AUTOMATED LAYUP OF SHEET PREPREGS ON COMPLEX MOULDS

Michael Elkington*, Carwyn Ward and Kevin Potter

Advanced Centre for Composite Innovation and Science (ACCIS), Department of Aerospace engineering, Bristol University, Queens Building, University Walk, Bristol, BS8 1TR, UK.
michael.elkington@bristol.ac.uk, www.bristol.ac.uk/engineering/people/michael-p-elkington
c.ward@bristol.ac.uk, www.bristol.ac.uk/engineering/people/carwyn-ward
k.potter@bristol.ac.uk, www.bristol.ac.uk/engineering/people/kevin-d-potter

Keywords: Rollers, convex, concave, double curvature.

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 single 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 a thesis by the author entitled ‘The evolution and automation of sheet prepreg layup’ [1], and there is an accompanying video online [2].

1. Introduction:

The use of advanced composites in engineering is expanding rapidly. Previously only used in performance driven, small scale industries such as military aircraft or Formula 1 racing, they are now being adopted by higher volume cost driven markets such as automotive and civilian aerospace industries [1][3]. This shift in applications brings with it much greater demands on the manufacturing processes . The main challenge in composites manufacturing is turning a flat fibrous material which is essentially inextensible along the length of the fibres into doubly curved shapes, while maintaining the fibre orientation and straightness 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 structural performance [5]. Other technologies such a diaphragm forming or hot drape forming have been shown to suffer from severe wrinkling as geometries become more doubly curved. For automotive applications such compromises can still be cost effective, but more performance critical applications require more precise production methods to ensure the structural quality of the composite.

For the production of the highest quality doubly curved components from prepreg materials, there are only two commercially viable options, either automated methods such as Automated Fibre Placement (AFP) or Automated Tape Laying (ATL) or Hand layup. All these methods ensure each ply is aligned laid down wrinkle free using a layer by layer approach, consolidating tows progressively along their length to avoid bridging or wrinkling. Other techniques forming multiple plies at once have generally struggled with severe wrinkling problems [6]. Hand layup, which has been used for over 30 years can layup the most complex components. It involves manipulating entire plies of composite material into shape by hand [7]. In contrast AFP and ATL involve thin tapes of unidirectional composite material being laid onto a mould using a robotic systems. They are limited in the complexity of parts they can produce but can have much higher production rates [8]. ‘Complexity’ in this context means the

Excerpt from ISBN 978-3-00-053387-7

presence of features such as double curvature, tight corners and steep ramps or gradients. 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 and will be referred to from here on as the 'U-shaped panel'. ATL would be unable to produce this part, and using AFP would be very difficult and slow [9]. Hand layup is ideal for making such complex parts, an attribute which is likely to become increasingly important as designers look to further reduce weight by integrating fixtures and fittings into new parts. However the production rate is quite limited and can only be increased by linearly scaling every aspect of the production facility. The aim of this work was to develop an automated layup process which could combine the speed of AFP with the capability for complex parts of hand layup. 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.

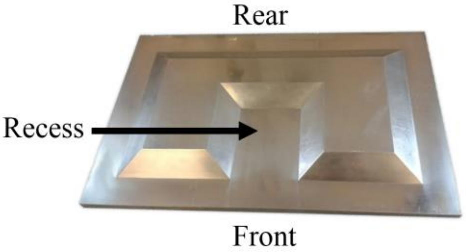

Figure 1: Mould for the U-shaped panel

2. Hand layup

They key factor in composite layup is that doubly curved shapes are typically 'undevelopable', such that a flat sheet cannot be wrapped around the shape without being folded or sliced [9]. However, woven prepreg can exhibit large in-plane deformation via 'trellis' shear which enables it to be formed over otherwise 'undevelopable' doubly curved shapes and this is the basis of hand layup. Despite hand layup's continued importance to the composites industry, there is very little detailed literature on the subject. An in-depth study of hand layup was carried out by the author and is published separately [7]. It was observed that the laminators manually applied the required shear to the woven prepreg in localised regions, typically 1-10cm^2 at a time. For shear angles up to 5°, this shear was generally created passively by the in-plane forces generated as the ply was smoothed out. For higher shear angles, the laminators directly applied 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 challenges simultaneously that makes automation of layup particularly difficult, and most previous attempts have very limited capabilities. For example Newell [11] and Molfino [12] 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. This has been studied in other

Excerpt from ISBN 978-3-00-053387-7

industries with some success, but the technology is far away from being commercially viable [13]. The concept of replicating hand layup directly using a bio-mimetic grasping robot system appeared to be an unlikely source of success.

