 1 racing or military aircraft, they are now crossing over high volume cost driven markets such as the civilian aerospace and automotive industries [1][2]. This shift in applications brings with it very large demands on manufacturing processes [3]. The main difficulty in manufacture of composites stems from the challenge of turning a flat fibrous material which cannot deform plastically along the length of the fibres into doubly curved shapes, while maintaining the fibre straightness and alignment required for structural performance [4]. Alternative high volume manufacturing methods such as that used to make the BMW i3 which have achieved high rates, but at the expense of fibre straightness and performance [5]. For this automotive application such a compromise was still cost effective, but more performance critical applications such as aerospace require much more aligned and hence structurally efficient fibres. Other technologies such a diaphragm forming or hot drape forming have been shown to suffer from severe wrinkling as geometries become more doubly curved. This is primarily related to the inter-ply friction, which causes plies to wrinkle rather than deform in-plane when they are shaped onto the mould [6]. The only way to avoid this effect is to construct the laminate layer by layer, ensuring each layer is free from wrinkles [4].

For the production of the highest quality doubly curved prepregs components, there are only two commercially viable options, either Hand layup or automated methods such as Automated Fibre Placement (AFP) or Automated Tape Laying (ATL). Both these automated methods use a layer by layer approach but they are two very different processes with contrasting capabilities and limitations. Hand layup, which has been used for over 30 years, involves manipulating entire plies of composite material into shape by hand [7]. In contrast AFP and ATL involve thin tapes of composite material being laid onto a mould using a robotic system. For a detailed history of tape laying technologies see the recent review paper by Lukasewicz [8].

Before reviewing these processes in detail it is worth defining what ‘complexity’ means in the context of composites manufacturing. Features such as double curvature, tight corners and steep ramps or gradients are just some of the features which make a part ‘complex’. Thus an example of a ‘simple’ part might be a wing skin, which although large, is relatively flat. An example of a typical ‘complex part’ is the mould shown in Figure 1 which features a raised U-shaped section surrounded by ramps. This geometry was chosen as a target product for this study as it has been used in previous layup studies as a reference point for hand layup [9] and will be referred to from here on as the ‘U-shaped panel’. Hand layup is ideal for making such complex parts, but the production rate is very limited and can only be increased by linearly scaling every aspect of the production facility [10]. AFP can potentially offer much higher layup rates, but it has limitations on the complexity of the components it can produce [8]. The aim of this work was to try to develop an automated layup process which could combine the speed of AFP with the capability for complex parts of hand layup, an attribute which is likely to become increasingly important as designers look to further reduce weight by integrating fixtures and fittings into new parts [11]. Instead of trying to add additional capability to an existing automated system, it was decided to first look into the traditional hand layup process to understand and then harness the mechanisms behind the production of such complex shapes.

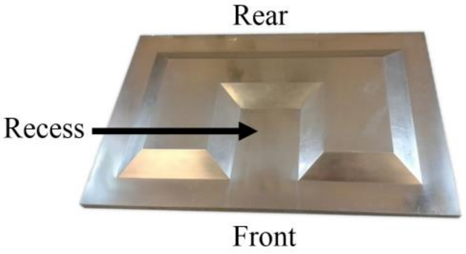

Figure 1 – Mould for the U-shaped panel

2. HAND LAYUP

In the absence of any suitable detailed literature, an in-depth study of hand layup was carried out by the author and is published separately [7]. The key focus was on how the laminators actually create in-plane deformation in the plies. Doubly curved shapes are typically ‘undevelopable’, such that a flat sheet cannot be wrapped around the shape without being folded or sliced [12]. However, woven prepreg can exhibit large in-plane deformation via ‘trellis’ shear which enables it to be formed over normally ‘undevelopable’ doubly curved shapes. In hand layup the laminators manually applied this shear to the woven prepreg in localised regions, typically 1-10cm^2 at a time. For shear angles up to 5°, this shear was created automatically by the compressive in-plane forces generated as the ply was smoothed out. For higher shear angles, the laminators created shear by directly applying in-plane tension to the ply using a variety of techniques depending on the mould shape, direction of tension required and other factors.

Once an area had been appropriately sheared, it was adhered to the mould surface and then the shearing of the neighbouring areas began. This iterative area by area approach makes layup especially complicated. Firstly it means that the laminators are constantly having to assess if each area of the ply needs shearing, and then deciding on the direction and amount of shear and then applying the shear using multiple actions. Secondly, as small regions of the ply are sheared, the surrounding regions can begin to fold or wrinkle because of the discontinuity in in-plane strain across the ply. This folding of the prepreg had to be carefully managed by the laminators to prevent unwanted contact between the ply and previous plies or with itself, which can be difficult to undo due to the high tack of the material.

2.1. Difficulties of automation

It is tackling these two challenges simultaneously that makes automation of layup particularly difficult, and most previous attempts have very limited capabilities. For example Newell [13] and Molfino [14] both created systems which used four robotic arms to grasp corners of the plies and lower it into or around a mould, with potential to create some simple shear defamation in the material. Crucially these both relied on the ply being in a predefined location when first picked up and all the manipulations being carried out using only the initial grasping locations. However it was seen that the human laminators used a multitude of different grasps and actions required *during* layup to form prepreg over complex parts. Automating this would involve the robotic system navigating around a potentially folded cloth to find specific locations, which may change each time a ply is laid up. One application where the understanding and handling of folded sheets is being studied is that looking at the automated laundry folding industry. Work at Berkeley has been successful in this, but the rates are still vastly slower than a human at present [15]. Add to this that prepreg material carries the added complexity of being tacky and non-linear which makes it difficult to handle, and also being black and shiny which make computer vision difficult, and the concept of replicating hand layup directly using a bio-mimetic system appeared to be an unlikely source of success.

