Feasibility Study Final Report

of

Virtual Un-manufacturing of Fibre-steered Preforms for Complex Geometry Composites

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Executive Summary

State of the art Automated Fibre Placement (AFP) is ideally suited for manufacturing large structures with relatively simple geometry, due to its robustness, high throughput and repeatability. However, the processing conditions, machine tolerance and tape steering in AFP has limitations for directly laying up fibre tapes onto complex 3D shapes. The need for defect-free manufacture constrains the head speed, making manufacture time consuming and thus costly. In most cases, complex geometry composite components are designed based on ideal or theoretical fibre angles, with little or no consideration of the manufacturing processes or constraints, as a result of which in-situ fibre direction in as-manufactured parts may deviate significantly from the design intent. This feasibility study focused on an alternative manufacturing process, as a replacement for direct AFP processing onto complex 3D geometry, i.e. lay-flat and form processes, in which fibre tows are steered and deposited to create a flat preform; and then this flat tailored preform is formed into a 3D complex shape. The fibre path/angle of the flat tailored preform prior to forming was derived from an 'un-manufacturing' (i.e. un-forming) virtual process of the part with ideal fibre paths. The primary manufacturing process used in this research is a double diaphragm forming of fibre-steered prepregs deposited using the Continuous Tow Shearing (CTS) technique. Through numerical process simulations of forming, un-forming and re-forming, with experimental validation, this feasibility study not only showed the feasibility of the virtual un-manufacturing process in combination with 'lay-flat-and-form' manufacturing but also demonstrated that the proposed processes leads to a reduction wastage compared to manually laying unidirectional (UD) prepreg onto complex 3D shapes.

1. Introduction

Automated fibre placement (AFP) is an automated composite manufacturing process that combines fibre tape deposition, tacking (or melting) and consolidation into a single step with significantly improved production rate, quality, accuracy, and reduced material waste and labour cost as a replacement for equivalent multiple manual processes [1]. In the last two decades, the increased demand of the aerospace sector for unidirectional (UD) preimpregnated (prepreg) carbon fibre material has been a key driver for the continuous improvement of this technology [2]. Most AFP machines are able to process fibre tows of width ranging from 1/8″ to 1″, which is the key enabler for this technology to manufacture curved, contoured or multi-stiffened composite parts (that could not be automatically manufactured in the past), and this has helped to considerably widen the application and performance of composite structures. AFP has also been playing key role in the development of variable angle tow (VAT) composites where fibre tow paths are deposited with alignment to the critical load-bearing paths thus allowing for drastic improvements of composites' structural performance [1].

However, due to the complexities of the AFP machines and the large number of geometrical and material dependent settings required that can impact part quality, the quality of the part produced needs to be thoroughly checked manually and AFP parts often need to be reworked. These take up to 63% of the overall process window (even exceeding the machine layup time), and ultimately leads to high running costs [3]. Part of the reason for rework comes from random or recurrent manufacturing defects during machine layup. These processing-induced defects persist either in UD or VAT layup and eventually lead to uncertainties in mechanical performance and structural integrity of the parts [4–7]. AFP machines are normally designed to process large parts with relatively simple geometries (e.g. fuselage in Boeing 787 [8] and Airbus A350 wing skins [9]), but are not well-adapted for complex 3D shapes as the geometry and quality requirements make manufacture time consuming and thus costly. In most cases, complex geometry composites components are designed based on ideal or theoretical fibre angles and optimised towards the best possible mechanical performance, with little or no consideration of the manufacturing processes or constraints involved in delivering them. For AFP processed parts with variable angle tows, orientation of tow path in as-manufactured parts may deviate significantly from as-designed, and this deviation can further accumulate as complexity of the part shape and designed tow trajectory increases. Therefore, there is a strong need for alternative manufacturing processes that produce preforms with fewer uncertainties and lower cost for small to large parts with complex 3D geometries to replace direct AFP deposition.