3. Introducing preshearing

The next step was to investigate hand layup further to see if it could be 'simplified' in some way by modifying the process. 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 any contact with the mould. A study of this process was completed by the author and is published separately [14]. It showed 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 apply tension to the prepreg was dramatically reduced or in some cases not required at all. 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 create 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.

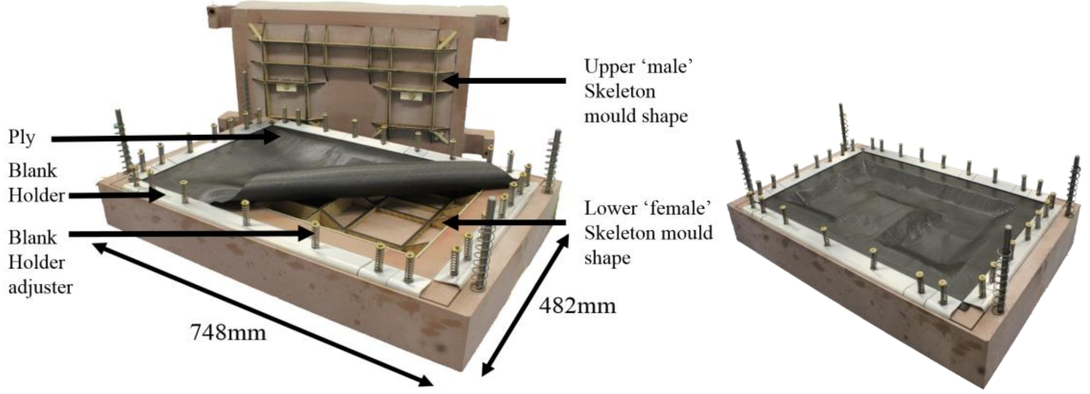

Figure 2: (Left) Preshearing press, shown with a ply peeled back to expose the skeleton mould shape, (Right) a presheared ply in the press.

Observation of previous studies using presses or stamp forming showed that the use of blank holders to prevent wrinkling is crucial [15]. It was decided therefore to use spring loaded blank holders around the perimeter of the press to clamp 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 multiple spring loaded elements to allow the tension to be adjusted in different regions, a concept explored further in the full thesis. One issue encountered during the preshearing work was the 'un-doing' of applied preshear after tension has been released. A study by the author detailed in the thesis showed that heating the prepreg to 40˚C during preshearing can prevent spring back up from to 15˚ of shear.

Excerpt from ISBN 978-3-00-053387-7

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 down 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 these give very little control over the ‘order’ in which areas of the ply are adhered to the mould surface, making ‘progressive’ consolidation near impossible. A alternative method was developed, featuring a hybrid of automated tape laying and hand layup was developed to enable progressive layup over complex features.

5.1. Multiple end effectors

The key shortcoming of AFP is that the consolidation head is integrated into the material feed, meaning it has to attempt to layup many different shapes with just a single end effector, leading to defects and reduced production rates. During manual layup, laminators used their hands in many different configurations alongside numerous additional extra tools to adapt to the wide variety of mould features such as tight internal radii. This concept was adopted for the automated system, because 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. A range of different end effectors were developed to tackle specific geometries and these are introduced individually in section 5.1. Up to three end effectors were mounted to an ABB IRB 140 6-axis robot at once. To switch between them, the head of the robot simply re-orientates, allowing rapid changeovers.

