STEERED YARN INTERLACED, THICK & NEAR NET-SHAPE CARBON FIBRE PREFORMS

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Keywords: *Preforms, 3D reinforcements, Draping*

ABSTRACT

Carbon fibre reinforced polymer matrix composites (CF PMCs) are increasingly used in state-of-the-art aerospace applications. Aerospace manufacturers favour components made of CF PMCs over those made from traditional metallic alloys because of their light weight and corrosion resistance, which lead to significant improvements in fuel consumption and payload capacity. However, the manufacturing of CF PMC components is performed differently than traditional material at all stages of design, prototyping and production. This work presents a textile/preform manufacturing process for producing thick 3D preforms for liquid composite moulding processes. The custom preforms are designed individually towards parts of specific geometry. They are manufactured flat with in-plane steered yarns to enhance draping. The manufacturing process enables the production of thick, near net-shape preforms of variable thickness and levels of through-thickness yarn interlacing. The design & manufacturing process relies on kinematic drape optimization (CAD) software coupled with automated dry fibre placement machinery.

1 INTRODUCTION

Carbon fibre polymer matrix composites (CF PMCs) are increasingly used in state-of-the-art aerospace applications as they offer significant advantages over other common structural materials, namely metallic alloys. In the aerospace industry CF PMCs are highly sought after as their extremely high specific mechanical properties enable the design of lightweight airframes, which provide significant improvements in fuel consumption and/or increased payloads. Recently, major aerospace manufactures drastically accelerated the integration of CF PMC primary and secondary load bearing structures for civil aviation. This shift has facilitated the development of environmentally friendly, spacious and inexpensive civil aircraft to operate. Structural CF PMC components manufactured to meet strict tolerances and airworthiness requirements are typically manufactured using autoclave-cured prepreg. Manufacturing components from prepreg requires large capital investment towards acquiring the processing equipment. Furthermore, storage and handling of unprocessed prepreg contributes to added cost.

As a result of economic and practical limitations of manufacturing CF PMC components from prepreg, airframe manufacturers began exploring the use of out-of-autoclave and liquid moulding processes such as resin transfer moulding (RTM), RTM-light, vacuum infusion (VI) and resin film infusion (RFI) for making primary and secondary load-bearing aircraft structures and skins [1-6]. However, liquid moulding processes also present challenges; they require that dry preforms be manufactured by cutting, positioning and draping superimposed patches of dry textile material cut from roll-stock. The manufacturing of each preform is typically carried out manually and individually. This process is inherently time-consuming and introduces concerns over manufacturing consistency. Automating the production of dry preforms from roll-stock has been demonstrated [7, 8]. However, it suffers from severe limitations in the geometries that may be produced [9-11]. As a result, a production method for dry preforms as textiles requiring little or no further assembly or trimming work and close to final shape is, highly sought after. Preforms produced with such characteristics are referred to as 3D and net-shape respectively and their production has been investigated [12-24]. In an ideal scenario, such preforms would be suitable for a large array of PMC part geometries, manufactured using largely automated processes [25-28], exhibit high part-to-part consistency and feature fibre orientations optimized for processing [29] and structural performance. Designing and manufacturing such preforms as self-contained textiles demands thorough planning and understanding of limitations in preform construction. Often, changes must be made to the component geometry to ensure manufacturability.

This paper focuses on assessing the feasibility of manufacturing final-thickness, near net-shaped, drapable preforms featuring steered yarns for airframe components. It presents the major developments made to a process for producing thick 3D preforms with great versatility. The paper discusses the development of the overall process and implementation of automated manufacturing equipment suited to the automated production of the preforms. The equipment includes an electromechanical actuation system capable of interfacing directly with an instructing computer, and software post-processor that is capable of translating outputs from a drape optimization software developed at the University of Ottawa into an ordered set of instructions coded in a machine-language.

2 LITERATURE

2.1 Woven 3D Reinforcements

Three-dimensional weaving is an extrapolation of conventional 2D weaving where thick, multilayered fabrics are produced essentially by binding layers similar to conventional woven fabrics with an additional, third set of yarns spanning in the through-thickness direction of the fabric [30]. These yarns, referred to as binder or Z-binder yarns, are typically continuous filaments with a weight in the 50-500 tex (g/km) range, woven into the fabric. Binder yarns often run orthogonal to the layers of warp and weft yarns; they may also run at an oblique angle [18].

