PREDICTIVE SOFTWARE TOOL FOR THE DESIGN OF MANUFACTURING PROCESSES FOR TEXTILE PREFORMS

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ABSTRACT

The design of the sequential process operations involved in the manufacturing of multilayer textile preforms used in liquid composite moulding (LCM) processes such as infusion and light RTM is heavily dependent on the input of highly experienced expert staff. In a context of manual draping, the choice of a specific draping strategy is crucial to the control of manufacturing costs and to the quality/consistency of the preforms to be produced. The number of different potential draping strategies that could be implemented for producing preforms for a part of a given geometry is very large, with numerous variable parameters to be selected: fabrics, numbers of patterns, draping starting points and starting orientations, sequence of draping operations, and the positioning of pattern joints must all be defined. In most industrial cases this selection must be done quickly in a context of competitive tender, without a physical mould available for development trials: engineers must determine how to drape the preform for maximum cost and maximum quality, and they must do this quickly. Whether physical trials can be conducted or an available draping simulation software package is used, the design of preform manufacturing process operations is often done by trial and error, with the simple goal of identifying one draping sequence that simply works. Current technology for draping simulation does not enable systematic probing of a large number of potential draping strategies, with the goal of identifying the best one - and producing a plybook for it. Even if the most advanced software tools available are used.

This paper discusses a predictive software tool for the design of manufacturing processes for textile preforms, which fulfils this objective. CAD models of industrial parts are split into areas of no curvature, single curvature and double curvature, starting from local sub-surfaces – labelled base surfaces – readily defined in CAD models. These base surfaces are parametrised using the conical frustum, a mathematical tool developed for this work. Once the parametrisation is complete, draping strategies are created using a dynamic programming optimization Tabu search algorithm. Two databases are queried repeatedly when evaluating draping strategies: the first database features yarn orientations and shear angles defined over parametrized base surfaces – hence a database of results obtained using existing draping software over 'building blocks' surfaces. The second database features mechanical properties of dry fabric stacks in bending, bending spring back, in-plane shear, and friction. Both databases use base surface parameters as input, along with the starting position, initial yarn orientations and initial shear angle for the draping of each base surface. A cost and a quality are calculated for the draping of each base surface draped following a given strategy, and values are summed for the complete strategy. Total sums are compared for different strategies and the most favourable strategy is chosen for the production of a plybook.

The different components of the software tool are briefly presented.

1 INTRODUCTION: OBJECTIVE, CONTEXT AND LITERATURE

1.1 Objective

The work concerns the design and manufacturing of multi-layer textile preforms for non-structural aeronautical parts made by LCM where yarn orientations aim at faster and more reproducible draping only. Costs associated with fibre loss are minor; greater losses are justified if they accelerate and/or simplify draping. The focus is the design of industrial methods, steps and patterns for manufacturing the preforms, known as preforming. The aim is to develop software that designs the preform and associated patterns for a given part geometry, selects the reinforcement, locates darts and anchors, identifies the sequence of manufacturing steps, and produces a plybook. The software identifies the option that maximises quality through low variability, and reduces manufacturing time hence cost.

1.2 Context

Draping software that predicts yarn orientations and fabric shear resulting from draping over complex geometry is available [1, 2]. However, usefulness to industry is limited in terms of connection to actual practice and preform design process. 1) Draping software do not simulate practical aspects of preforming such as darting, anchoring, or localised binders. 2) They do not account for different behaviors of different fabrics; for spring back in bending, on corners and in shear; or for preforms being made from multi-layered stacks and not single plies. 3) Preforming time and variability are not considered. 4) Most preforms are not made from a single continuous multi-layered stack of fabric. Limits on fabric drapability require several multilayer stacks, called patterns, each covering part of the mould; hence a preform consists of neighbouring patterns overlapping at lap joints. Preforms are made of a few patterns featuring superimposed plies of the same fabric, stacked in the same orientation then cut simultaneously to specific shapes. Low numbers of patterns draped in few steps reduce preforming times. Draping software do not consider the existence of patterns, the positions of joints, nor the sequence of manufacturing operations. The information obtained from current software is not superior to what an experienced technician can deduce by observation. Preform development remains a matter of trial and error, whether draping software is used or not.