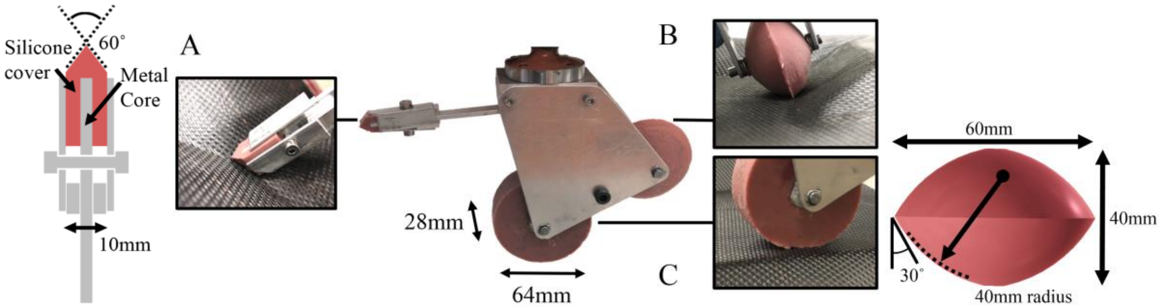

Figure 3: (A) Silicone ‘wedge’ end effector, ideal for tight double curvature internal corners. (B) ‘Profiled’ roller for single curvature internal corners. (C) Cylindrical roller for Flat, convex and lightly concave surfaces.

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

	Flat	**Single curvature**				**[1] Double curvature**					
		Convex		**[2] Concave**		**[3] Convex**		**[4] Concave**		**[5] Saddle**	
Radius	N/A	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

5.1.1. 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. These will occur on even the most ‘complex’ moulds, therefore it was decided to include a cylindrical roller as one of the end effectors. The current roller is 28mm wide with a 64mm radii and constructed from compliant M242 silicone (donated by ACC silicones) to allow it to deform over different shapes.

Excerpt from ISBN 978-3-00-053387-7

5.1.2. Profiled end effector

Cylindrical end effectors are typically ineffective in concave internal corners . A new style of roller was designed which featuring the 'profiled' shape seen in Figure 3. Also constructed 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 plastic tool and a more distributed pressure provided by compliant silicone based end effectors.

6. Programming the layup process

The order of layup needs to be carefully controlled to prevent situations such as that depicted in Figure 4. For example if the raised ridge section (labelled A in Figure 4) was all adhered to the mould first this would lead to the tows running across the *recess* (area B) being adhered to the mould in *two* separate areas, and not progressively stuck down along its length. Thus the free length of the tows between these already adhered sections which is available to form into the recess will likely either be too short, leading to bridging or too long, leading to wrinkling.

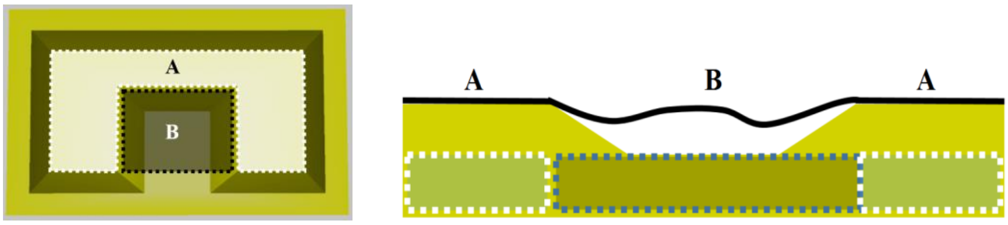

Figure 4 : An example of how sticking down a whole region containing similar features, in this case *flat*, could cause double constraint. Key: **A** = Region adhered to the mould surface, **B** = Area where tows are now doubly constrained.

To prevent scenarios such as Figure 4 from occurring a detailed layup order was established prior to programming the robot. Layup tasks were divided up into discrete areas that satisfy two criteria; They only contain geometries which can all be adhered to the mould using a single end effector and the separate areas must tessellate together so they can be completed sequentially without sticking down any tows in two separate locations. Figure 5 shows an example of a simple layup which has been divided up into different layup steps. The colour coding shows which end effector was required for each section of the mould.