The two main types of 3D woven fabrics are known as 3D interlock and 3D orthogonal non-crimp. In the former type, warp, weft and binder yarns interlace to produce a fully interlocked fibre structure [18, 30]. The resulting fabric is analogous to a stack of conventional 2D fabrics bound together by yarns interwoven through the thickness of the preform in alternating directions [30]. In the latter type, warp and weft yarns are stacked as discrete layers similar to multiple stacked plies of unidirectional reinforcements. No interlacing exists between the structural warp and weft yarns. As a result, orthogonal non-crimp fabrics lead to composites with higher in-plane stiffness than those produced with interlocked 3D weaves [18]. Binder yarns are typically used for holding multiple plies of the warp and weft structures as one [31], or as structural yarns in warp-interlock woven reinforcements, providing through-thickness reinforcement [32]. Whilst binder yarns are woven into the fabric at volume fractions ranging 0.5% to 10% [30] and most often represent less than 10% of total fibre mass, they enable inter-laminar shear strength (ILSS) and impact properties superior to those of traditional laminates, at the expense of in-plane strength [1]. This makes woven 3D composites well suited to applications requiring high levels of damage tolerance, such as military airframes [1, 33].

Woven 3D reinforcements are produced using looms that are similar to conventional 2D weaving machines. Given the added mechanical complexity involved in producing fabrics that include a binder yarn, 3D weaving equipment is limited in terms of the diversity of fabric types that may be produced. One such limitation impacts the ability to produce fabrics with in-plane yarn orientated at angles other than 0°/90° [1, 18]. Hence, composites produced with woven 3D fabrics tend to have inferior performance compared to stacked multidirectional 2D weaves when subjected to shear and torsional loading [1]. As such, 3D weaves are sometimes deemed unsuitable for application in primary aerospace structures where materials well suited to resisting torsional and in-plane shear loading are required [1].

2.2 Stitched 3D Reinforcements

Three-dimensional fabrics can be produced by introducing an element of through-thickness reinforcement via stitching operations. High strength thread is inserted into stacks of unidirectional or woven fabric stacks such that it acts as a Z-binder and to lesser extent, structural reinforcement [1]. Stitching is achieved using equipment as simple as single needle machines similar to those found in households, or more complex setups that are capable of performing single sided stitching operations. Single sided stitching equipment is complex and often utilizes multiple computer-controlled needles that are housed in units mounted to articulated robotic arms. Stitching can be performed using various types of high strength threads of thermoplastic, glass, aramid or carbon fibre, depending on the application and amount of through-thickness reinforcement sought. Similar to various types of thread materials, various thread weights are available, the most commonly used in the range of 100-2000 tex (g/km) [30].

Various stitch angles (orthogonal and inclined) and patterns can be achieved using computer controlled equipment. The three most common locked-stitch patterns used are the lock stitch, chain stitch and modified lock stitch, the most popular type being the modified lock stitch as it imparts the least degree of crimp on the reinforcement's in-plane fibres [18]. Stitch can be inserted into fabrics at varying stitch density, usually in grid patterns. Surface stitch densities of 1 to 25 stitches/cm^2 are common, equating to stitch volume fractions of roughly 0.1% to 10%, similar to those observed in woven 3D fabrics [30]. Stitching is performed on fabrics after weaving or following some degree of preform layup, hence stitching can be used for introducing an element of through-thickness reinforcement without restriction on preform fibre directionality. This allows the production of through-thickness reinforced multidirectional laminates, and allows designers to introduce increased damage tolerance associated with the presence of Z-binders to laminates with in-plane mechanical properties resembling those of conventional 2D fabrics. Additionally, restrictions in terms of the maximum stitched preform thickness, approximately 40mm [34], rarely surface as a design concern.

2.3 Z-pinned and Tufted 3D Reinforcements

Z-pinning involves inserting pin-like reinforcing structures through the thickness of an existing preform or stack of fabric plies. Pins are usually made from extruded metal wire or pultruded fibre composite, with pin diameters ranging from 0.15mm to 1mm [18]. Z-pinning can be performed on dry reinforcements though it is most commonly used with prepreg, as is the only method by which through-thickness reinforcement can be applied to prepreg materials [30]. Many methods for inserting Z-pins exist including the UAZ® process which uses ultrasonic compressive stress-waves to drive pins into the reinforcement. The ultrasonic waves agitate the partially cured resin in the surrounding area and cause local heating. This action softens the resin and eases the insertion of the pin [18]. Once all pins are successfully inserted any excess, protruding pin material is shaven off and the composite is processed either in an autoclave or in the case of dry reinforcements, through one of the available LCM processes.

