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Novel textile preforming for optimised fibre architectures

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Abstract. Development of novel textile preforming concepts driven by multi-objective optimisation techniques will be reported here. One of the main goals here is to completely relax the manufacturing constraints imposed by conventional textile machinery. Several examples towards this goal are presented in this paper. Robotic/mechatronic concepts have been employed in creating optimised fibre architectures.

1. Introduction

Conventional textile preforming techniques, such as 3D weaving and braiding, are capable of producing a wide range of reinforcement architectures but these techniques impose significant constraints in terms of local tow densities, tow orientations and degree of through-thickness reinforcement. As a result, composites manufactured with traditional textile structures seldom achieve their true potential in terms of light-weighting and damage tolerance. However, the design of novel preforms not constrained by conventional textile machines and processes is a complex problem owing to an infinite number of possible design. Therefore, the design needs to be guided by numerical modelling which can predict properties of a composite before it has been manufactured.

It has been shown that by optimizing of yarns widths and spacing in a 3D woven reinforcement it is possible to achieve up to 20% weight-saving for structural parts [1, 2]. An optimization of the weave style of 3D woven reinforcements has been performed by Zeng et al. [3] to improve the buckling properties of a tubular section. Most of the previous studies were constrained to optimization of existing types of reinforcements e.g. orthogonal 3D woven or similar. However, various preforming techniques make it possible to create more complex reinforcements such as multi-axial 3D preforms [4] and even extended towards the less conventional preforms which are currently not produced. Such designs can be explored by using reinforcement optimization framework where the reinforcements have less manufacturing constraints than in previous studies. This paper aims to extend the existing approaches by adopting and extending TexGen schema along with multi-objective optimization.

The present framework relies on the unit cell modelling to optimise properties at the mesoscale (scale of a unit cell) [5]. The workflow consists of several steps. First, the geometry of a unit cell is automatically generated in TexGen via a Python script. Then the unit cell is discretised and the finite element model is used to obtain its properties. The results of the analysis are then used in an optimisation procedure based on the genetic algorithm (GA). Such modular approach can be modified and extended by replacing some of the steps/blocks without major changes to the others. This paper addresses two of

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the steps of the approach aiming to improve and extended each of them. In particular, the paper outlines a novel meshing approach and a multi-objective optimisation procedure. Results of the multi-objective optimisation of reinforcements with various manufacturing constraints are presented along with the steps towards its validation.

Manufacturing techniques for optimised fibre preforms are developed in two directions – 3D woven preforming and cylindrical preforming. Both of the techniques make it possible to place the off-axis yarns into preforms. These techniques will be used for the validation of the optimisation framework. Moreover, optimisation of fibre preforms with less manufacturing constraints will be driving further development of these techniques.

2. Numerical framework

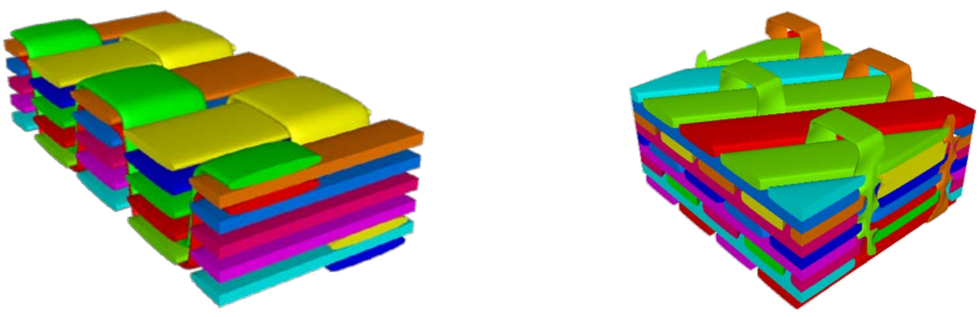
Multi-scale analysis of fibre reinforced composites is most often based on the unit cell approach when in the first step of the analysis a representative volume element of a periodic composite structure is used to derive the homogenised elastic properties of the composite [5]. These properties are then used for a macro-scale analysis of a composite part and then a subsequent sub-modelling of a critical location can be performed using the unit cell again. In some cases, this sequence of the multi-scale analysis can be reduced to a single analysis of the unit cell e.g. in the case of a uniaxial tensile or compressive load [3].