3. INTRODUCING PRESHEARING

The next step was to investigate hand layup further and modify the process to see if it could be 'simplified' in some way to make automation a more viable option. A new approach to layup called 'preshearing' was trialled. Instead of iteratively shearing small areas of prepreg during layup, all the deformation was put into the cloth *prior* to layup. A study on the effects of this process was completed by the author and is published separately [16] but will be summarised here. It was shown that preshearing the plies made the layup onto the mould much faster and in the words of the participants, 'easy'. They found that when using presheared plies, the use of techniques to directly apply tension to the prepreg was dramatically reduced or in some cases completely removed. This approach took what was a single complex process and converted it into two much simpler processes. Such a simplification made the previously ruled out possibility of automation worth revisiting, and this paper describes the automated solution developed as a result of these findings.

4. AUTOMATION: PRESHEARING

The objective of the preshearing stage is to take a flat ply and form all of the required out-of-plane and crucially *in-plane* deformation. As described previously in section 2, applying shearing in an iterative manner using some combination of robotic arms is very difficult. Instead it was decided to use a press type mechanism (shown in Figure 2) to form the ply into the approximate shape of the part in a single motion, thereby also creating the approximate in-plane shear at the same time. It is crucial to acknowledge that this press is *not* required to apply a through thickness force to stick down the prepreg onto any mould surface. Therefore it does not need to be as rigid, precise or hard wearing as a traditional press mould and therefore could well be made much more cheaply than many current press systems. The shape of the mould is formed of a 'skeleton' type structure, to minimise the contact with the resin to avoid as much contamination and transfer as possible. This skeleton, made here from 6mm MDF wood, highlights how lightweight and inexpensive such a press could be.

Observation of previous studies using presses or stamp forming showed that the use of blank holders to prevent wrinkling is crucial [17]. It was decided therefore to use spring loaded blank holders around the perimeter of the press to apply through thickness compression to the ply such that as the press is closed, the prepreg slips through the blank holders and friction will create the required *in-plane* tension. The blank holders were segmented into individual spring loaded elements to allow the creation of in-plane tension to be controlled via the spring compression to create preferential slip on one or more sides of the ply as explored further in section 6.1.3. Areas designated to slip had a low clamping force and areas where slip should be prevented had a much higher clamping force.

4.1. Combating ‘Spring-back’

One issue encountered during the preshearing study was the ‘un-doing’ of applied preshear after tension has been released. In hand layup once a portion of a ply has been sheared it is subsequently adhered to the mould, thereby securing the deformation. In preshearing this is not the case, and the viscoelastic nature of the epoxy can cause the applied deformation to undo or ‘spring-back’. The viscoelastic properties of epoxy resin are greatly affected by deformation rate, temperature, and other factors [18]. A study was completed by the author to assess the relative effects of these factors on the prepreg and the conclusion was that slow deformation rates and long relaxation times did not reduce spring back enough. The only effective method to minimise spring back was to heat the prepreg. A temperature of 40^{o}C was shown to be adequate to create sustainable shear at angles up to 15^{o}, but increased temperatures of up to 70^{o}C were required to sustain higher shear angles. The raised temperature was achieved in the press by a flow of hot air from a heat gun combined with a close fitting surround to hold the warm air inside the press. Figure 2 shows the finished press, along with a fully presheared ply, which has the approximate shape and deformation of the finished part. To ‘finish’ a ply it needs to be adhered to the mould, and this is tackled by an entirely separate process which is outlined in section 5.

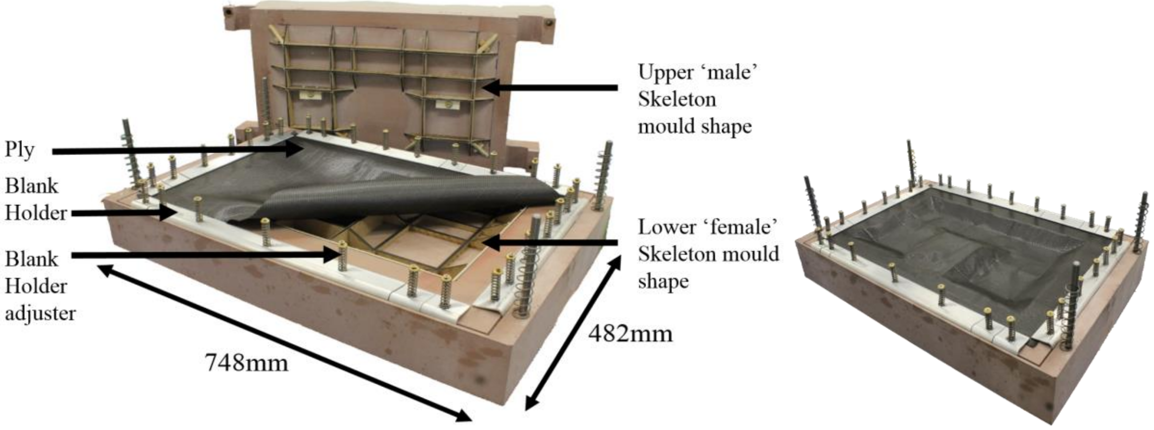

Figure 2: (Left) Preshearing press, shown with a ply peeled back to expose the skeleton mould shape, (Right) a presheared ply in the press.