Tufting is comparable to one-sided stitching performed using a single needle and thread. Structural thread is inserted in the through-thickness direction using a hollow needle that punches through the reinforcement. After the needle penetrates the entire thickness of the reinforcement it is withdrawn along the same path, with tension removed from the thread. Friction between the inserted thread and the reinforcement fibres grips the thread, leaving it embedded in the material. The result is a non-locked stitch, similar in structure to that produced by a conventional sewing machine with a malfunctioning or empty bobbin. Tufting leaves excess looped Z-binders on the underside of the reinforcement. The excess binder thread is either kept or shaved off prior to preform processing. Tufting is a simple process that can be performed using relatively simple equipment. It typically uses high-strength yet highly flexible thread such as aramid or other organic-based filaments [30].

2.4 Dry Fibre Placement

Depositing reinforcing dry carbon fibres is similar to tape-laying and advanced fibre placement (AFP). In despite of large initial capital costs it offers potential operation cost savings from reduced material waste and elimination of the preform tailoring process [35]. The use of dry fibres eliminates some difficulties associated with the use of prepreg, primarily in regard to storage and processing. Further, dry fibres show consistent behaviour in temperature changes, eliminating the need for pre-heating or chilling operations that increase prepreg tack and aid in cutting respectively [36]. Eliminating the systems responsible for such operations would reduce overall complexity and cost of dry fibre placement equipment. Dry fibres do not possess the ability to adhere or tack like fibres pre-impregnated with a partially cured resin. As such, dry fibre placement is usually performed by depositing fibres onto a flat substrate rather than on a mould of geometry similar to that of the finished component. The completed dry preform is subsequently formed into its contoured, three-dimensional shape during LCM-type processing, which imparts its intended geometry to the final component. As such, tow placement reduces tooling and set-up costs, simplifies preform handling and enables processing to be performed off site and/or at a later time [35]. Dry fibre placement technology is generally proprietary; few commercial units are available for procurement [35].

3 MANUFACTURING PROCESS

3.1 Overview of the Manufacturing Process

Physical preform manufacturing occurs in two distinct operations, implemented in two distinct machines: the laydown machine (LM) and the contour stitching machine (CSM).

Manufacturing begins on the LM, a CNC-device with four axes of motion and two service axes. The LM tracks above a part-specific manufacturing substrate while depositing individual tows. Deposition continues until the specified preform geometry and thickness are reached. The deposited tows are then transferred to the second machine, CSM, where a thermoplastic or semi-structural stitch is inserted to assemble the tows into a preform. The stitch secures the tows in final position; when sewn with a semi-structural thread it can provide limited through-thickness reinforcement.

3.2 Laydown Machine (LM)

The laydown machine (LM) was developed to automate tow placement, Figure 1. The machine operates on principles similar to those of tape or towpreg laying systems but the development of the LM was centred around deposition of dry carbon tows, most commonly 12K. Carbon tows are deposited via a deposition head that tracks above a large aluminium base using step motors actuators, Figure 2. The tracking system incorporates four position actuators, three linear (X,Y,Z) and one rotational (A), with open-loop control of the head's position, velocity and acceleration along four degrees of freedom (DOF). Additionally, the LM has two service axis (V, C); the V axis is used to control the tow pay-out system and the C axis is used to control the cutting system. Tows are deposited by tracking the deposition head along the intended trajectory and coordinating tow pay-out with tracking velocity. By coordinating motion along linear axes X and Y with rotation around the A axis, curved tow paths can be deposited in the X-Y plane, allowing production of reinforcements with local variations in tow spacing. Similarly, tow paths may be curved to better orient fibres along principal loading axes or to navigate around cut-outs and other structural or assembly features.

Laydown begins by positioning and levelling of the substrate designed for the intended reinforcement geometry, Figure 3. The deposition head is brought in contact with the substrate reference point and the head position is registered. A continuous carbon tow is loaded into the deposition head and final pre-operation checks are performed. The LM is programmed by loading a specific NC program and a cue for machine start is given, beginning tow laydown.