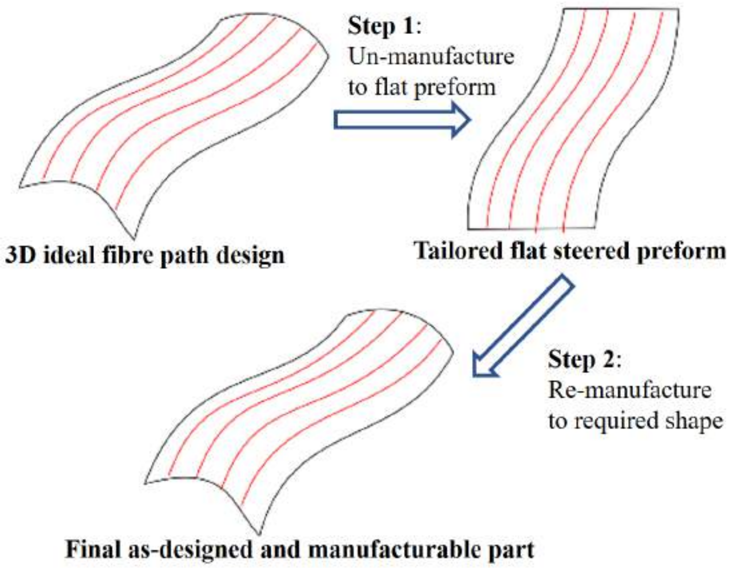


Fig. 1 Schematic of un- and re-manufacture processes in ‘lay-flat and form’.

The work presented here takes a novel virtual approach to "un-manufacture" the ideal designs for the case of formed composites. Un-manufactured (i.e. un-formed) flat tailored preforms of prepreg, with steered fibre paths, are created via the continuous tow shearing technique [10]. Then the tailored preforms undergoes simulation of the actual manufacturing process to form into a desired shape, this process is called "lay-flat and form", in Fig.1. The final as-designed manufacturable part is derived from the re-manufacturing (i.e. re-forming) step. It is expected to have similar fibre tow orientation as that of the ideal design. In order to obtain a flat tailored preform, a novel virtual un-manufacturing process based on finite element analysis is used, from which the fibre orientation can be derived and passed to the following re-manufacturing step. A similar un-manufacturing process was investigated by Rudd et al. [11] using a kinematic ‘undraping’ algorithm for optimum tow path for forming. In current work, the forming and un-forming process models are FEA-based and made fully-reversible, as well as validated via experiments.

Double diaphragm forming of a tailored preform was conducted as a proof of concept and to validate the process models. The fibre trajectory as input to CTS machine was directly taken from the virtual un-manufacturing process described above. The CTS approach reduces process-induced defects that are normally carried by conventional AFP tow steering methods, especially when tows are laid in small radii [10], which was considered to benefit the manufacturing of the tailored preform that is derived from a complex 3D part in this work.

Detailed description of the modelling and experimental strategy and workflow are presented in later sections together with the numerical and experimental results of a demonstrator developed in this work. This feasibility study was presented as a proof of concept for the proposed manufacture approach and focused only on single layer preform production.