5. AUTOMATION: FINAL LAYUP

Preshearing produces plies which have the approximate shape and in-plane deformation of the finished part but still need to be adhered to the mould. In section 2 it was identified that the only current way of achieving quality, wrinkle free laminates was to lay plies one at a time and stick them down progressively. The seemingly ‘simplest’ option would be to use a press type mechanism to complete the final layup, but this has several inherent problems. The quality of the contact between the epoxy resin and mould surface is highly dependent on the applied pressure [19]. In order to apply equal pressure to the whole ply using a traditional ‘rigid’ press such as used in metallic stamp forming, different moulds would be needed for every sequential ply as the laminate thickness builds up and this would be prohibitively expensive.

The second major challenge of using a press is that it gives very little control over the 'order' in which areas of the ply are adhered to the mould surface. This is particularly important because the prepreg on prepreg friction coefficient is very high, which makes interplay sliding during layup very difficult. An example of why this can be very important is illustrated in Figure 5. Using a press it is likely that when stamp forming the U-shaped mould shown in Figure 1 the raised ridge section (labelled A in Figure 5) would be adhered to the mould first. Unfortunately this would lead to tows running across the *recess* (area B) being adhered to the mould in *two* separate areas. Thus the free length of the tows between these already adhered sections which is available to form into the recess will likely be too short, leading to either bridging, or excessive tension causing the previous plies to be become distorted.

To prevent situations like these, the order of layup needs to be carefully controlled, something which hand layup can do very well, but will be very difficult with a press. Because of these drawbacks, it was chosen to use an alternative, more adaptable approach to layup, inspired by the techniques of human laminators.

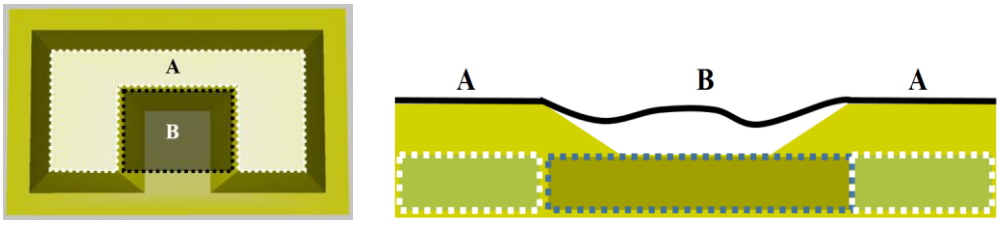

Figure 3 : An example of how sticking down a whole region containing similar features, in this case *flat*, could cause double constraint. Key: **A** = Region adhered to the mould surface, **B** = Area where tows are now doubly constrained.

5.1. Multiple end effectors

It has previously been observed [20] that laminators used their hands in many different configurations alongside numerous additional tools to adapt to different mould features such as tight internal radii. The key shortcoming of AFP is that its inherent 'one size fits all' approach, using a single cylindrical end effector limits its ability to layup many features. It is limited to a single end effector because it is integrated into the material feed. In the new system, the end effector is completely separate from the material, allowing it to theoretically be any shape and size and more importantly, allowing there to be multiple different versions. This approach was adopted in the development of a layup system, and a range of different end effectors were developed to tackle the features seen on the U-shaped panel shown in Figure 1. The system was based around an ABB IRB 140 6-axis robot, typically used for pick and place operations with a maximum carrying weight of 6kg [21].

For the U-shaped panel, there are a number of different mould features which required different end effectors. Presented in this paper are the three end effectors which between them were capable of tackling the entire U-shaped panel. They are pictured in Figure 3 introduced individually in sections 5.1.1 - 5.1.3, and their capabilities are summarised in Table 1. For simplicity during layup, all three end effectors were mounted to the same attachment on the end of robot. To switch between them, the head of the robot would simply re-orientate, allowing rapid changeovers. If a larger range of end effectors was required, carrying them all on the same head may be inconvenient, and an interchangeable end effector attachment system could be implemented.