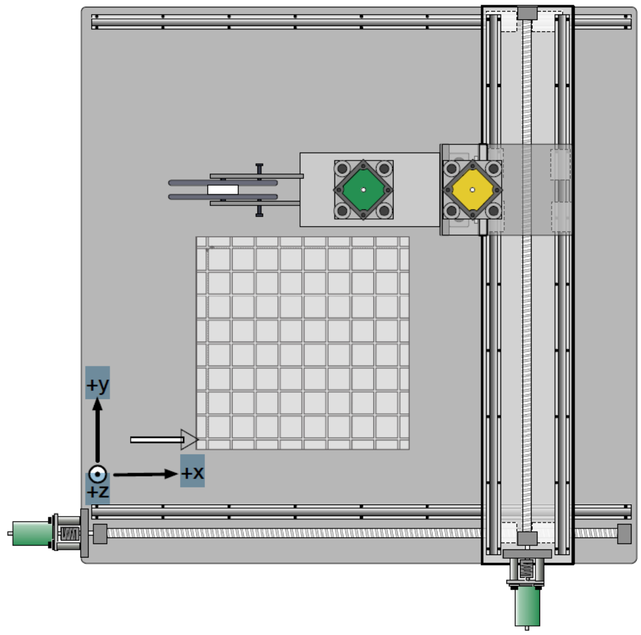

Figure 1. Laydown machine top view: solid arrows are machine's coordinate system; hollow arrow is substrate's first pin

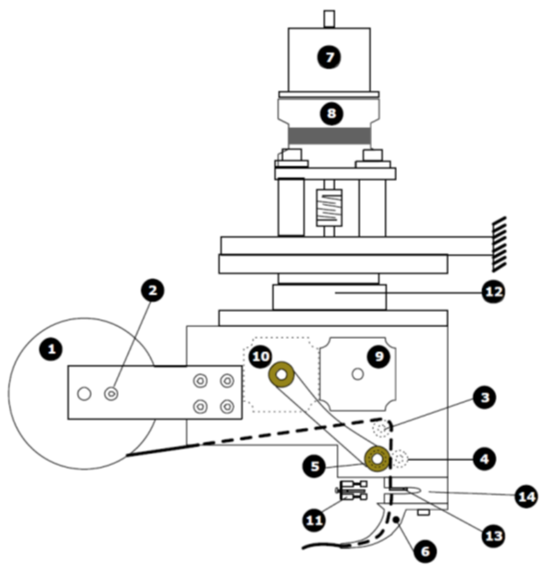

Figure 2. Components of the pay-out system: 1 tow reservoir, 2 inbound tow tensioner, 3 routing roller (idle), 4 traction tension roller (idle), 5 driven traction roller, 6 feed nozzle, 7 A axis stepper motor, 8 planetary gearbox, 9 C axis (cutting) stepper motor, 10 V axis (payout) stepper motor, 11 cutting carriage, 12 head-rotation, bearing, 13 fixed blade, 14 cutting block.

a) b)

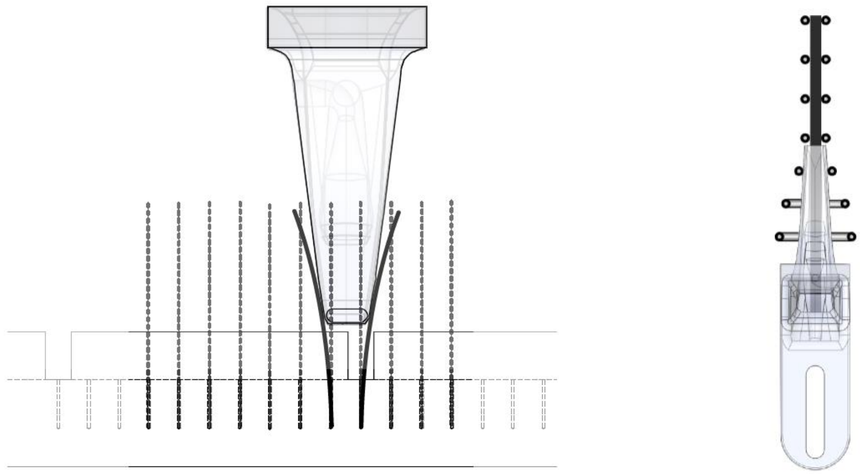

Figure 3: Interaction of feed nozzle and substrate pins. (a) Front view, pins' neutral positions show in dotted line; solid lines show pin's deformed positions. (b) Top view, interaction of feed nozzle and substrate pins.