2. Numerical Modelling Strategy

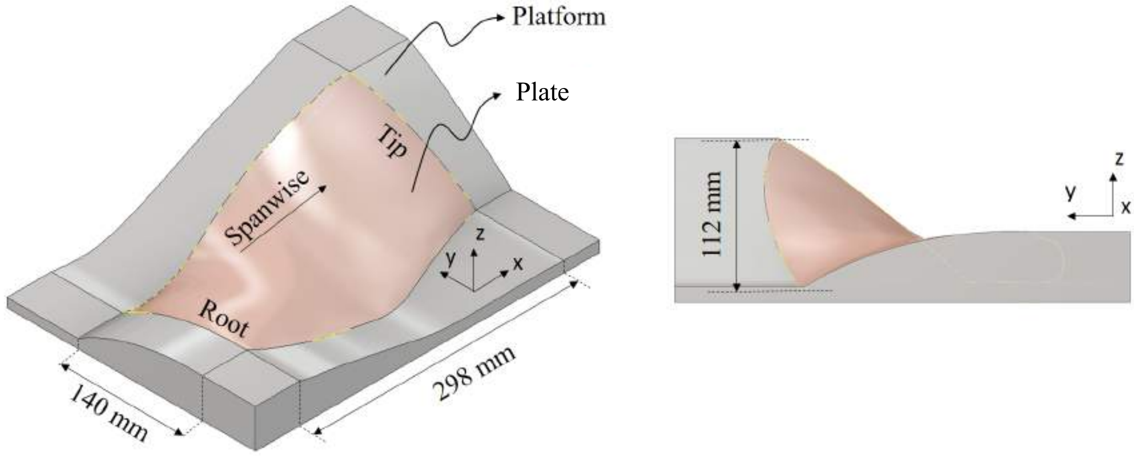


Fig. 2 Designed mould in CAD view with dimensions. The twisted plate part is highlighted in the centre of the mould

Double diaphragm forming is one of the most constrained forming processes with substantial interactions between preform and tooling (diaphragms), which was selected to demonstrate the feasibility of the proposed manufacture approach. Double diaphragm forming analysis based on finite element analysis (FEA) was implemented to simulate the un-forming of ideal preform (see Step 1 in Fig.1) and re-forming of tailored steered preform (Step 2 in Fig.1). FE models were pre-, processed and post-processed using Abaqus/Explicit.

To demonstrate the advantages of the proposed processes on a laboratory scale, a twisted, swept and doubly curved surface was designed and used as part of the forming mould. Fig.2 shows the designed mould with the dimensions; the part in grey is a platform extending from the part edge to prevent the flat preform from being folded around the edges of the part during forming when the preform is larger than the part. This CAD geometry was then imported to Abaqus for further processing. The top surface of the mould was modelled and meshed with S4R element (shell element with reduced integration points) to reduce computational cost, and rigid material properties were assigned to the mould part for later forming simulations. Another part CAD geometry (see Fig.2 highlighted region) was also transferred to Abaqus to model the preform part with ideal fibre tow paths (called the “ideal preform”). A mesh on part was created by Python script so that each spanwise strip of elements has a constant width. These strips of elements with a constant width represent the ideal fibre tow paths on the part. To accurately capture the behaviour of the preform during the forming/un-forming process, a hybrid approach (see [12]) was used to model the preform: shell (S4R in Abaqus) and membrane element (M3D4R in Abaqus) are superimposed to represent out-of-plane and in-plane material properties of preform, respectively. A material model based on a hypoelastic framework, implemented via a VUMAT subroutine, was used to model the preform. Details of the hybrid approach of the VUMAT material model is not elaborated in here but can be found in [12]. Ogden's hyperelastic material model with representative parameters given in [13] were assigned to diaphragms.

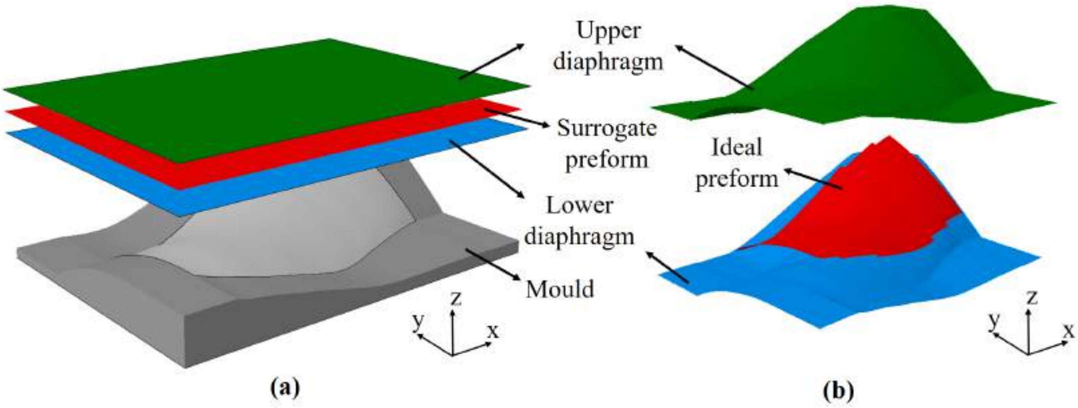


Fig.3. Illustration of (a) initial forming model, (b) unforming model. Note that diaphragms position relative to mould and preform and the size of preform are for presentation only.