1.3 Base surfaces and databases

Any CAD geometry of a mould to be draped is split into parameterized base surfaces (BaS) defined as planes, single and double curvature surfaces, and torsion surfaces. The core concept of this work is to perform draping simulations and fabric characterization prior to the industrial partner receiving any mould geometry, via two databases independent of any specific mould geometry to be analyzed. Database A features drape results for base geometries structured according to geometrical parameters (lengths, radii, angles) and layup parameters (start position, shear angle and orientation). Database B quantifies the loading and spring back behavior of fabric multilayers in bending, shear, over small radii corners, and the localized effect of friction and anchors. Upon reception, a mould geometry is split into parameterized base geometries. The core optimization algorithm queries databases A and B for numerous manufacturing scenarios (sequence of steps) to identify the scenarios/sequences that lead to low cost and high quality. Cost and quality are respectively proportional to sums of terms of strain energy required for draping all base surfaces along a given sequence, and to variability of said strain energy terms. The optimal sequence is coded into a plybook and instructions for a cutting table. All aspects are discussed further in following sections.

1.4 Literature

The shear behavior of single plies reinforcement was investigated extensively [3]. The shear behavior of multilayer stacks and the effect of misalignment between plies was also investigated [4]. The effect of misalignment on behaviour measured in hinged frames was noted [5]; however, this does not fully reflect industrial reality where relative displacements in stacked plies are possible during draping. Work on fabric shear has led to kinematic software for predicting orientations in single plies [6]. FEA draping/forming simulations were reported for dry fabrics [7] and textile prepregs [8]. However, demanding pre-processing, calculations and characterization efforts are not suitable with the rapid investigation of many scenarios needed here. Moreover, variability is not considered in such work. Finally, the forces required to impart various deformations to the fabrics are of no practical interest.

The bending behavior of single reinforcement plies was queried extensively [9]; the effect of the fabric structure was observed. An experimental method was proposed [10] to quantify spring back of single plies in single curvature bending. Few results describing the bending behavior of multilayers are available. Work on inter-ply friction was also produced [10], aiming at determining whether the plies of a multilayer stack tend to move as a whole or as individual relative to the others, when the stack is bent around a small radius.

2 BaS GEOMETRY, YARN ORIENTATIONS, IN-PLANE SHEAR, DATABASE A

2.1 Conical frustum

Complex mould surfaces are split into base surfaces that classify as flat, single curvature or double curvature, with or without twist. When draped in a sequence, each BaS alters yarn orientations and in-plane shear as a function of its geometric parameters, and draping parameters start position, shear angle and orientation. BaS geometry is parameterized using the conical frustum, a mathematical tool devised as a part of this work. Figure 1 shows BaS on a mould, the frustum geometric parameters, and measurement. Mathematical detail appear in [A].

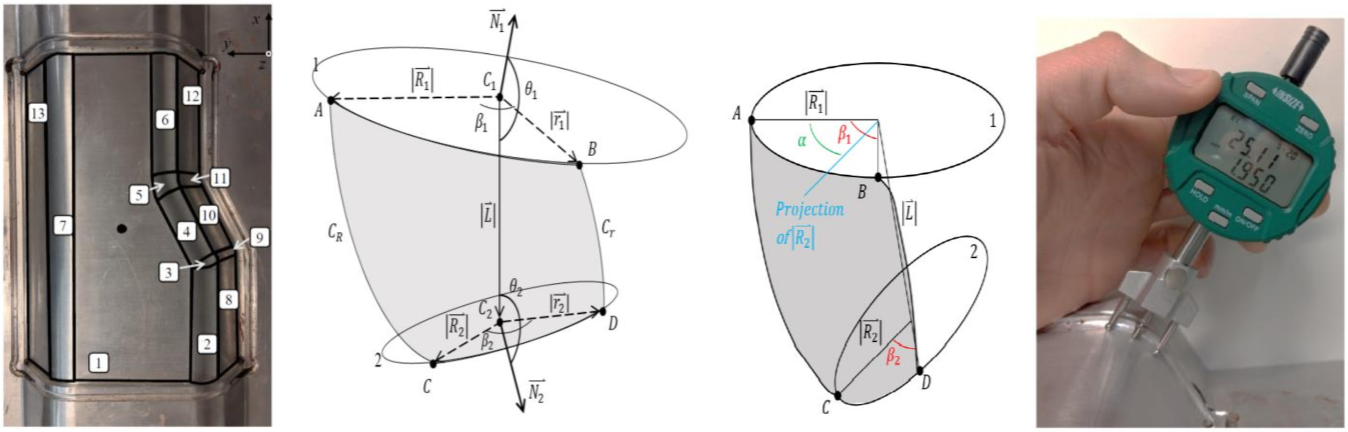

Figure 1. Base surfaces, conical frustum and its geometric parameters, along with measurements on mould [A]

2.2 Database A: yarn orientations and in-plane shear angles

Yarn orientations and in-plane shear angles were obtained for parametrized BaS through draping simulations [1] performed once, prior to work done on any mould, and stored in database A. The frustum geometric parameters and draping parameters, are used for structuring database A. Therefore, yarn orientations and shear angles can be retrieved quickly from database A upon draping a given BaS in a sequence being evaluated – all simulation work was done prior. Figure 2 shows example of results for draped BaS with set geometric and draping parameters.