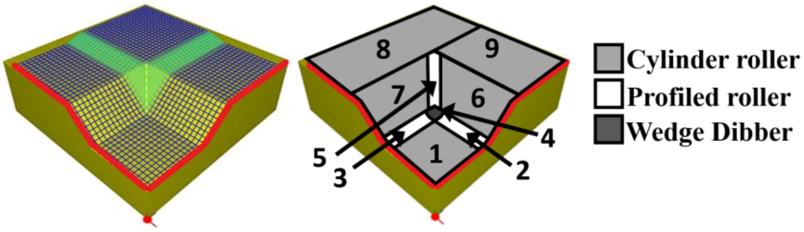

Figure 5: (Left) Diagram of the 'Simple' task. (Right) Layup order for the task.

The shape seen in Figure 5 was laid up using 200mm x 200mm plies which were approximately presheared by hand prior to layup. A layup program was constructed using a combination of manually

Excerpt from ISBN 978-3-00-053387-7

jogging the end effectors into position with the ABB pendant controller and offline programing. Initial trials were largely successful although a small number of defects occurred such as small wrinkles, bridging and some non-contact areas. These were tackled using a combination of reducing the roller speed in key areas and repeating some end effector applications. The modified program showed that the combination of three end effectors could successfully layup plies onto doubly curved moulds. Creating a successful layup from a very approximate preshear demonstrated 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 5 was also successfully laid up using only the cylindrical and profiled rollers as it did not feature any concave double curvature. More details of these layup processes are given in the full thesis and accompanying video [1][2].

7. 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 twill weave carbon material with Hexcel 913 resin were presheared into shape such that they contained all the shear required to take up the shape of the finished part and fit onto the mould. As described in section 6, the first stage of automated layup was to work out an 'order' that would enable effective layup. An extensive story board is included in the full thesis and a video is also available online but due to size constraints it is not possible to describe the full layup process in this paper [1]. The layup started at the rear of the tool, into the recess and then finishing on the near side. A program was then developed in the same manner described in section 6, utilising all three end effectors. Initial trials were largely successful but a few small wrinkles appeared, as well as some bridging in the internal corners of the recess. Much of the bridging was caused by previously stuck down prepreg in the base of the recess area coming unstuck later in layup and sliding across the tool surface while the internal corners were consolidated. This effect was partly countered by slowing the rollers down and adding repeat applications in key locations. Using the revised layup program, two trials of three plies each were presheared and then laid up over the whole mould without any visible wrinkles or bridging. The layups were cured in the autoclave and the finished parts were largely successful, besides a few resin rich areas around the internal recess corners and images of one of the finished parts are shown in Figure 6.

A fourth sample panel was constructed using regular hand layup by an operator who had previously been classified as being 'intermediate' in previous hand layup research by the author and can be seen in image C of Figure 6. What is immediately apparent comparing this to image B of Figure 6 is that hand layup appears to suffer from very 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.

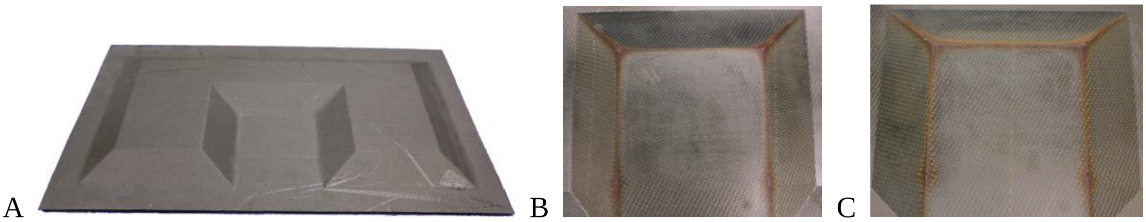

Figure 6: *(A)* Finished panel constructed using automated layup. *(B-C)* Lower (mould) side of the recess area of the panel made by automated layup and hand layup respectively, red (darker in black and white) areas are resin rich.

Excerpt from ISBN 978-3-00-053387-7

8. 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. By using multiple different end effectors, plies were able to be progressively consolidated across a range of different geometric features. 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. 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 automated process were identified and are explored in section 9. 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.