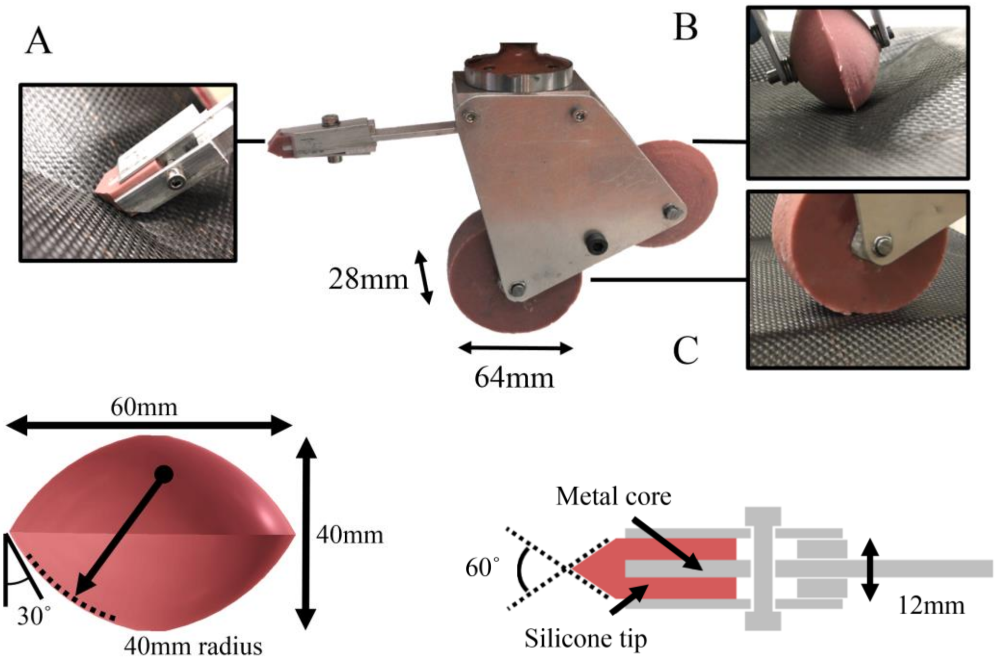

Figure 4 (A) Silicone ‘wedge’ end effector, ideal for tight double curvature internal corners. (B) ‘Profiled’ roller for single curvature internal corners. (C) Cylindrical roller for Flat, convex and lightly concave surfaces.

5.1.1. Cylindrical end effector

It was highlighted in section 5.1 that existing AFP systems equipped with a cylindrical rollers were sufficiently capable on flat, convex and mildly concave surfaces. Even the most ‘complex’ moulds will still likely feature large regions which a cylinder would easily be capable of. Therefore it was decided to include a cylindrical roller as one of the end effectors. It was chosen to construct the roller from a compliant silicone material, in this case M242 silicone manufactured by ACC silicones [22]. This enables the roller to use its inherent compliance to form around convex and mildly concave features. This end effector was actually used to stick down the majority of the area of the plies, but it struggled in other areas, and this is where the additional end effectors were required.

5.1.2. Profiled end effector

The key areas in which cylindrical end effectors have been shown to be ineffective are concave internal corners [24]. In manual layup it was observed that laminators used hard plastic or composite tools to apply localised high pressure into tight internal corners. Trials using ‘rigid’ type end effectors which ‘slid’ cross the surface were unsuccessful. Firstly the sliding caused prepreg to distort, and the highly localised pressure only created resin-mould contact in a small region of the ply. To overcome these issues, a new type of roller was designed which featured a ‘profiled’ shape and this can be seen in Figure 3. Made from M242 silicone its shape is that of a sphere with a slice taken out the middle and sides re-joined, such that it forms a sharp ridge at the outermost point which allows it to apply pressure into tight internal corners. The width of the roller is a compromise between being narrow enough to fit into tight corners of moulds, while also being wide enough near the tip to maintain lateral stability under load.

5.1.3. ‘Wedge’ end effector

For tackling tight concave *double* curvature, a third end effector was required. This design, shown in Figure 3 consists of a silicone wedge, reinforced internally by a 4mm aluminium plate. This hybrid of rigid and compliant elements was designed to provide a compromise between the localised high pressure available with a rigid dibber and a more distributed pressure provided by compliant end effectors. The layup storyboard in Figure 7 shows the ‘wedge’ in action in stages F to I. It enables a 15mm section to be adhered to the mould at one time, which negates the need for sliding along the prepreg surface, thus avoiding the possibility of creating distortion in the reinforcement.

Table 1: End effector capabilities: **3** = Recommended for these features, **2** = Capable, but may be limited or slow, **1**= Possible but not recommended, **0** = will not work.

	Flat	**Single curvature**				**Double curvature**					
		Convex		**Concave**		**Convex**		**Concave**		**Saddle**	
Radius		*Open*	*Tight*	*Open*	*Tight*	*Open*	*Tight*	*Open*	*Tight*	*Open*	*Tight*
Cylinder	3	3	3	1	0	3	3	1	0	1	0
Profile	2	2	2	3	3	2	2	3	1	3	2
Wedge	1	1	1	1	2	1	1	2	3	1	3

5.2. Layup order

It was previously discussed in section 5 that it is crucially important to stick down the different areas of the prepreg in the right order, depending on both the mould geometry and fibre orientation. To achieve this, layup tasks were divided up into discrete areas that only contain geometries which can all be adhered to the mould using a single end effector. Additionally the separate areas must tessellate together so they can be completed sequentially without sticking down any tows in two separate locations. Figure 6 shows an example of a simple component which has been divided up into different layup steps. The colour coding shows which end effector was required for each section of the mould. There are many different combinations of areas and orders which could have been used and the chosen order shown here may not be the ‘optimum’ possible solution which would likely be the one which minimises the number of required end effector switches.

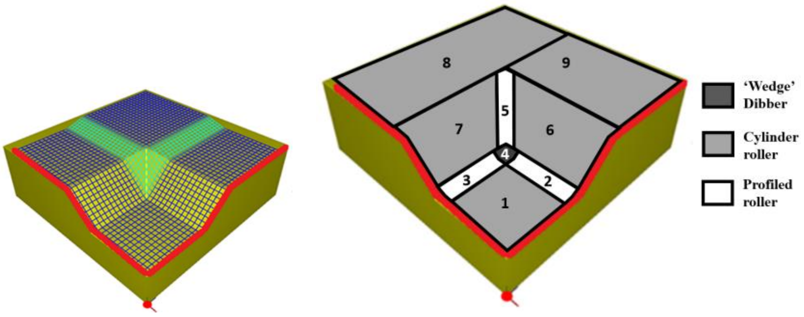

Figure 5: (Left) Diagram of the ‘Simple’ task. (Right) Layup order for the task.