As opposed to conventional manufacturing processes, unforming cannot be experimentally validated as it does not physically exist. In the models, it is therefore considered as the directly reversed process of forming. This way fully reversible forming and unforming simulations can be validated simultaneously. An initial forming simulation was first performed. The nodal 3D displacement history of the diaphragms was extracted, stored and used for the un-forming simulation. During unforming, these nodal displacement histories were assigned to nodes on diaphragms but with the opposite sign so that both diaphragms can deform back to their original states.

As shown in Fig.3 (a), four parts were modelled, i.e. the two flat double diaphragms, the mould and the surrogate preform. The surrogate preform has the same material properties as that in unforming simulation. During the initial forming, frictional interaction between diaphragms and preform can significantly affect the shear behaviour of the preform as materials respond differently when they are formed into the same shape. A surrogate preform was expected to capture these interactions and provide accurate simulations. At the end of initial forming simulation, the diaphragms fully conform to the top of the mould, and the deformed diaphragms become the initial shape that will be used in un-forming. Double diaphragms are restored from the deformed shape (see Fig.3(b)) to the flat position (see Fig.3(a)) during the un-forming simulation, together with the ideal preform that is sandwiched between them. Hence, the ideal preform is forced by the double diaphragms to un-form from the twisted part shape with element orientations along the ideal fibre tow paths (ideal preform in Fig.3(b)) to an un-formed shape with tailored fibre tow paths (see Step-1 in Fig.1).

To avoid any localised response (i.e. in-plane shear) in the un-formed preform and to make it manufacturable, the un-formed preform then was further processed and re-meshed by a developed Python script so that spanwise strips of elements can have a constant width representing AFP or CTS tapes. This numerical tool was designed to convert FEA results to AFP- and/or CTS-manufacturable preform geometries.

In this feasibility study, CTS technique was selected to demonstrate the feasibility of the unforming process. Because the width of the designed part is around 140 mm, two 100 mm wide prepreg tapes along the preform width were used in CTS process, a single fibre tape trajectory was then extracted from tailored preform from the mid-chord position of the part geometry.

3. Experiment

In this work, deposition of a steered fibre preform followed by double diaphragm forming was conducted, and results were used as proof of concept to the proposed manufacturing approach, as well as for finite element model validation. A steered fibre preform was manufactured by the CTS technique using the fibre trajectory extracted from virtual un-manufactured tailored preform. Double diaphragm forming of a manually-laid unidirectional prepreg sheet was also carried out for comparison with the fibre steered preform to highlight the benefits of proposed method.

A double diaphragm forming rig was designed and built to accommodate a small- to medium-sized mould. During forming, the preform was placed between two diaphragms, and vacuum was applied between them. After the preform was correctly positioned and secured, then the forming rig chamber was evacuated for forming. The mould, with identical geometry as in the numerical part of this work, was built by 3D plastic printing.

The steered preform deposited by CTS machine using 100 mm wide unidirectional prepreg tape (MTM49-3/T800, Solvay, BE) on a flat surface, is shown in Fig.4. To identify the fibre path and make comparison to different preforms before and after forming, lines parallel to the fibre directions on the prepreg tape were marked before the prepreg was fed to the CTS machine. The fibre path in 2D cartesian coordinate format from the FEA results was converted to CTS machine code, using a previously developed code (see [14,15]).