9. Further work

The speed at which the end effectors can operate is a trade-off between reducing the time and ensuring good resin-mould contact. There are a wide variety of potential strategies for enabling increased speed. Most prepreg materials have a greatly increased tack within a specific temperature window, something which could be used to allow faster layup [16]. The surface preparation of the tool is also important, with different free coating and resin film combinations producing a range of tack levels. For the specific mould used here, the tight internal radii make layup particularly difficult, and more open radii would allow further increased 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, or harder rollers apply greater pressures which would allow increased layup speeds.

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] M. Elkington, *The evolution and automation of sheet prepreg layup*, PhD Thesis, University of Bristol, 2015.

[2] ACCIS, University of Bristol, ‘*Automated layup of sheet pre-preg onto complex moulds*’, youtube video, https://www.youtube.com/watch?v=eJ1YvKxgb4M, Accessed 25/04/2016, 2015.

[3] M. Freitag, ‘*Produktionsprobleme beim BMW i3*’, Online Article, Available from: (http://www.manager-magazin.de/unternehmen/autoindustrie/carbon-bmw-hat-nachschubprobleme-beim-bau-des-i3-a-954274.html), Accessed 12th January 2015, 2014.

[4] L. D. Bloom, J. Wang, & K. D. Potter, Damage progression and defect sensitivity: An experimental study of representative wrinkles in tension, *Composites Part B: Engineering*, 45(1), 449-458 2013.

[5] DH-A. Lukaszewicz ,Composites at BMW, *International conference on manufacture of advanced composites*, Bristol, University of Bristol, June 24th - 25th 2015.

[6] P. Hallander, M. Akermo, C. Mattei, M. Petersson, & T. Nyman, An experimental study of mechanisms behind wrinkle development during forming of composite laminates, *Composites Part A: Applied Science and Manufacturing*, Vol 50, 54-64, 2013.

[7] M. Elkington, D. Bloom, C. Ward, A. Chatzimichali, & K. Potter, Hand layup: understanding the manual process. *Advanced Manufacturing: Polymer & Composites Science*, 1(3), 138-151 2015.

Excerpt from ISBN 978-3-00-053387-7

[8] DH-A. Lukaszewicz, C. Ward, & K.D. Potter, ‘The engineering aspects of automated prepreg layup: History, present and future’. *Composites Part B: Engineering*, vol. 43, 997-1009, 2012.

[9] R. Lichtinger, et al. "Simulation and experimental validation of gaps and bridging in the automated fiber placement process." *Science and Engineering of Composite Materials*, 22.2 (2015): 131-148.

[10] C. R. Calladine, Theory of shell structures, Cambridge University Press, Cambridge, 1989

[11] R. O. Buckingham, G. C. Newell, Automating the manufacture of composite broadgoods, *Composites Part A: Applied Science and Manufacturing*, 27(3), Pages 191-200, 1996.

[12] R. Molfino, M. Zoppi, F. Cepolina, J. Yousef, and E. E. Cepolina, Design of a Hyper-flexible cell for handling 3D Carbon fiber fabric, *Recent advances in mechanical engineering and mechanics*, 165, 2014.

[13] J. Maitin-Shepard, M. Cusumano-Towner, J. Lei, & P. Abbeel, Cloth grasp point detection based on multiple-view geometric cues with application to robotic towel folding. *In Robotics and Automation (ICRA), 2010 IEEE International Conference on*, pp. 2308-2315, IEEE, May 2010.

[14] Elkington, M., Ward, C., Chatzimichali, A., & Potter, K. (2015). Studying effects of preshearing on hand layup. *Advanced Manufacturing: Polymer & Composites Science*, 1(2), 80-93.

[15] M. Hou, K. Friedrich, Stamp forming of continuous carbon fibre/polypropylene composites, *Composites Manufacturing*, 2(1), Pages 3-9, 1991.

[16] Crossley, R. J., Schubel, P. J., & Warrior, N. A. (2011). Experimental determination and control of prepreg tack for automated manufacture. *Plastics, Rubber and Composites*, 40(6/7), 363-368.

Excerpt from ISBN 978-3-00-053387-7