3.3 Contour Stitching Machine (CSM)

The contour stitching machine (CSM) is an automated two-sided stitching machine, the second machine used within the process, Figures 4, 5. The CSM inserts lock stitch lines into the preform in the through-thickness direction. The stitch is primarily intended to hold tows within the position they were deposited in; transforming the output of the LM from an organized but loose stack of tows into a sturdy preform able to withstand handling and processing operations. Stitching may be performed with thermoplastic or semi-structural thread. When the latter is used, limited structural through-thickness reinforcement may be provided. A thread weight of 27-60 Tex [g/km] is typically compatible with the CSM stitching head. One important feature of preforms manufactured using the process is that in order for them to be drapable, stitch lines must be implemented along paths that correspond to those of the tows. If tow paths are curved, stitch lines must be curved, which may be created using the CSM.

Stitch points may be inserted at variable density along a stitch line. However, generally a pitch of least one stitch per tow is inserted, holding each individual tow. The pattern most commonly used inserts a stitch over each tow, where the sewing needle inserts stitch at the points were substrate pins contacted tows during deposition, Preforms specifically manufactured to comply with a design must be stitched along the path of tows.

4 SOFTWARE IMPLEMENTATION

4.1 Laydown Post-processor Background

Software algorithms are the foundation of the postprocessor. The post-processor, which is written in the MATLAB language, is used for translating the design outputs obtained from proprietary uO-Drape software into G-code which is used to run the LM and CSM. The post-processor can be broken into numerous elements: sub-operations and subroutines. Each elements performs a distinct function that contributes to generating a G-code file. Many of these elements are required in multiple instances through a single run of the post-processor; However, their algorithms do

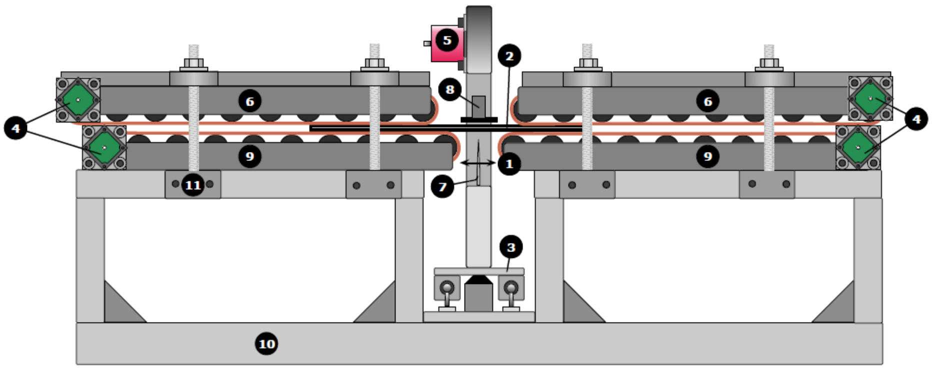

Figure 4. Side view of the CSM; 1 stitching gap, 2 preform and frame, 3 Y axis linear carriage, 4 X axis conveyor steppers, 5 stitching head and Z axis stitching head stepper, 6 X axis top conveyors, 7 sewing needle, 8 rotary hook bobbin, 9 X axis bottom conveyors, 10 base chassis, 11 top carriage alignment screws.