5.3. The layup process

Once the layup order had been established, the actual layup program for the robot was developed using a combination of manually jogging the end effectors in position with the ABB pendant controller and offline programing. Rather than tackle the U-shaped panel straight away, two simpler moulds which represented portions of the panel were trialled first, one of which is shown in Figure 6. Figure 7 shows a storyboard of the layup process for this simple part along with Table 2 which contains additional information on each step. The 200mm x

200mm plies were approximately presheared by hand prior to layup, using manual techniques similar to those described in the previous hand layup study [7]. The plies were then placed by hand onto the mould and the robot ran through the program shown in Figure 7. The speeds were initially based on earlier tests (which are discussed in the thesis but will not discussed further in this paper) but were then adjusted to ensure sufficient prepreg-mould contact, slowing down the rollers where necessary.

On the first trials a number of defects were encountered. Image A of Figure 8 shows small wrinkles developed in the prepreg at the junction between the recessed and top sections (the upper most part of region 4 in Figure 6). This was dealt with by extending the path of Step K in Figure 7 and slowing the roller from 35mm/s down to 10mm/s to enhance the resin-mould contact. Image B in Figure 8 shows this modification was effective in removing wrinkles. There is still a slight visible disruption of the weave pattern, but this is due to a shallow recess in the mould surface. A second ply was then adhered to the surface with no visible defects.

These trials proved that the combination of three end effectors could successfully layup plies onto doubly curved moulds. It also proved that the rollers can *create* some shear deformation during layup, similarly to how humans were observed doing in the hand layup study [7] suggesting the accuracy of preshearing is not crucially important to a achieving a wrinkle and bridge free layup. An inverse ‘male’ version of the mould show in Figure 6 was also successfully laid up using only the cylindrical and profiled rollers as it did not feature any concave double curvature. More details of this are given in the full thesis.

Table 2: Notes on the automated layup steps shown in Figure 7.

Stage	**Roller**	**Speed/Delay**	**Displacement (mm)**	**Additional information**
A	n/a	n/a	n/a	Presheared ply placed on mould.
B, C	Cylinder	150mm/s	-5	Roller stops before contact is made with the ramp section to avoid double contact.
D, E	Profile	35mm/s	-6	Avoids contact with the ramp section as in stages B to C
F , G	Wedge	2.5 s delay	-5	In the first contact, the corner of the wedge is 5mm away from mould vertex, in the second, the corner is directly in the vertex.
H	Wedge	3.5s delay	-5	Extended contact time to enhance contact.
I	Wedge	2.5 s delay	-5	
J, K	Profile	35mm/s	-6	Roller is slowed to 10mm/s at point K to avoid wrinkling as seen in Figure 8.
L, M, N	Cylinder	150mm/s	-5	Moves up ramp section and onto top. Repeat 4 times until the whole ramp is adhered to the mould, and mirror on other ramp face.
O, P	Cylinder	50mm/s	-7.5	Passing roller over the concave allows a larger displacement to be used than on flat surfaces.
Q, R	Cylinder	150mm/s	-5	Repeat twice until edge of ply is reached.
S, T	Cylinder	150mm/s	-5	Starting point overlaps the area previously adhered to the mould during steps Q and R. Repeat twice until edge of ply is reached.