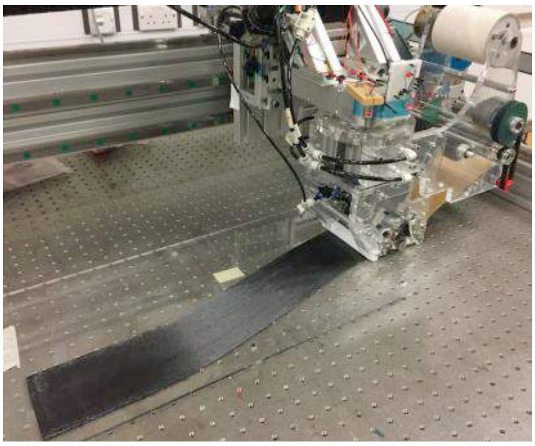


Fig. 4. Wide tape CTS machine steering a 100 mm wide unidirectional prepreg tape.

4. Results and Discussions

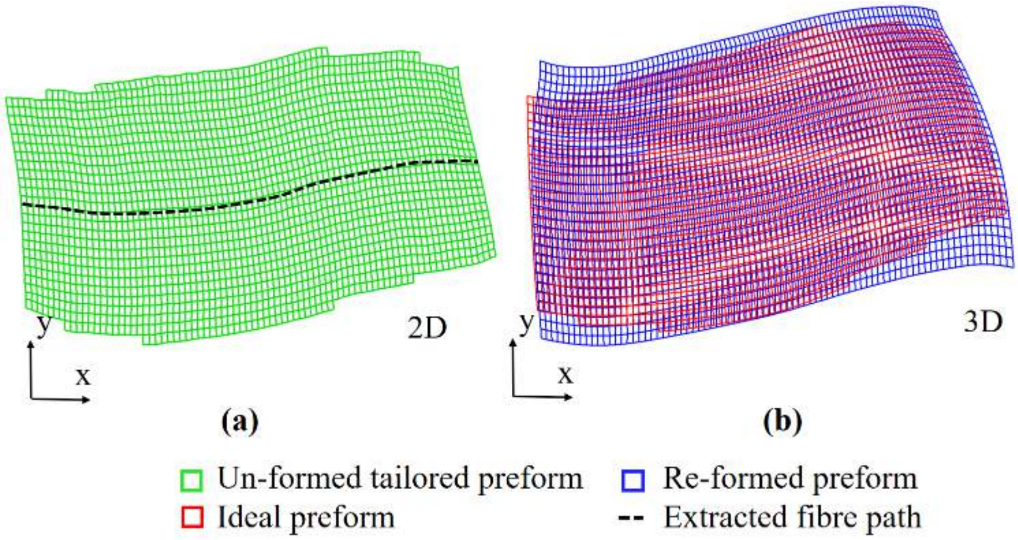


Fig. 5. (a) Un-formed preform model with extracted fibre path at mid-chord, (b) comparison of fibre path between ideal preform and re-formed preform.

Numerical simulations of the initial forming, un-forming and re-forming were performed according to the modelling strategy described in the previous section. In forming and un-forming models, the experimental forming rig was not entirely modelled, and the forming process was realised by changing the pressure on the diaphragms. During initial forming simulation, the same uniform pressure distribution was given to both upper and lower diaphragms in the opposite directions. After diaphragms and preform were stable, then the pressure acting on the lower diaphragm was gradually reduced so that double diaphragms were formed onto the part, and the preform that is sandwiched between the diaphragms was draped to the shape.