The geometry of a unit cell, dimensions of yarns, spacing between yarns and the binder path, can be parametrised which make it possible to perform the optimisation of these parameters in an optimisation framework. However, this requires robust and automated procedures to generate a unit cell geometry and a corresponding mesh. Furthermore, a fast computation of the elastic properties is also desired since these properties are needed for evaluation of both constraints and objective functions.

2.1. Model generation

A unit cell geometry of a conventional 3D woven textile can be parameterised within TexGen by a range of parameters such as number of the warp/weft yarns in the unit cell, number of layers, dimensions of the yarns, spacing between the yarns, number of the binder yarns and their path in between the layers. The latter can be coded for each of the binder yarns as a vector which defines the position of the binder yarn within a stack of layers at each intersection of the binder and weft yarns. A unit cell geometry can be made more complex by introducing e.g. off-axis yarns which also can be parameterised.

TexGen pre-processor Python library allows the geometries to be created via a Python script. Examples of the geometry are given in Figure 1.



(a) (b)

Figure 1. (a) Orthogonal 3D woven preform; (b) 3D preform with off-axis yarns (top yarns removed)

2.2. Mesh generation

Evaluation of the mechanical properties and local stresses within a unit cell requires a good quality finite element mesh of the geometry. However, a conformal finite element mesh for complex textiles is difficult to generate. Voxel mesh has been used in many studies showing good results for relatively simple geometries [6] but exhibiting spurious stress concentrations in more complex geometries [7].

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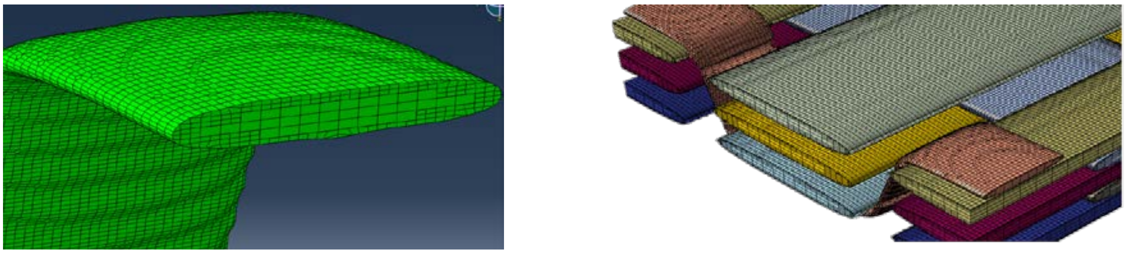
A novel meshing techniques, a combination of two existing techniques, has been implemented within TexGen to generate meshes for the geometries of arbitrary complexity. The meshing starts with creating a uniform voxel mesh with the element size being the maximum desired size in the mesh. This is then followed by an iterative octree refinement of each voxel, a procedure when a voxel is split into eight equally size voxels if the voxel consists of more than one material as defined by its corners. The octree refinement is continued until no more voxels need to be refined or the maximum allowable level of the refinement achieved. The refined voxel mesh is not conformal and contains hanging nodes which must be constrained to the neighbouring nodes of larger elements using linear constraints [8].