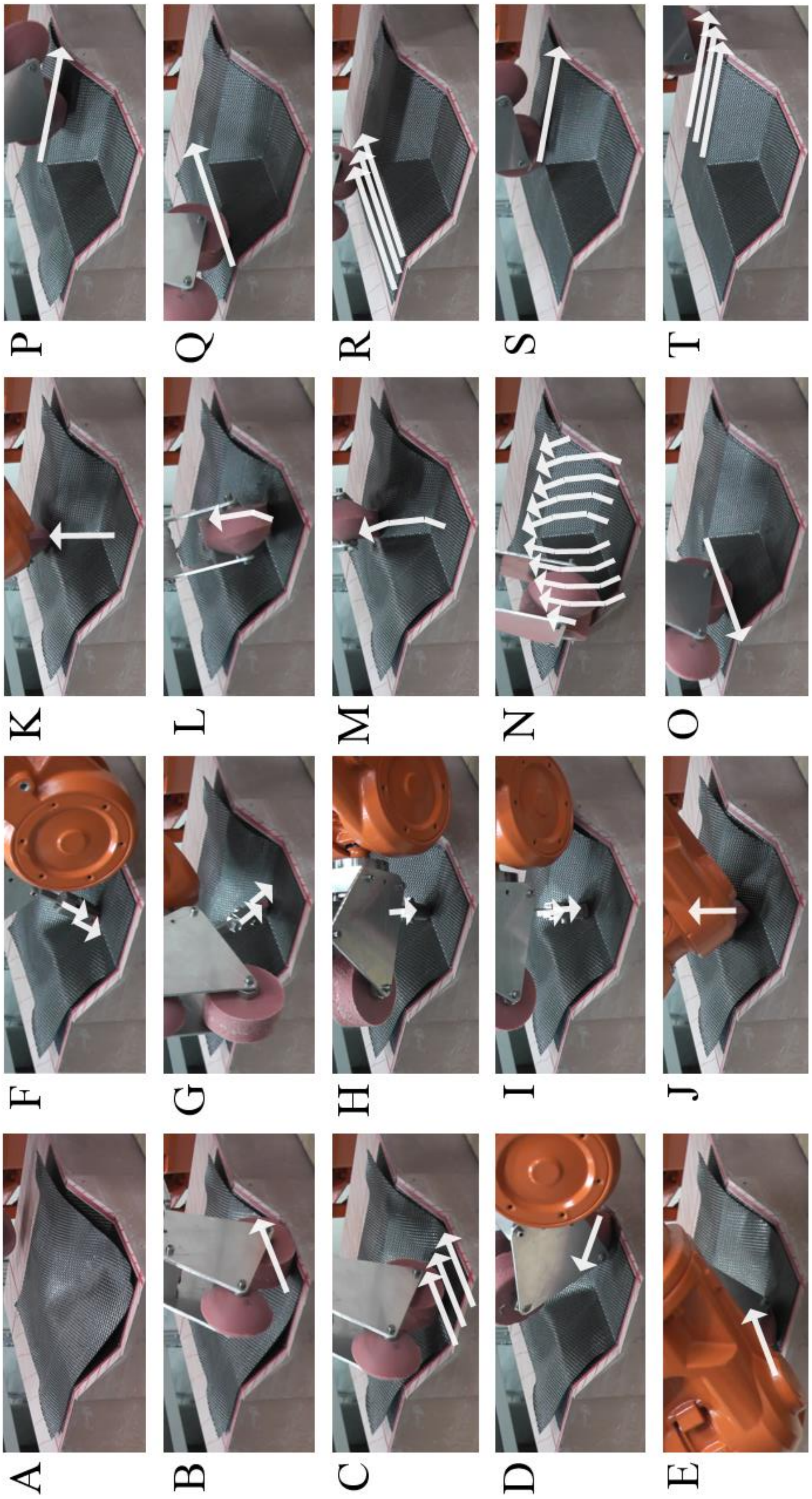

Figure 6: Storyboard of automated layup for the layup of the female task. The ply measures 140mm x 140mm. For notes on individual steps see Table 2.

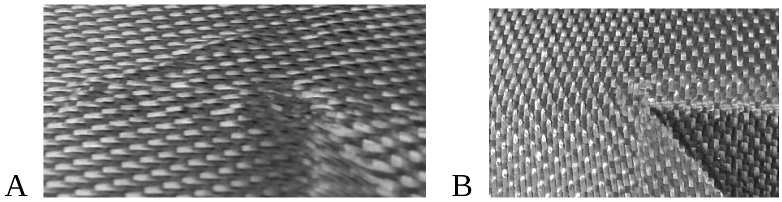

Figure 7: (A) – Wrinkling at the top of the ramp corner, (B) – Satisfactory top corner layup.

6. U-SHAPED PANEL LAYUP

Using the knowledge and experience from the trials on the smaller plies, the next step was to tackle the full U-shaped panel shown previously in Figure 3. Using the pressing process described in section 4, plies of woven 913 twill weave carbon material [23] were presheared into shape such that they contained all the shear required to fit onto the mould. As described in section 5.2, the first stage of automated layup was to work out an ‘order’ that would enable effective layup.

A program was then developed in the same manner described in section 5.3, using all three end effectors. Due to size constraints it is not possible to describe the full layup process in this paper, but an extensive story board is included in the full thesis, and a video is also available online [25]. An initial program was written and tested, proving largely successful. Figure 9 shows some defects that were experienced during early trials. The rest of this paper focuses on the additional subtleties and modifications added to the layup program to improve the layup quality.

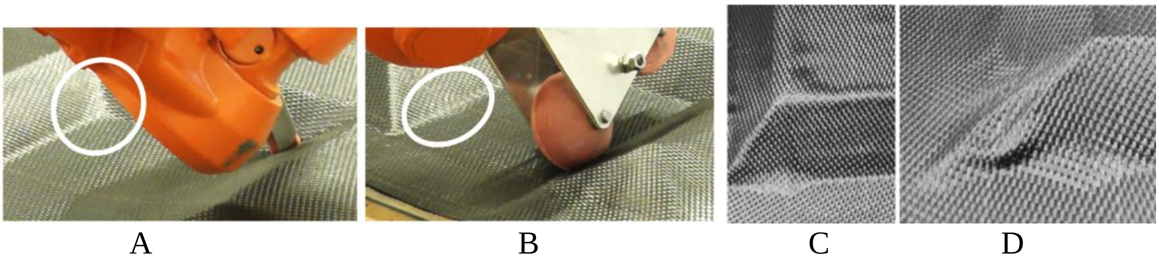

Figure 8: Example defects seen during the first layup trials. (A, B) - Bridging appearing in vertex as the opposite corners are adhered to the mould surface. (C) – Prepreg coming off the surface around the convex corner regions, (D) – Wrinkle at the bottom of the outer corner sections at the nearside of the tool.