(a) **(b)**

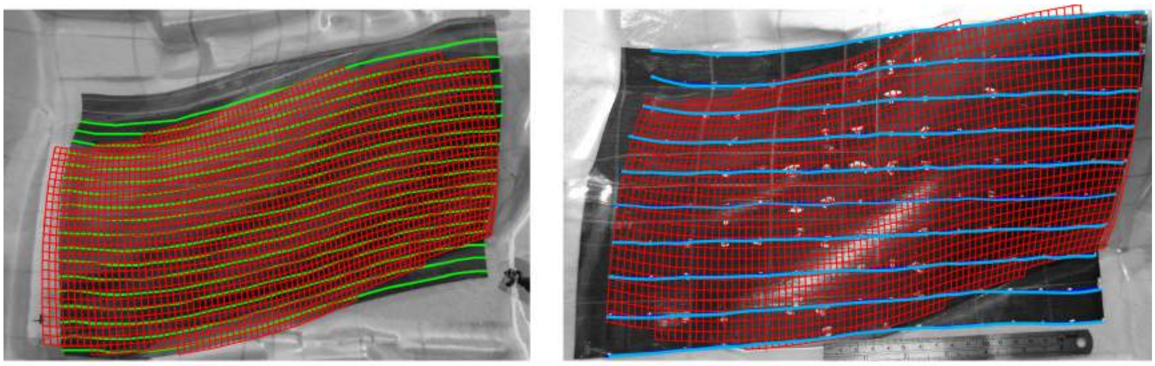
Fig. 6. (a) flat preform deposited by CTS machine; (b) CTS preform formed onto twisted part in double diaphragm forming rig.

Fig. 5 (a) shows the un-formed tailored prepreg derived from the un-forming simulation with the fibre trajectory highlighted. Since there was no highly localised shear deformation required for this geometry, a single trajectory was able to represent the fibre path for the entire preform. Fig. 5 (b) compares the 3D re-formed preform with the 3D ideal preform. The re-formed manufacturable preform (re-formed preform) was derived from the single fibre path extracted from un-formed preform shown in Fig.5 (a). It can be seen that the fibre path (represented by strips of element) in the re-formed preform is in good agreement with the ideal preform.

This extracted single fibre trajectory (see Fig.5 (a)) was then passed to a post-processer [15] to convert to CTS machine code for the CTS machine. Due to the tow width and the size of the twisted plate, two wide tows were laid by CTS machine in parallel and then trimmed manually to the same size as that of the preform in the FEA models (see Fig.6 (a)). The CTS preform was then placed into the forming rig and formed into shape. Fig.6 (b) shows the formed CTS preform. During the forming test, no splitting between the two tapes at the joined boundaries was observed. Several trails were done before the preform was successfully formed to the shape with full coverage. The formed position of the CTS preform is sensitive to the initial contact position between the diaphragms and the mould. The preform needed to be properly aligned with the mould as any point within the preform uniquely corresponds to one position on the mould. The same forming test was performed with a manually laid unidirectional prepreg sheet to highlight the benefits of the proposed method.

For validation, the forming simulations of both cases were performed, as shown in Fig. 7 (a). It can be seen that the fibre path represented by green lines on the formed CTS steered preform is in good agreement with the ideal fibre path predicted by the model (represented by red finite element mesh). More iterations of the virtual un-formed re-forming process (step 2 in Fig.1) may be required to obtain a better comparison of the obtained formed preform to the original ideal design. However, the initial position of the steered preform in the forming experiment and its interactions with the diaphragms may still cause a mismatch. For the purpose of proof of concept, the current validation process was deemed to be sufficient.

The layup accuracy using steered fibre preforms in forming of 3D complex shapes become more noticeable when comparing with the fibre paths of a manually laid UD preform that was formed to the same shape as that shown in Fig.7 (b).



(a) (b)

Fig. 7. (a) Comparison of finite element based projected ideal fibre path (red) and projected fibre path (green) of formed steered preform from test on twisted part; (b) comparison of finite element based projected ideal fibre path (red) and projected fibre path (cyan) on formed UD preform from test on twisted part.

The fibre orientation in the formed UD preform significantly deviated from the ideal path, which could lead to a significant mismatching of the structural performance between the as-designed and as-manufactured models. It was also found that the required material amount of the fibre steered preform was lower than the UD preform, and it also leads to more material being trimmed (i.e. wasted) to fit the formed UD preform to the part shape.