2.3 Database A structuring & populating, Taguchi plans, parameter hierarchy

Database A will potentially contain a very large amount of results even with only two modalities for each geometric and draping parameter. Database A was structured using Taguchi plans, enabling a drastic reduction in the number of simulations minimally required for populating the database. Taguchi plans offer clear quantification of parameter

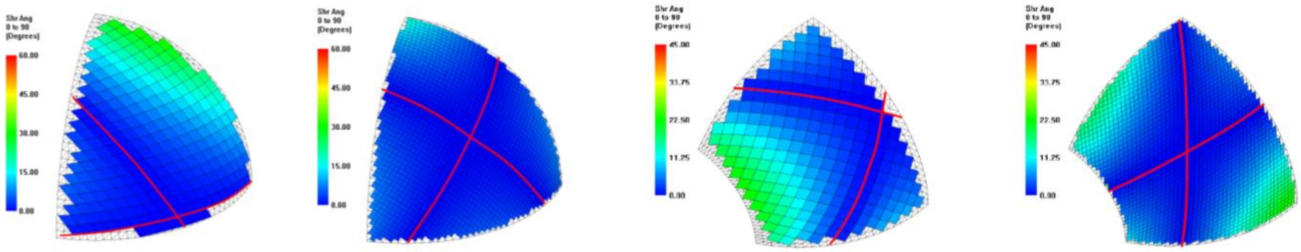

Figure 2. Draping simulation results on two BaS, each with two sets of draping parameters [A]

effects and their hierarchy. They also lead naturally to linear interpolating functions between database results [B]. Interpolating is needed as parameters of BaS on industrial moulds will never match the discrete parameter modalities in the database exactly. Populating database A is an ongoing process; Figure 3 shows average shear values and interpolation results for set combinations of parameters, as the amount of information in the database increases. Interpolations are good even with few interactions, and they improve progressively with more. Parameter modalities and the processing of orientations and shear angles along BaS edges into output responses appear in [A].