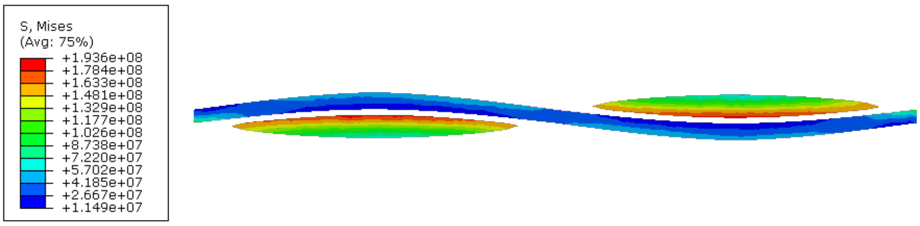
The refined voxel mesh does not resolve the problem of artificial stress concentrations caused by sharp angles in the voxel mesh. This can be resolved by applying Laplacian smoothing to all the surface nodes of the refined mesh. Examples of the refinement and smoothing are shown in Figure 2.



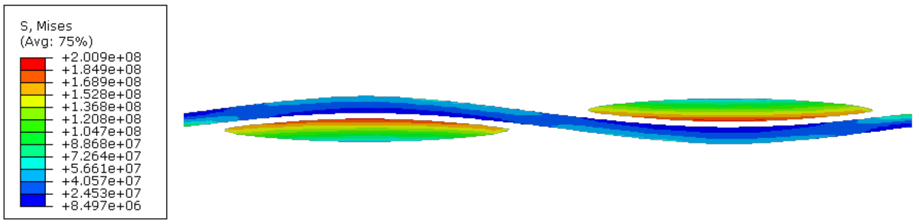
(a) (b)

Figure 2. (a) Refined and smoothed binder yarn; (b) Refined and smoothed 3D orthogonal weave

The proposed meshing technique was validated against conformal meshing using a unit cell of a plain weave textile composite. Stress distributions in one of the cross-sections of the unit cell is given in Figure 3. The difference between the maximum Mises stresses is about 3.5%.



(a)



(b)

Figure 3. (a) Stress distribution in the conformal mesh; (b) Stress distribution in the smoothed octree mesh

2.3. Orientation averaging

The optimisation algorithm requires multiple evaluations of the constraints and objective functions. Therefore, any speed up in these evaluations will translate in a significant speed up of the overall optimisation procedure. The elastic properties can be evaluated using the orientation averaging (OA) approach, an analytical approach based on the iso-strain assumption for the yarns and matrix within a unit cell.

The OA has been implemented within TexGen framework via a Python script which extracts local yarn orientations and volumes of sub-sections. Comparison with the FE analysis showed that the properties predicted with the OA are within 5% for the in-plane Young's modulus while the Poisson's ratios are up to 20-30% different as it can be seen from Table 1.

Table 1. Comparison of the elastic properties of a plain weave (VF=37%)

	FE	OA
E1 / GPa	32.9	28.5
E2 / GPa	32.9	28.5
E3 / GPa	5.6	7.6
G12 / GPa	6.2	4.76
ν12	0.1	0.065

When compared to an FE analysis the OA procedure was up to 7 times faster and took only 1 minute in order to create a reinforcement and compute the elastic properties using high discretisation. The time saving was achieved not only by avoiding the FE analysis but also by avoiding the mesh generation.

2.4. Optimisation algorithm

The optimisation of the parameterised unit cell geometry was carried out using the GA implemented within Matlab. The single-objective optimisation was performed using the standard implementation of the GA. The multi-objective optimisation was performed using a non-dominated sorting GA (NSGA-II) [9] which can provide faster convergence towards the optimum solution.

The range of the parameters defining the binder path in a reinforcement has only one constraint which ensures that the modelled preform is held together by binder yarns interlacing either entire stack or subsequent parts of it.

3. Case studies

3.1. Single-objective optimisation of the buckling resistance: comparison of FE and OA approaches

A previous study [3] performed optimisation of the composite landing gear in buckling. The problem has been reduced to the analysis of a dimensionless buckling coefficient given by a combination of the elastic constants:

$$\beta = \frac{D_{12} + 2D_{66}}{\sqrt{D_{11}D_{22}}} \tag{1}$$

where D_{ij} are flexural stiffnesses of a homogenised unit cell.