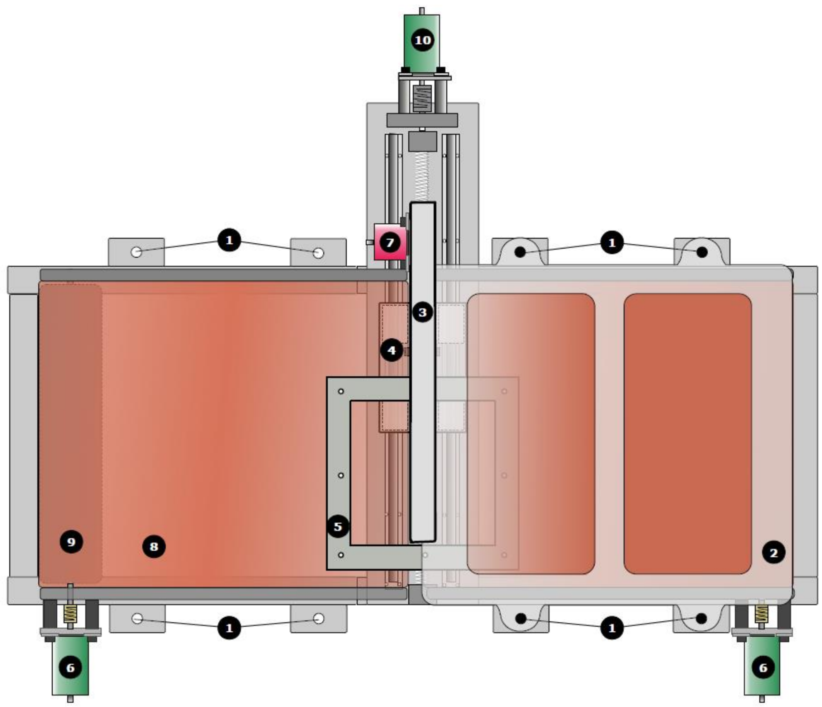

Figure 5. Top view of the CSM shown with top-left conveyor removed and top-right conveyor semi-transparent; 1 alignment screws, 2 X axis top-right conveyor chassis, 3 stitching head, 4 Y axis stitching head carriage, 5 preform/frame, 6 X axis conveyor steppers, 7 Z axis stitching head stepper, 8 X axis bottom-left conveyor, 9 X axis bottom-left conveyor drive roller, 10 Y axis carriage stepper.

not change. G-code is generated by the post-processor via progressing through the flow of the post-processors main algorithm shown in Figure 6.

Running of the post-processor starts by providing files obtained from a uODrape simulation. Next, the post-processor is passed a number of parameters by the user. These parameters inform the post-processor about the aspects of LM and CSM operation which are independent of the manufacturing geometry; parameters include: tow laying rate, feed rate and how many time the tow cutting cycle should be repeated per tow. Next, an NC file is created and is initialized with headers that format the file for the LM and CSM. The position generator is summoned to calculate the coordinates for where tow intersections are located. After intersection coordinates are determined, the X and Y direction G-code generators can begin writing G-code instructions to the NC file. The tow cutting and clearing G-code generator is summoned after each laydown cycle to separate the tow from the deposition head.

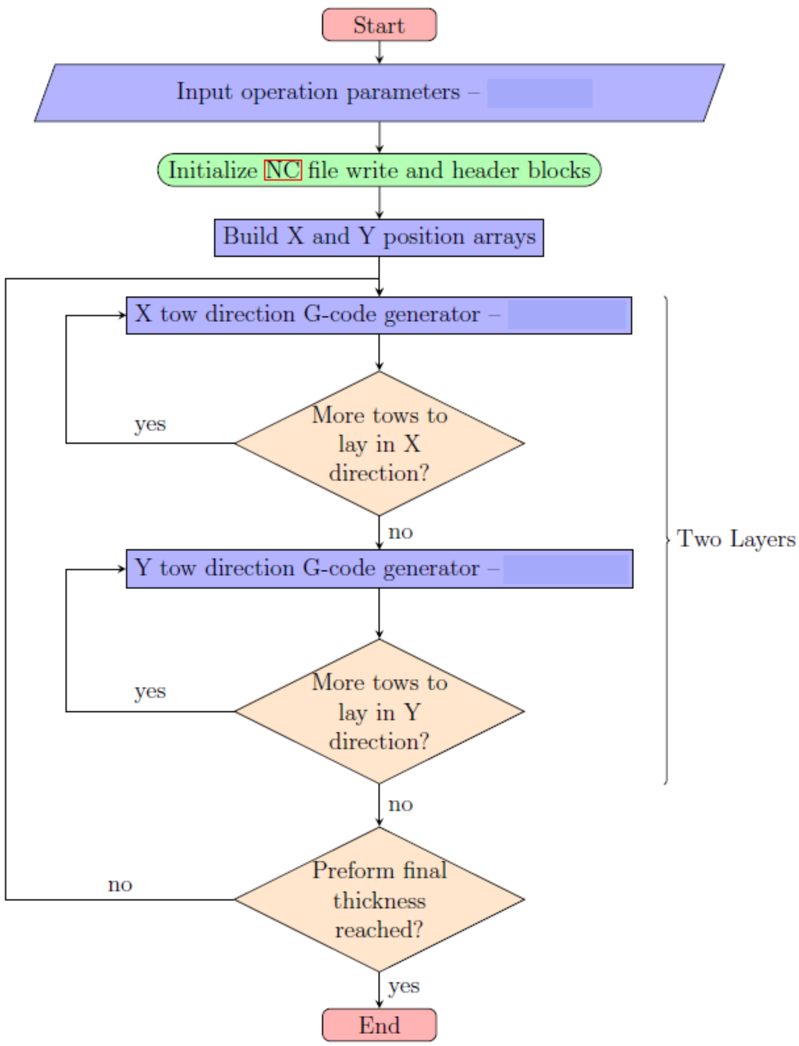

Figure 6. Post-processor for G-code generation (pointGenerator.m) flowchart.