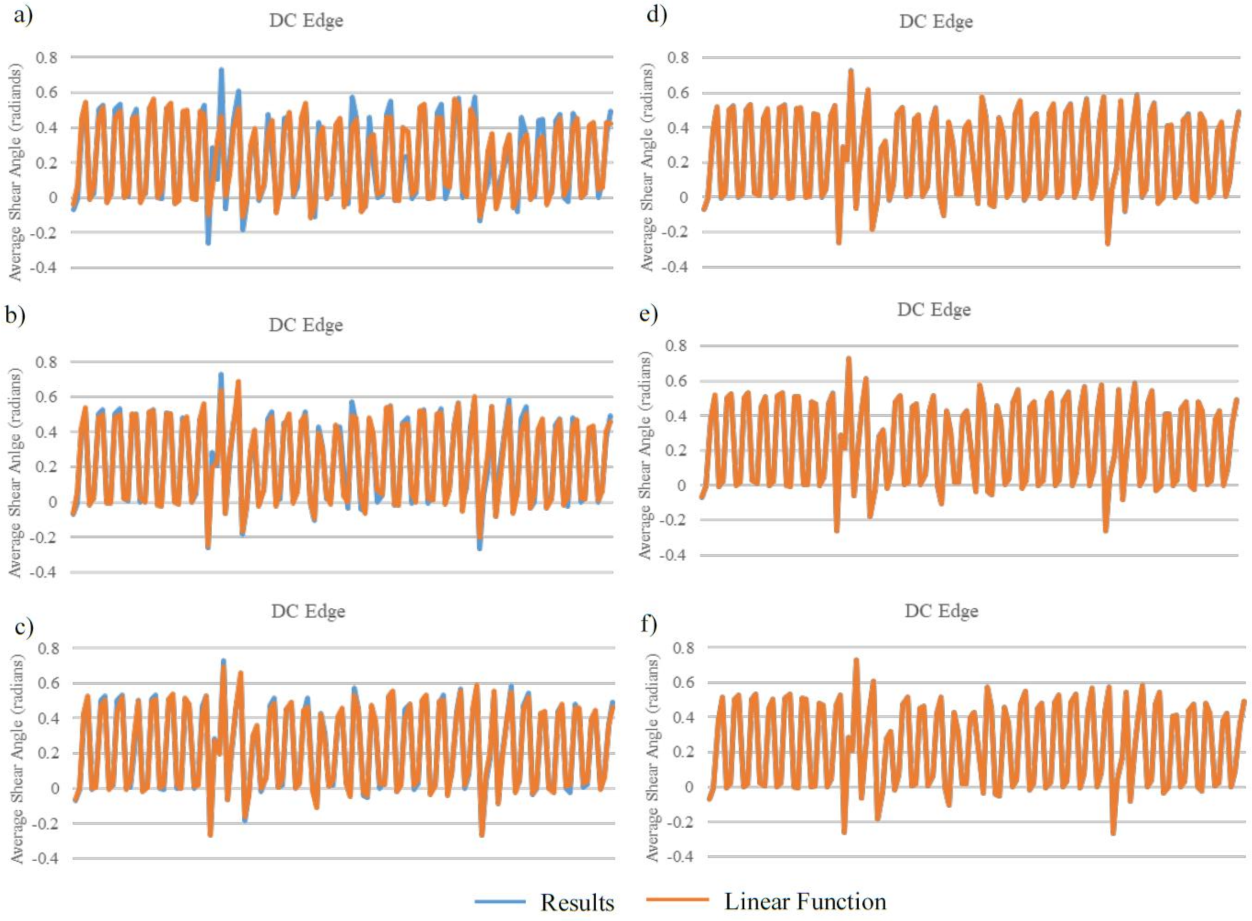

Figure 3. Line plot comparison: a) interactions of 2; b) interactions of 3; c) interactions of 4
d) interactions of 5; e) interactions of 6 f) interactions of 7 parameters

3 MATERIAL PROPERTIES OF REINFORCEMENT STACKS, DATABASE B

Challenges in draping and their relations with measurable material properties were identified by expert technicians. Relevant material properties of industrial reinforcements were quantified for single layer and multilayer stacks: bending stiffness and bending spring back, in-plane shear stiffness and spring back, friction between plies and on moulds, and stability of the fabrics at anchors. All tests were conducted along the warp (0°), weft (90°) and bias (45°) directions for three reinforcements. Strain energy and variability were quantified for all tests.

3.1 Bending and in-plane shear stiffness

Bending stiffness was characterized using cantilever bend tests following a modified version of ASTM-F3260 [C]. The in-plane shear behaviour was characterized using picture-frame shear tests. Results appear in [D], Figure 4.

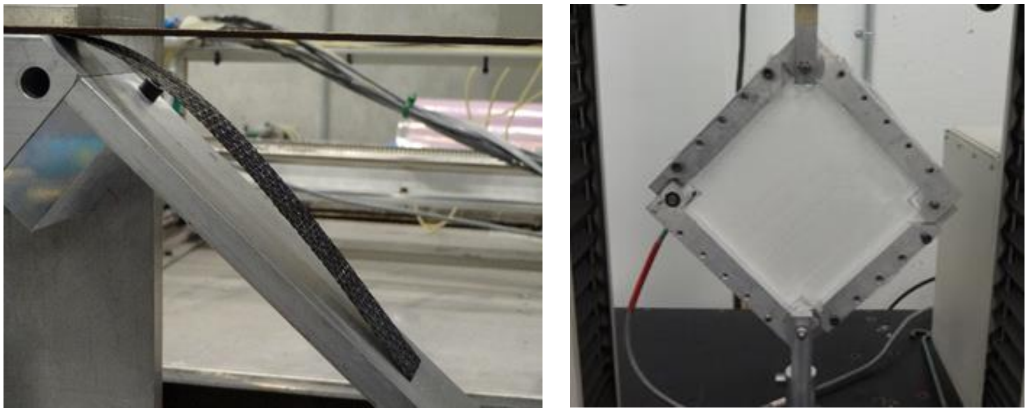

Figure 4. Testing for bending and in-plane shear stiffness [D]

3.2 Bending spring back, in-plane shear spring back, friction, stability at anchors

New testing methods were developed for characterizing bending spring back, in-plane shear spring back, friction between plies of fabric and with moulds, and fabric stability at anchors. In bending spring back tests a fabric or fabric stack is draped on a small radius mould and load is released. Spring back data were obtained for convex and concave corners of radii 0 mm to 12.70 mm (1/2”), Figure 5. Results appear in [D] and will be published separately.