5. Conclusions

In this work, a lay-flat and forming process as a cost-effective alternative to direct AFP deposition on complex 3D shapes is proposed, and the feasibility of the method is demonstrated.

A set of numerical tools composed of FEA models and Python scripts were developed for generating ideal fibre paths on arbitrary shapes, the results of which were validated against forming experiments. It showed that the 2D steered preform obtained from un-forming of the ideal preform can be derived or predicted via a virtual un-manufacturing process. The whole process could potentially lead to significantly lower cost and part development time than direct AFP deposition on complex shape. It was also found that parts manufactured by the proposed process is closer to the ideal design and uses less material compared to a part manufactured through forming of a UD preform. The forming quality was found to be sensitive to the initial relative position between fibre steered preform and the mould in double diaphragm forming, which could be reduced by other controlled forming techniques such as a method using closed tools where the preform can be secured in position at the beginning of forming and formed by rigid tools rather than diaphragms.

The proposed approach is suitable for manufacturing small to medium sized composite components with complex shapes, however limitations comes in dealing with increasing complexity of the part shape requires further investigation.

References

[1] Lukaszewicz DHJA, Ward C, Potter KD. The engineering aspects of automated prepreg layup: History, present and future. Compos Part B Eng 2012;43:997–1009.

[2] Wu KC, Stewart BK, Martin RA. ISAAC advanced composites research testbed. CAMX 2014 - Compos Adv Mater Expo Comb Strength Unsurpassed Innov 2014.

[3] Maass D. Progress in automated ply inspection of AFP layups. Reinf Plast 2015;59:242–5.

[4] Woigk W, Hallett SR, Jones MI, Kuhtz M, Hornig A, Gude M. Experimental investigation of the effect of defects in Automated Fibre Placement produced composite laminates. Compos Struct 2018;201:1004–17.

[5] Heinecke F, Willberg C. Manufacturing-Induced Imperfections in Composite Parts Manufactured via Automated Fiber Placement. J Compos Sci 2019;3:56.

[6] Belnoue JPH, Mesogitis T, Nixon-Pearson OJ, Kratz J, Ivanov DS, Partridge IK, et al. Understanding and predicting defect formation in automated fibre placement pre-preg laminates. Compos Part A Appl Sci Manuf 2017;102:196–206.

[7] Falcó O, Lopes CS, Mayugo JA, Gascons N, Renart J. Effect of tow-drop gaps on the damage resistance and tolerance of Variable-Stiffness Panels. Compos Struct 2014;116:94–103.

[8] Hiken A. The Evolution of the Composite Fuselage: A Manufacturing Perspective. Aerosp. Eng., IntechOpen; 2019.

[9] Nathan S. Automating aerospace manufacturing. Theengineer 2017.

[10] Kim BC, Potter K, Weaver PM. Continuous tow shearing for manufacturing variable angle tow composites. Compos Part A Appl Sci Manuf 2012;43:1347–56.

[11] Rudd CD, Turner MR, Long AC, Middleton V. Tow placement studies for liquid composite moulding. Compos Part A Appl Sci Manuf 1999;30:1105–21.

[12] Thompson A, Belnoue JP, Hallett SR. Numerical Modelling of Defect Generation During Preforming of Multiple Layers of 2D Woven Fabrics. ECCM17 - 17th Eur Conf Compos Mater 2016:26–30.

[13] Chen S, McGregor OPL, Endruweit A, Elsmore MT, De Focatiis DSA, Harper LT, et al. Double diaphragm forming simulation for complex composite structures. Compos Part A Appl Sci

Manuf 2017;95:346–58.

[14] Kim BC, Weaver PM, Potter K. Computer aided modelling of variable angle tow composites manufactured by continuous tow shearing. Compos Struct 2015;129:256–67.

[15] Kim BC, Zympeloudis E. Improvement of Fibre Placement Accuracy in Continuous Tow Shearing Process. 20th Int. Conf. Compos. Mater., Copenhagen: 2015, p. 19–24.