6.1.1. Improving adhesion to the mould: Speed reductions in key areas

The cylindrical roller applied more than enough force to initially flatten out and stick down the prepreg to some degree but sometime after the original roller contact some areas of prepreg started to peel off the mould, especially around the external corners (images C and D in Figure 9). Previous trials detailed in the full thesis showed that reducing speed can improve the resin-surface contact. Taking advantage of this, the roller was locally slowed in the corner regions from 150mm/s down to 20mm/s. In addition to the speed reduction described previously, every time the cylinder or profiled roller approached an external corner, the roller was aligned such that it moved in the plane of the top surface, but it actually made first contact with the nearer face of the sloped surface before rolling onto the top surface (step A in Figure 10). In doing so, it meant pressure was applied to the corner region for a second time (assuming is has already been covered in a previous operation) to ensure it is securely adhered to the mould before moving on to the top surface.

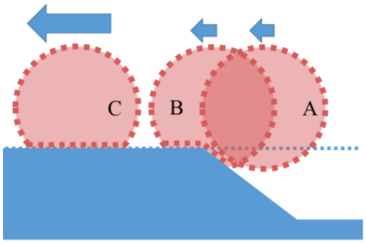

Figure 9: Schematic of revised process for sticking down corners. (A) Roller is aligned so it is *below* the top surface of the mould. First contact is with the angled surface on the ramp. (B) When the roller is in contact with the corner (A-B) it is slowed to 20mm/s, (C) While on the flat top surface (B-C) the roller is increased to 150mm/s.

6.1.2. Reducing bridging: Repeated and extended actions

Bridging was present in the internal corners of the recess region, as seen in Images A and B of Figure 9. The left side (as pictured in image A) was adhered to the mould first and showed no signs of bridging but as the right hand side was adhered to the mould, the previously adhered prepreg in the recess area came unstuck and slipped across the mould surface rather than material being drawn in over the raised section from the right hand side of the mould. This caused the bridged regions seen in Figure 10. To counter this, additional passes of the cylindrical roller across the recess region were added to improve contact and prevent the slippage.

6.1.3. Switching the deformation pattern: Starting in the highest shear areas

As the layup progresses over the mould, some additional shear was required in the ply to correct for slight discrepancies between the presheared ply and final shape caused by errors in preshearing or ‘spring-back’ (see Section 4.1). This results in an accumulation of an increasing amount of shear needing to be added to the ply during layup. Initially, the layup was attempted using the deformation pattern shown in the left hand image of Figure 11. The layup process worked from the back to the front of the mould (down the page as pictured). Thus layup started at the least shear regions and finished on the most sheared regions. As a result all the accumulated extra shear in the whole ply had to be added to the most highly sheared part of the ply. The in-plane stiffness of prepreg increases with shear angle [26], so in these high shear areas, trying to add shear to already sheared prepreg tended to lead to the wrinkling as seen in image D in Figure 9.

It was decided to reverse the presheared deformation pattern, switching from the left hand diagram in Figure 11 to the one shown at the right. As a result, when the final (bottom as shown in the picture) corners came to be laid up, the accumulated shear was being added to prepreg which had a much lower initial shear angle and therefore shear stiffness and hence was much less prone to wrinkling. This was achieved by simply turning the skeleton mould shape structure in the press (see Figure 2) through 180˚ while maintaining the original blank holder settings. This approach reduced the wrinkling dramatically and leads to the broader conclusion that it might be preferential to deliberately start, rather than finish, in the areas featuring the highest shear angles.

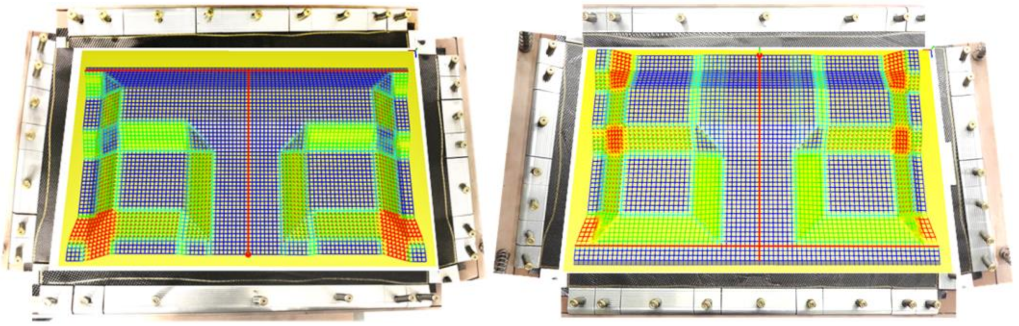

Figure 10: Diagrams of two presheared plies with different deformation patterns, surrounded by photographs showing the fibre deformation marked with a gold paint pen. Image produced using ‘Virtual fabric placement’ software [27].

Blue = 0°-5° shear Green = 5°-10° shear Red = 10°-15° shear

6.2. Trial layups

Once the modifications listed in sections 6.1.1 to 6.1.3 had been made to the layup process, it was capable of laying down plies which were deemed to be of an acceptable standard for curing. Two trials of three plies each were presheared and then laid up without any visible wrinkles or bridging. The layups were cured in the autoclave at 125˚C at 7 Bar, for 70 minutes with an additional 60 minutes high temperature dwell to allow the large aluminium mould to come up to temperature. Before each layup, the aluminium mould was cleaned with acetone, and given two coats of Loctite$^{\text{TM}}$ 700-NC$^{\text{TM}}$ release agent, brushed on by hand, and given 20 minutes to dry at approximatly 24˚C [28]. The general layup was successful, but there were a few resin rich areas around the internal recess corners and images of one of the finished parts are shown in Figure 12.