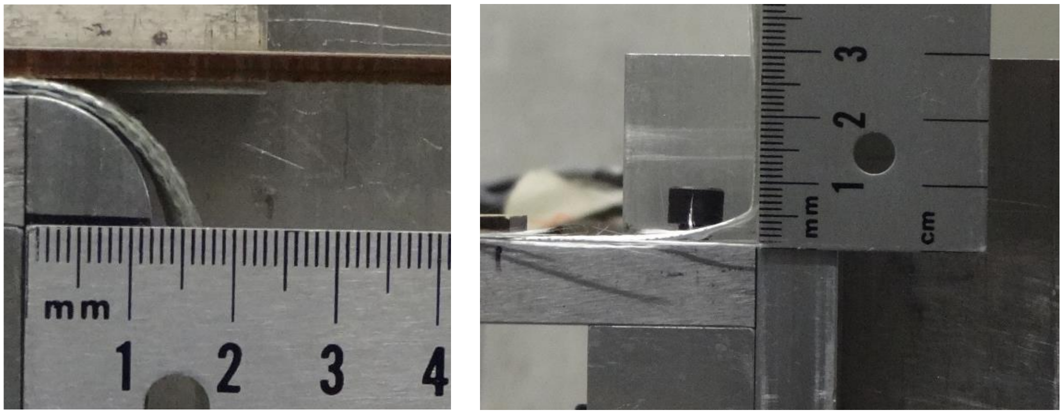

Figure 5. Testing for small radii, convex and concave bending spring back [D]

Load was recorded during both loading and un-loading phases of picture-frame in-plane shear tests. The angle at which shear force returned to zero was used for characterizing in-plane shear spring back of fabrics. Typical curves featuring variability and spring back appear for single layers and multilayers, Figure 6. Friction tests were inspired by ASTM-D1894 [E]. A universal tensile frame was used for sliding a bloc over a reinforcement; load was used for calculating the coefficient of friction. Stability at anchors involved measuring the load-displacement curve in the plane of an anchored fabrics up to the point of fabric disentanglement. No additional details can be provided here.

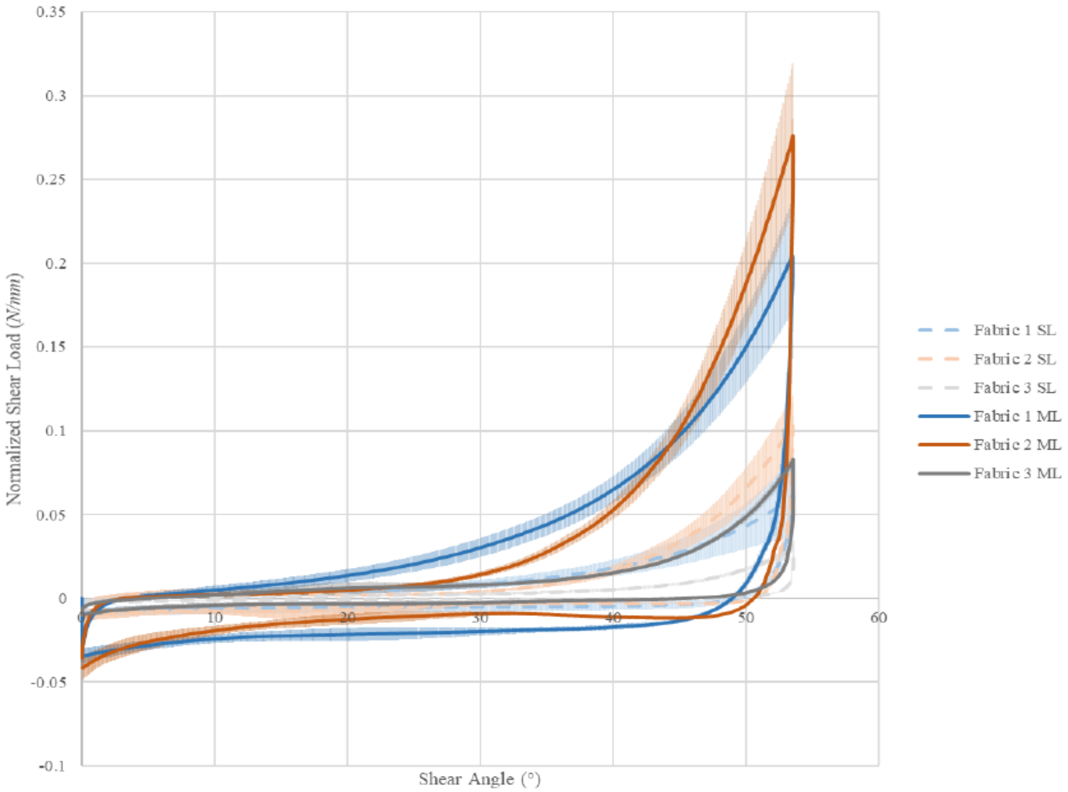

Figure 6. Typical in-plane shear curves featuring variability and spring back, single layers and multilayers [D]