The optimisation framework with the FE analysis found that a 3D woven composites with the reinforcement having two binder yarns separated by a layer of weft yarns and running parallel have the buckling coefficient almost 50% higher than a conventional orthogonal 3D woven composite. It was reported that the optimisation procedure took up to 420 minutes on a desktop with 5 CPUs employed and assessed about 300 possible designs.

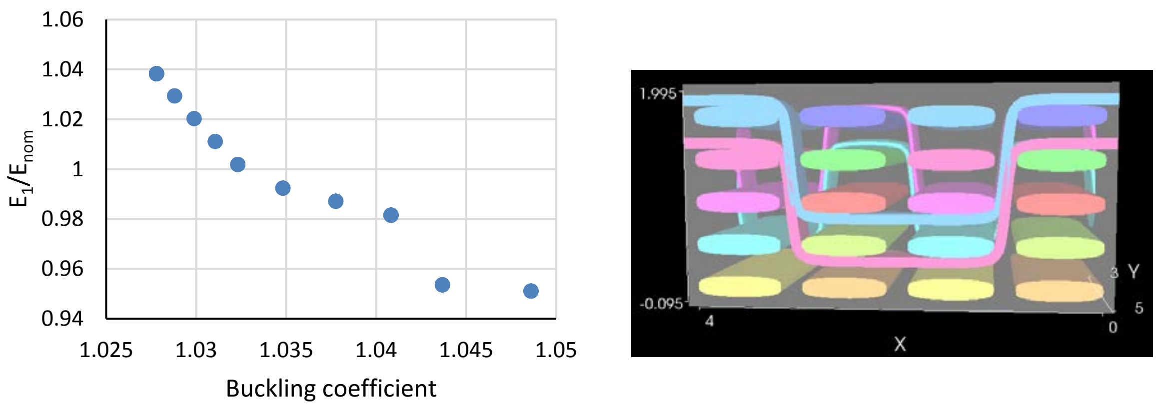
An identical optimisation was performed using the OA approach which yielded the identical design of the binder path. However, the overall optimisation time was about 70 minutes which is 5 times faster than FE based optimisation. The resulting binder path is shown in Figure 4.

Figure 4. Reinforcement with the binder path optimised to achieve maximum buckling coefficient

3.2. Multi-objective optimisation using OA

The OA approach has been utilised for the multi-objective optimisation of in-plane stiffness and the buckling coefficient (1) of 3D preforms. These two objective functions can be viewed as competing targets as they depend on the amount of the in-plane and through-thickness reinforcement, respectively.

A multi-objective optimisation provides a collection of the solution, so-called ‘Pareto front’ shown in Figure 5, with each of them being an optimum. The point of the maximum buckling coefficient corresponds to the reinforcement described in the previous section and the point of the maximum in-plane stiffness represents a trivial solution with straight binder yarns. The points in between these two maxima can be selected according to the design preferences. Some of the examples of the reinforcements are shown in Figure 5.



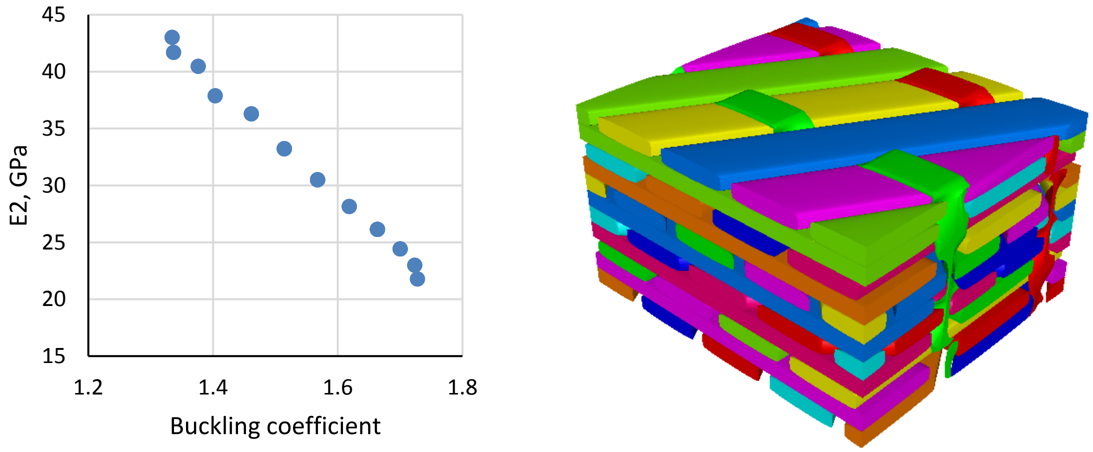
(a) (b)