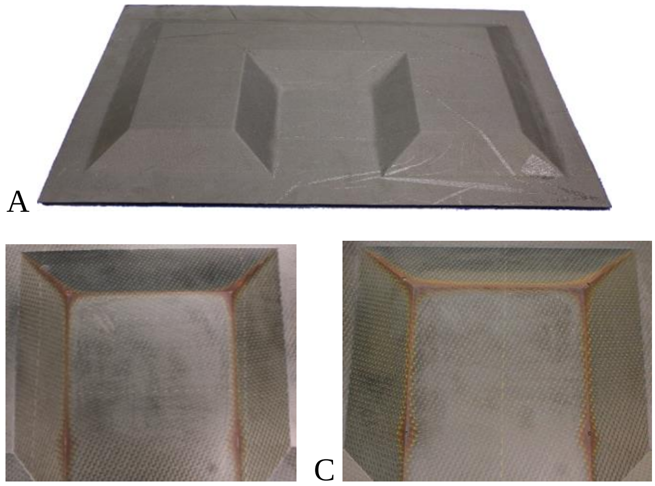

Figure 11: *(A)* Example of a cured panel constructed using automated layup. *(B)* Lower (mould) side of the recess area of the panel made by automated layup, red (darker in black and white) areas are resin rich. *(C)* Lower (mould) side of the recess area of the panel made by Hand layup, red (darker in black and white) areas are resin rich.

A fourth sample panel was constructed using regular hand layup with the same mould and material and an image of resulting cured part can be seen in image C of Figure 12. It was constructed by an operator who had previously been classified as ‘intermediate’ in previous hand layup research by the author [7]. What is immediately apparent comparing this to image C of Figure 12 is that hand layup appears to suffer from similar defects as robotic layup, mostly resin rich areas due to bridging around the recess region of the part. This shows that the performance of the automated system is very approximately level in terms of quality with hand layup for this particular part, although over such a small sample size it is difficult to make firm conclusions about the exact differences.

7. CONCLUSIONS

As far as the authors are aware this work represents the first time an automated system has been able to lay up a truly complex composite part to high quality standard. Two layups of three plies each were laid up using the robot and cured into a finished part. The finished parts were largely successful bar a few small resin rich areas. An additional trial part made using regular hand layup methods showed similar if not worse defects, suggesting that defects such as these are to some extent inherent with the mould geometry, especially the tight internal corner radii, and not an issue caused directly by robotic layup. The main source of defects being identified as slippage of the prepreg across the mould surface during layup leading to bridging in the recess region. As well as having similar resin rich areas and wrinkles, the time taken to complete layup for the robot and for regular methods were very similar, at around 7-8 minutes per ply (excluding preshearing). Thus at present the process does not provide a significant advantage over hand layup and is not ready to break into industry, but it must be considered that there are so many variables in the layup process that are yet to be optimised. The automated process has the potential to provide better repeatability and consistency than hand layup, especially where parts are made by many different laminators. Numerous methods to potentially speed up the lamination process were identified and are explored in section 8. Additional works on improving the usability of the preshearing press and well as integrating an existing ‘pick and place’ type mechanism to move plies between the different stages of the process are essential to make this into a commercially viable process.

8. FURTHER WORK: INCREASING LAYUP SPEED

The speed at which the end effectors can operate is a trade-off between reducing the time and ensuring good resin-mould contact and there are a wide variety of potential strategies for enabling increased speed. For example work by Crossley [29] showed that an independent tack test can identify a temperature range in which prepreg tack is increased dramatically. If this can be utilised there is likely to be scope to significantly increase the roller speeds and reduce the layup time. It was also observed in this work and by Crossley [29] that there is a significant drop in tack when the mould surface was coated with release agent. During regular lamination of sandwich panels the first ply is often preceded by a layer of resin film adhesive, which will dramatically increase the adhesion [30]. At present the robotic layup speeds were tuned to achieve good prepreg-mould adhesion with release agent coat, so with better surface tack the speed could likely be dramatically increased.

The U-shaped mould also featured sharp corners which required slow roller speeds and multiple end effector changes but it is recommended in the Handbook of Composites that corner radii should be between 4.75mm and 12.75mm for optimal layup [31]. In reality ramps on sandwich cores are often cut off so the minimum thickness is a few millimetres and the ramp smoothed into the base using edge reinforcing filler material [30]. These techniques would create a corner with has a more open radii, potentially allowing increased layup speeds.

The geometry, compound and size of the three end effectors used in this prototype are by no means optimised and they could all be improved. Using a robot which could apply higher force would enable the use of wider rollers which could complete layup in fewer passes. Alternatively the additional force could be used to allow the use of harder compound rollers to provide greater pressure, allowing the rollers to run faster or use smaller time delays and still achieve sufficient prepreg-mould contact. Having multiple robots would obviously allow two areas to be adhered to the mould simultaneously, but they could also work together, with one end effector securing the prepreg to the mould to prevent slippage while the other worked on internal corners elsewhere on the ply. Using two robots will however add a large degree of complexity and cost to the process.

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