3.3 ANOVA and strain energy terms

Parameter hierarchy for experimental tests was determined using ANOVA [B]. Typical results appear in graphic form in Figure 7 for convex spring back of single layer and multilayer stacks over a 1.59 mm (1/16”) radius. Further details are available in [D]. Numerical methods for calculating terms of strain energy associated with all deformation loads listed above were developed. Strain energy was calculated for each test. As all tests were replicated 10 times, hence variability of strain energy was also quantified for all reinforcements and test conditions. Mathematical detail appears in [D]. The aim is to sum the strain energies and their distributions to identify the draping strategy requiring the least energy towards lower cost, as well as the draping strategy showing the least variability towards quality.

4 COST AND QUALITY FUNCTIONS

4.1 Continuity of orientations

Warp and weft orientations in database A are defined using local set of axes. Continuity of warp and weft yarns from one BaS to the next is attained by using output from database A for a draped BaS as input to database A for

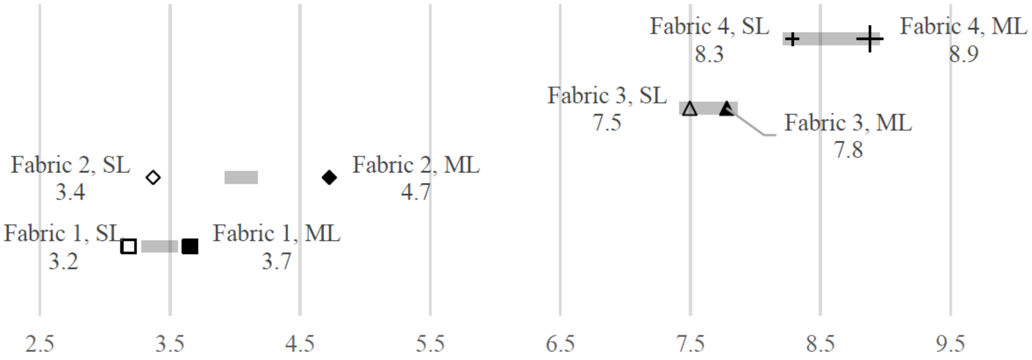

Figure 7. Typical ANOVA results, convex spring back, single layer and multilayer, 1.59 mm radius [D]

the next BaS to be draped. Conversions of references axes are achieved using vectors defining the common edge of both BaS [F]. An example of a starting point and common sets of axes at the edges appears in Figure 8.

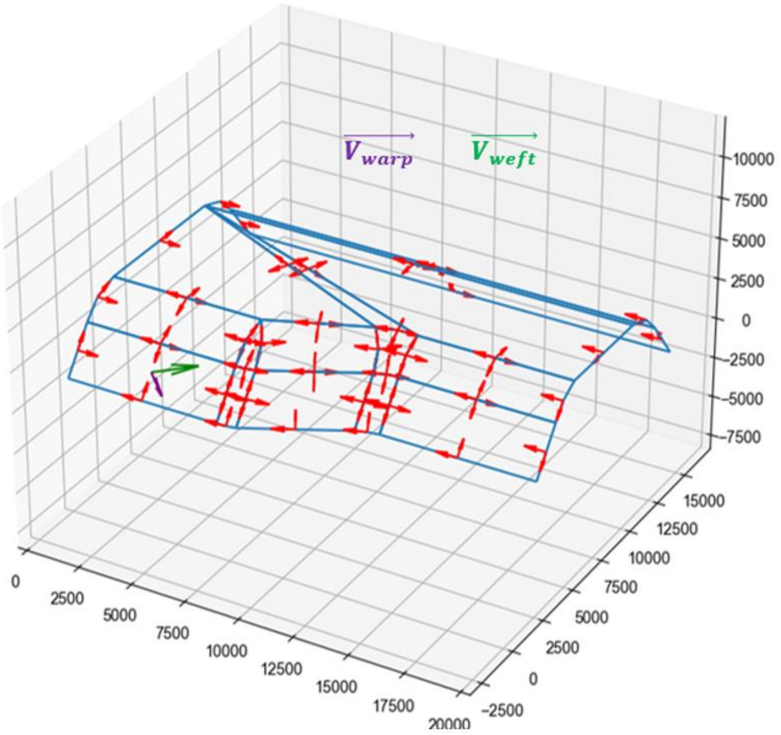

Figure 8. Drape starting point and sets of axes common to neighbouring BaS [F]