Figure 5. (a) Pareto front for the multi-objective optimisation; (b) Example of a reinforcement from the Pareto front

3.3. Multi-objective optimisation of the multi-axial composites

Optimisation of the buckling coefficient and the transverse Young’s modulus was performed for multi-axial preforms. The design variables were rotations of the layers while the binder path was fixed to follow an orthogonal pattern. The layer orientation was limited to the range between 20° and 60° with a step of 5°. The lower and higher orientations were not considered owing to a large size of the unit cell required for the analysis. Properties of the composites with the multi-axial reinforcements were calculated using OA approach.

The multi-objective optimisation results in the Pareto front shown in Figure 6. As in the previous example, it can be seen that the two objectives are “competing” against each other. The resulting front can be used to select a solution which is the most suitable for a particular design criterion.



(a) (b)

Figure 6. (a) Pareto front for the multi-objective optimisation of multi-axial preforms; (b) Example of a reinforcement with β=1.56 and E_2 = 30.5 GPa ([30°/0°/90°/0°/-30°/0°/30°/0°/90°/0/-30°])

4. Optimised 3D woven preforming with novel manufacturing technologies

A certain degree of optimisation is possible on the conventional weaving technologies, such as varying density, varying thickness, binder density, but it is not possible to place stuffer tows in off-axis direction or weave near-net preform. The preforming approach in this study will not be constrained by the architecture that can be manufactured by using the conventional weaving technologies.

Traditionally, in order to weave a T-shape the 3D fabric is woven flat and then the web is lifted up post weaving. This post lifting of the web creates fibre distortion in the joint section of the web and the flange as well as resin rich area. Resin rich/delta-fillet can be seen in Figure 7 [10]. 3D Weaving machines that are used currently in the composites industry was originally developed for weaving 2D fabrics. These machines work well for the yarns that are flexible and stretchable. In the traditional machines shed is changed for every weft. The issue of using traditional weaving machine to weave 3D carbon fibre is the filamentation during the weaving process; this is due to the brittle nature of the carbon fibre that causes a lot of fibre damage, especially in the shedding area.

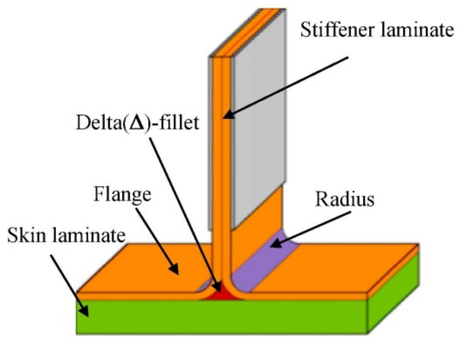


Figure 7. T-structure with delta-fillet/ resin rich area [10]

Two novel preforming prototype machines are being developed and are driven by optimisation. In the first approach, a multi-weft insertion 3D weaving machine for manufacturing near-net ultra-thick composite was developed, as seen in Figure 8 [11]. In this new approach, angle-interlock binders can be used to place off-axis fibres. In this multi-weft weaving system, the fabric is woven near-net in the shape of T. This weaving technology also has the advantage of salvage on either side, preventing the tows from falling out of the structure. In the multi weft weaving system, the damage in the shedding area is considerably less because multiple sheds are opened and less movement of carbon fibre.