4.2 Input: uO-Drape Tow Spacings Lengths

After a composite component's preform is designed in uO-Drape, Figure 7, tow paths within the designed preform are mapped onto flat for manufacturing. uO-Drape outputs this flat design as a set of two CSV files, which contain the name of the design and an appendage: `XLengths' or `YLengths'. The XLengths file contains tow spacings along the X direction and the YLengths file contains spacings along the Y direction, where the spacings stored correspond to locations of tow intersections.

The XLengths and YLengths files each consist of a 501 rows by 501 columns array where the row and column indices map to physical rows and columns of tows in the grid-like arrangement in which they appear in the preform. For example, the initial spacing in the X direction between the 14th and 15th tows running in the general X direction is given by the cell XLengths[15; 1]. uO-Drape always outputs Lengths files of size 501 by 501, limiting the maximum dimensions of a manufactured geometry to approximately 501 tow-widths by 501 tow-widths. However, larger preforms may be manufactured by combining multiple uO-Drape outputs and inputting them into the post-processor.

When the lengths files are inputed to the post-processor they are mapped to two 501 by 501 arrays within the working memory of the post-processor respectively named x file and y file; these files are of identical format to the lengths files. As only non-zero and positive array indices are permitted within the MATLAB programming language, median tows in the centre of the preform are mapped to the median row and column within each array: row 251 and column 251. Following this notation, the tow intersection located in the top-right corner of the preform corresponds to indices [1; 501].

4.3 User Input: Machine Operation Parameters

The post-processor requires the user to input machine operation parameters. These parameters control the machine's tracking speed as well as other aspects that ensure reliable and safe operation. The operation parameters and their default values are displayed in Table 1. As they are critical to safe machine operation, parameter values are intentionally provided in imperial units.

4.4 Output: NC-File Initialization

First a NC file is created and four initial code blocks are written to it. The code blocks are:

```
%
G20 (inch selection)
G17 (XY plane selection)
G90 (absolute coordinates)
```

These blocks format the file as G-code which will operate with the LM or CSM. The first block informs the MCU where the code begins, and the following three insure that machines will run as intended. Three more code blocks are appended to the file:

```
G40 (cancel tool radius compensation)
G49 (cancel tool length offset)
G80 (cancel canned cycles)
```

These blocks are used to cancel any programmed cycles or position offsets, which may remain within the MCU's memory from previous manufacturing operations. Further details and a complete description of algorithms can be found in reference [37].

Parameter	Symbol	Default value	Unit
Geometric parameters			
Nozzle offset length	R	1.0	[in]
Forward cutting length - scissor advance	fcl	150.0	[1]
Backward cutting length - scissor return	bcl	3.0	[1]
Tow bleed length	yb	0.0	[in]
Tow height	yh	0.0079	[in]
Feed nozzle length	nl	3.5	[in]
Feed-from height (must have $fh > ch$ & $fh < sh$)	fh	0.25	[in]
Spool-out height ($ch < fh < sh$)	ch	0.0394	[in]
Safe (rapid) height ($sh > fh > ch$)	sh	0.875	[in]
Tow clearing length (distance traveled to allow the tow to eject from nozzle after each lay)	ycl	4.0	[in]
MCU position for deposition head at 90^o	noznine	233.3	[1]
MCU position for deposition head at -90^o	nozineneg	-233.3	[1]
Non-geometric parameters			
Compaction pause after each layer (1 for yes, 0 for no)	pau	1	[1]
Number of cutting cycles	cn	3	[1]
Rates			
Feed rate	fs	90.0	[in/min]
Plunge rate	ps	10.0	[in/min]
Nozzle preload rate	ns	36.0	[in/min]
Nozzle clearing rate	cs	35.0	[in/min]
Head rotation rate	hs	200.0	[1/min]
Cutting rate	cfs	200.0	[1/min]

Table 1. User provided machine running parameters; the unit presented for each parameter is critical to proper machine operation.