4.2 Cost and quality functions

Cost and quality for a given draping strategy are defined by functions. Cost is proportional to the sum of strain energy terms associated with all deformation modes and all BaS making the surface of the mould. Amplitudes of strain energy terms depend on BaS geometry, draping input parameters and mechanical behaviour of the textile stacks draped over the BaS. Quality is inverse to the sum of strain energy variabilities similarly associated with all deformation modes and all BaS. The hypothesis for cost is that a pattern that requires more energy to be draped over a BaS will require more manual effort and time as it undergoes more strain, be it in bending or shear, and to stay in position once draped; bending a thicker stack to a small radius and keeping it in position will require more strain energy, and cost, that draping a thinner stack over a flat surface. The hypothesis for quality is that stacks showing more variability in mechanical response as they are draped will lead to a more variable preform overall. Considering m deformation modes j = 1 to m and a sequence covering BaS i = 1 to s, equations for the total strain energy $E_t(i)$ for BaS i and all m deformation modes j, total cost C for one sequence, total variability in strain energy $\Delta E_t(i)$ and total quality Q for the same sequence are as follows:

$$E_t(i) = \sum_{j=1}^{m} E_{BaS}(i,j) \tag{1}$$

$$C \sim \sum_{i=1}^{s} E_t(i) \tag{2}$$

$$\Delta E_t(i) = \sum_{j=1}^{m} \Delta E_{BaS}(i,j) \tag{3}$$

$$Q \sim \frac{1}{\sum_{j=1}^{m} \Delta E_{BaS}(i,j)} \tag{4}$$

Terms in (1) and (3) detailing the contributions of strain energy in bending, bending spring back, in-plane shear, shear spring back, friction and anchoring are presented in [16].

5 GENERATING AND EVALUATING DRAPING SEQUENCES

5.1 *Defining sequences*

Draping sequences are lists of transitions between individual BaS, hence they are written as successions of edges common to neighbouring BaS. Draping continues until the mould is covered or drapability limits of a fabric are reached, in which case a new pattern is started. Figure 9 illustrates vertices, edges and mould direction.

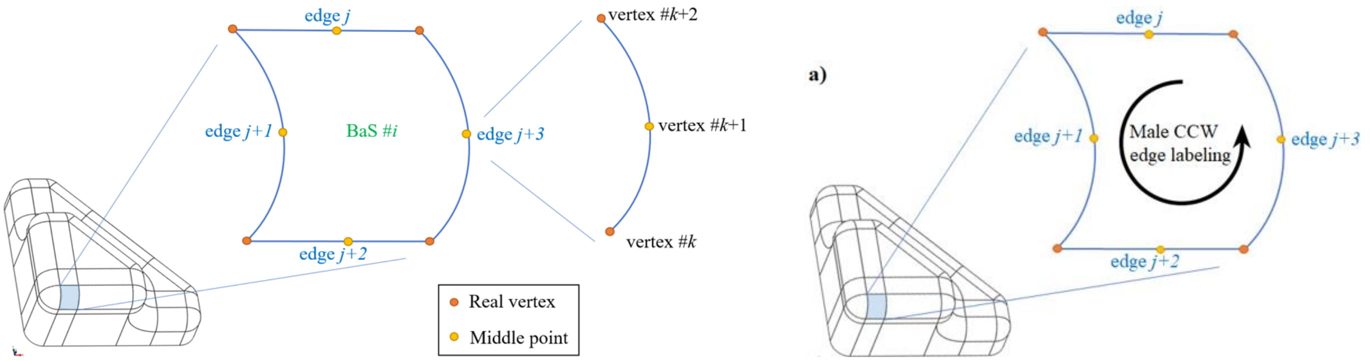

Figure 9. Examples of vertices, edges, BaS and direction for a full mould

5.2 *Enumerative techniques, dynamic programming, tabu search*

Exhaustive numerical optimization methods were not retained as they are not viable for BaS numbers beyond ten. Enumerative techniques were favoured in writing code that creates sequences simulating draping progression. Dynamic programming (DP) is highly suited as it identifies a global optimum from several local optima. At every step along a sequence, cost and quality are evaluated from all BaS available for progression along multiple branches, Figure 10. The solution is obtained through recursive optimization of every decision along the decision sequence. DP has proven its efficacy for trajectory optimization [17], which applies to this work as the draping process is a trajectory made of a series of sequential decisions.