Current multi weft system developed for this study can insert twenty-two wefts simultaneously, and one beat-up push all twenty-two wefts into the fabric fell. Multiple weft systems give higher output with less weaving motion compared to that of the conventional loom.

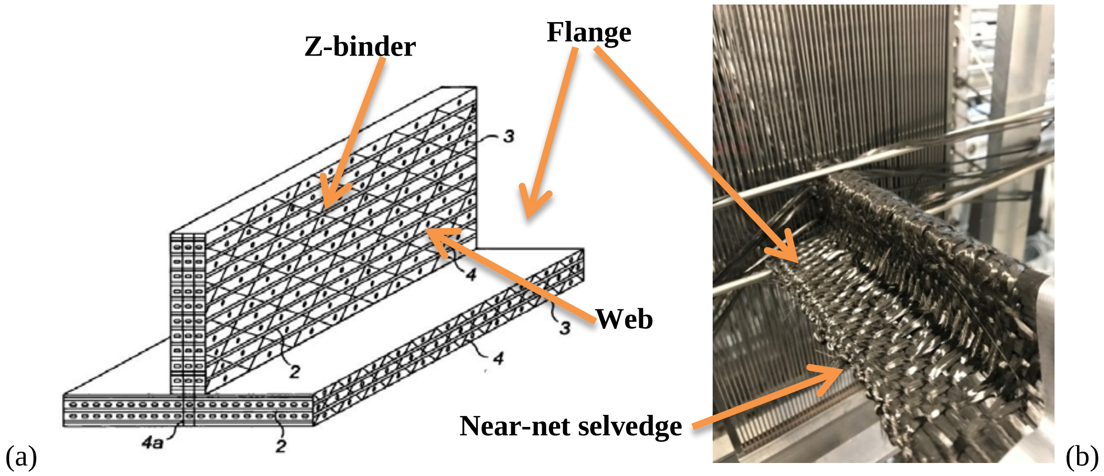


Figure 8. (a) Near-net 3D preform concept [11] and (b) Near-net 3D woven T shape fabricated using a novel weaving equipment developed at the University of Manchester

In the second preforming process the prototype machine can place stuffer in any off-axis angle, as seen in Figure 9. To study this 3D orthogonal fabric, samples are being developed by changing the number of layers, tow size and off-axis angles.

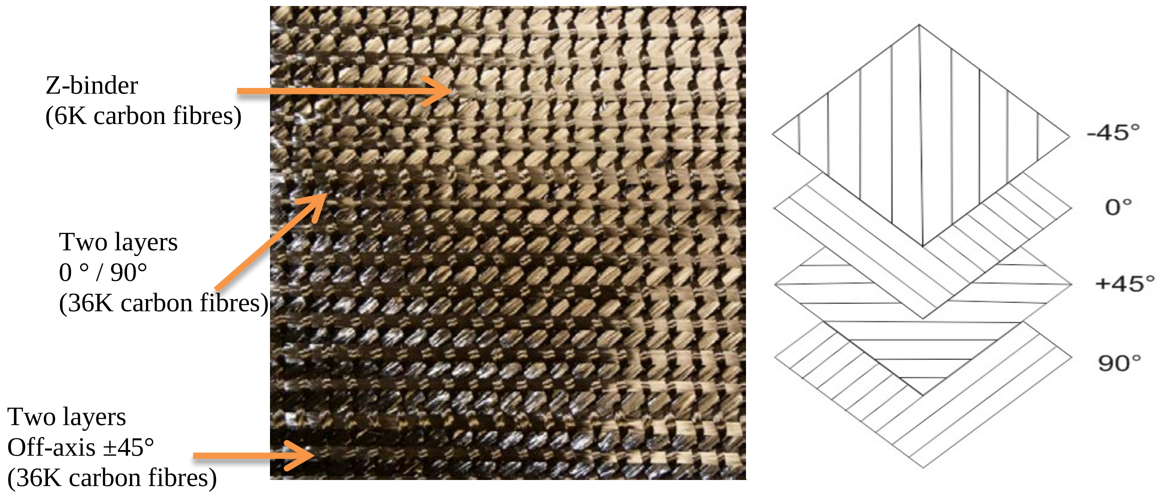


Figure 9. Multiaxial fabric with orthogonal binders

5. Cylindrical preforming for optimised fibre architecture

Braiding and filament winding are widely used for manufacturing cylindrical and closed shape structures using continuous fibres [12]. However, these technologies have their own limitations in achieving desired fibre path for an optimum design of composites. Since this study aims to develop preforms based