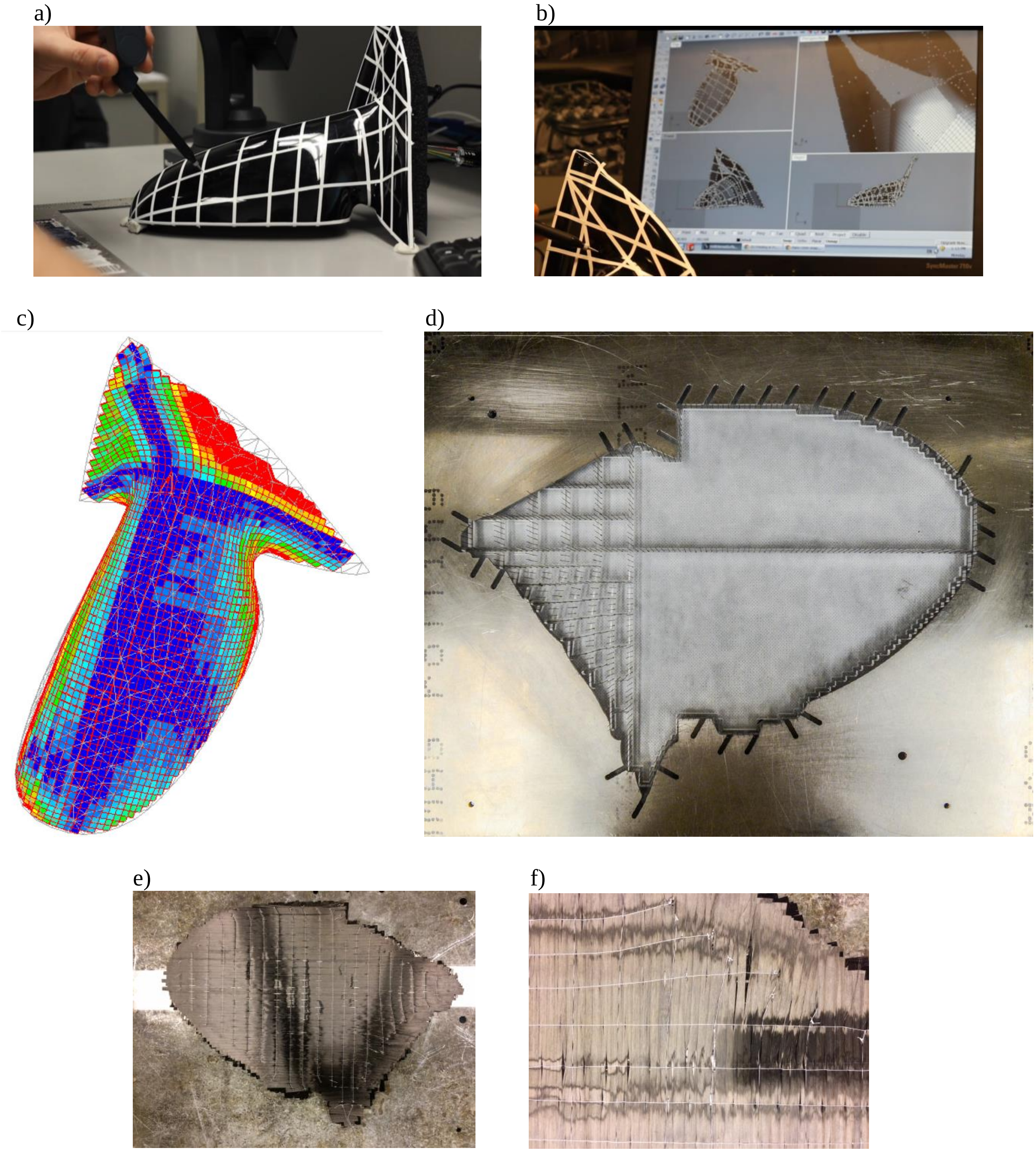

Figure 7. Design and make of a preform. a) Initial geometry. b) Acquisition of geometry. 3) Design of preform optimized for drape coverage. d) Plates and substrate for guiding of tows. e) Preform. f) Detail.

5 CONCLUSION

Objectives for the work were completed successfully. The process was developed through design, manufacturing and implementation of the equipment and support systems necessary to automate manufacturing of preforms with the characteristics sought.

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