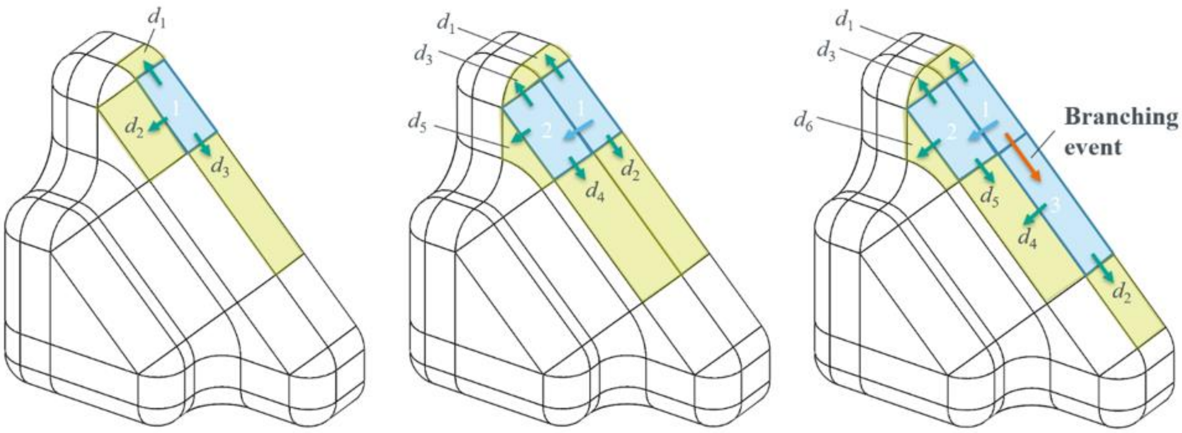

Figure 10. Decisions made at different points along branches of draping sequences

A guided random search technique (GRST) tabu search (TS) was also implemented as an alternative enumerative solution [18]. TS lists information from previously calculated solutions to avoid reprocessing. The approach avoids cycling around local optima through weak inhibition of certain moves when documenting the neighbourhood of local optima. Most GRST algorithms also include rules for avoiding premature convergence of the search, to prevent being trapped in local optima. The main tabu rules divide into short and long term memory. Weak inhibition rules are used for balancing intensification and diversification of the local optima search space, respectively.

6 FLATTENNG AND PLYBOOKS

Once the sequence is determined, individual drape results for BaS draped by the same patterns are flattened and brought back to the same x-y set of reference axes. Shear is removed through trigonometric functions, bringing warp and weft back to a relative angle of 90°. Flattened pieces are assembled into a patterns, which are then prepared for inclusion into the final plybook and for instructing the cutting tables.

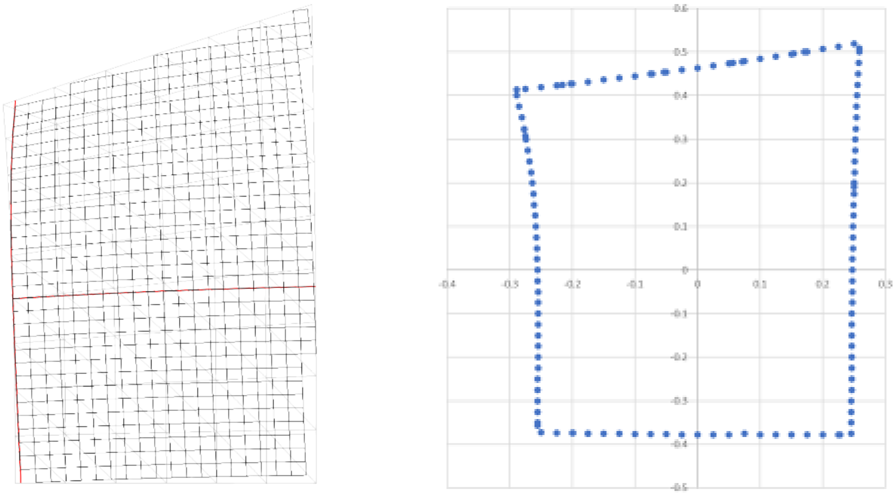

Figure 11. Draped reinforcement over BaS and flat pattern to be sent to cutting machine and plybook

7 CONCLUSION

The work highlighted above is being validated on 8 development demonstrators and 20 industrial demonstrators. Rather than assessing draping scenarios over complete moulds, investigating the draping behaviour over individual base surfaces and linking the results allows numerous draping sequences to be probed quickly from draping simulations and characterisation tests performed beforehand. The predictive software will drastically reduce the time required for designing draping strategies, assisting in producing quotes more quickly and more reliably.

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