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on the optimisation framework that uses numerical modelling to predict composite properties, individual constraints of both braiding and filament winding are addressed in this section. In addition, other available technologies for producing 3D preforms were reviewed. A concept of a novel technology for manufacturing cylindrical preforms is also proposed to eliminate the design constraints of braiding and filament winding.

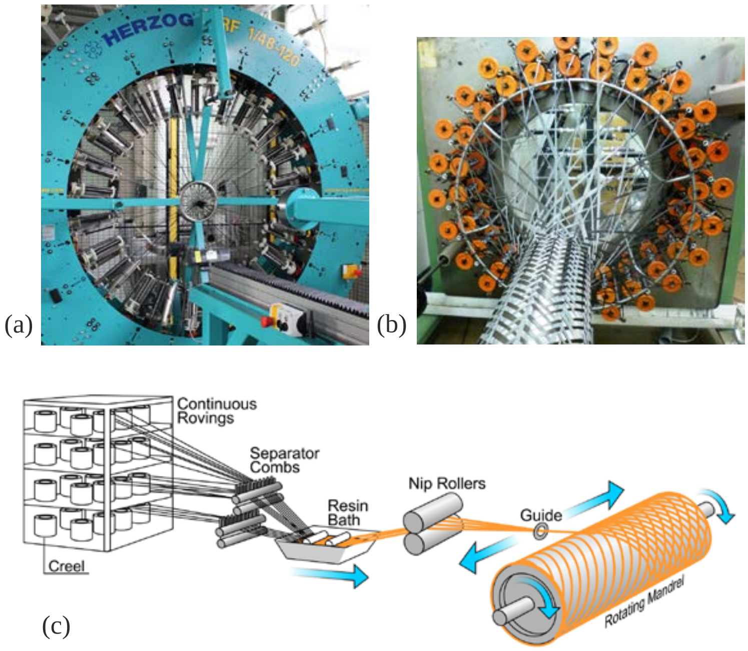


Figure 10. Cylindrical composite preforming technologies (a) Radial braiding (b) Maypole braiding (c) Filament winding [13]

Conventional two-dimensional (2D) circular braiders - maypole and radial (Figure 10) both can produce cylindrical textile preforms with fibres along three different axes. Braid structures usually have fibres running along helical paths and fibres from bobbins rotating in opposite directions interlace with each other to produce a biaxial structure. The bias fibre orientations in a braid range from about ±10° to ±85° and the third set of fibres are placed between the interlacing fibres and along the cylinder axis (0°) to generate a triaxial braid structure [14]. High braid angle often generates very high crimp and higher crimp affects the in-plane properties of the composite as observed by previous studies [15, 16]. Hence achieving higher angle or hoop (near 90°) orientation without compromising the mechanical properties is a limitation of conventional braiding. The undulation of fibres can contribute to impact damage tolerance when compared with filament wound composites [17]. However, the undulation effect is limited to a single braided layer and often composite is manufactured using multi-layer of 2D braided structures. Hence, 2D braiding method lacks the capability of producing a thick multi-layer cylindrical preform with through-thickness fibres which is one of the design requirements for improved impact resistance.

Filament winding (Figure 10c), on the other hand, can conveniently generate hoop and helical fibre orientations. However, through thickness fibre path is not possible to achieve as the structure is mostly non-crimp. Also, placing fibres along the cylinder axis (0°) is not convenient as it requires additional arrangements such as pinwheels [18, 19]. Overall the filament winding process on its own is capable of producing a triaxial structure (±α/90°) with small undulations similar to a non-crimp architecture.

Three dimensional (3D) braiders, as opposed to 2D braiders, can produce a structure with through-thickness reinforcement eliminating one of the constraints mentioned above. However, often 3D braiding machines produce solid preform structures those are not suitable for over moulding on a core or even produce large cylindrical structures. Using the concept of interconnecting tracks, 3D braiding equipment was developed in vertical deck arrangements [20, 21]. In these equipments, the through-the-thickness fibre paths are often at an angle as these paths are generated by braider bobbins running along helical directions and also fibre undulations are likely to be high.

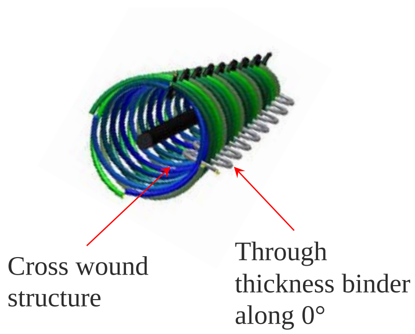
At the initial steps of the novel manufacturing concept development, two unique types of equipment were developed in Manchester as part of the feasibility studies. One of the concepts was a multi-axis filament winding with an increased degree of freedom for winding complex shape preform (Figure 11a). In order to increase the number of fibre axis in a preform over-winding of a triaxial braid can achieve a quadriaxial structure [19]. In the second concept, an equipment was developed that can produce a preform with two layers of helical reinforcement and the axial reinforcement passing through the thickness (Figure 12) [22].

(a)

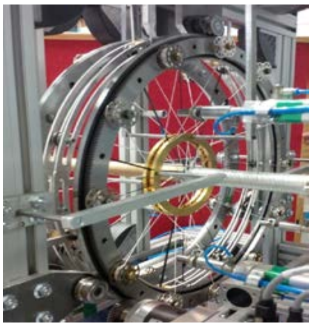
(b)

Figure 11. (a) Prototype multiaxis winding developed at the University of Manchester (b) The multi-axis winding concept used in commercial equipment developed by Cygnet Texkimp UK Limited

In order to optimise a preform based on the numerical modelling requirement, the constraints of traditional equipment need to be overcome. As part of the initial investigations, two multiaxis winding types of equipment provide the necessary foundation to develop novel equipment that can produce a multi-axis reinforcement that none of the existing equipment can produce. This equipment will be capable of combining multiple layers of $\pm\alpha$ fibre orientations with 0°/90° orientation as well as through-thickness reinforcement. In addition, since fibre at $\pm\alpha$ orientation have crimp, in the new concept, the fibres at $\pm\alpha$ orientation will not be interlaced thus have the potential to improve in-plane properties by minimising fibre undulation. Since individual tows will be inserted from different bobbins, local fibre densities can be changed by changing the fibre linear density.



(a)



(b)

Figure 12. (a) Schematic of a 3D cylindrical preform concept (b) Novel winding concept developed at the University of Manchester incorporating through thickness fibre reinforcement [22]

6. Conclusions and Future Work

The paper presented the extended framework for the optimisation of 3D preforms. It was shown that approximate OA technique for the computation of the elastic properties can be used to accelerate the optimisation procedure. OA approach was used in the multi-objective optimisation of the reinforcement where two objective functions are essentially “competing” against each other. The generated Pareto fronts can be used as design guidelines in the selection of the appropriate reinforcement design.

The novel meshing technique has been presented but not yet fully utilised in the framework which is now limited only to the optimisation of the elastic properties. The further work will include multi-objective optimisation which includes failure onset as one of the objective functions.

Finally, the validation of the generated Pareto front for the multi-axial preforms is now enabled by the development of the multi-axial preforming technologies such as 3D multiaxial cylindrical preforming and 3D woven preforming.

Acknowledgements

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