PREDICTIVE MODELLING OF PROCESSING AND PERFORMANCE PROPERTIES OF TEXTILE COMPOSITE UNIT CELLS: CURRENT STATUS AND PERSPECTIVES

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ABSTRACT

In developing new markets for textile composites the industry needs to further capitalise on their unique advantages whilst reducing the risk associated to their processing. Both objectives require fast and reliable predictive modelling of the processing and performance of composite parts. Ideally, designers should have the capability to consider alternative materials and processes simultaneously as development unfolds. When modelling textile composites a number of difficulties hinder the inclusion of exhaustive data required, for example, in introducing novel commercial reinforcements or attempting unproven manufacturing scenarios. 1) The properties of the materials are complex, both in their initial and processed states. They may vary with position, direction, time, scale, and deformation level. 2) Most processing properties are intricate functions of other processing properties. For example the compliance of dry textiles affects all aspects of processing and performance. 3) Complete modelling often involves data pertaining to microscopic (fibres), mesoscopic (unit cell) and macroscopic (part) scales. Failure under load is a good example of this. 4) The configuration of textile reinforcements is statistical in nature, and this has obvious effects on processing and performance. Statistical data, however, is rarely generated.

Numerous models of properties related to the processing and performance of textile composites are available. Established models can be found in textbooks whilst more novel, complex or debated ones are developed through conferences and the scientific press. Models apply to 2D or 3D domains and are expressed as closed-form analytical equations, semi-empirical expressions or numerical algorithms. Some apply to any general reinforcement whilst others come with restrictive definitions of the precise classes of reinforcements for which they were specifically developed. Out of the numerous models of a given property that are proposed over time many become evolutionary steps towards more advanced models, many fall in disuse, and some become established in their original form. For any given property, disposing of a few established models that stem from different approaches is useful as it allows cross-validation and better understanding, and reduces risk.

Efforts in predictive modelling of local properties should be directed towards developing and refining such models of physical properties and, crucially, towards the integration of these physical models within a framework where they may be applied interactively to any textile reinforcement. That framework should support constant input from and output to parallel simulations of phenomena defined at the microscopic and macroscopic scales. Nottingham has established foundations for such a framework and has integrated a number of physical models of various types. This work is ongoing. This paper presents fundamental elements of this integrated framework. The basic concepts are discussed and their actual implementation, which takes the form of a general geometric modeller for textile reinforcements - TexGen - is presented. Important features as well as input and output possibilities and characteristics of the modeller are reviewed.

1. INTRODUCTION

Designing textile composite parts and structures whilst ensuring reliable manufacturing and optimal use of the material's potential is a major challenge. There are four reasons for this.

The first reason is the general difficulty in obtaining meaningful data for part processing and performance simulations. Ideally it should be easy and straightforward to consider alternative reinforcements and ancillaries at the early stages of design. But the relative complexity of the materials and manufacturing operations, coupled with the vast array of reinforcements and ancillaries that may be obtained commercially or purposely engineered, lead to an open-ended field of data that is difficult to define, let alone to document. Frequently this is compounded by some uncertainty over what actually needs to be modelled. The problem is often simplified actively by designing the preform around a single criterion of perceived prime importance such as the structural response to one load case, and passively by giving undue prominence to practical factors such as material availability. This is unlikely to produce an optimal design but thorough cross-evaluations of different possible solutions remains rare with composites.

The second reason is the overlap in the manufacturing of the composite material and part. Contrary to metal parts, parts made of textile composites are not machined out of bulk material or obtained through simple processes such as extrusion or casting. The performance properties of textile composites are inherently related to their processing properties, which are themselves inter-related. Any simulation work attempting to predict the performance of a part requires thorough consideration of the processing route, whilst optimisation requires integral or interactive simulations. The effect of draping on fibre orientation, resin flow and structural performance constitutes a classic example of this.

The third reason is that most physical phenomena involved in the processing and performance of composite parts must be modelled at multiple scales. Textile composites are heterogeneous and the inner geometry of most preforms is complex. The properties of textile composites, their failure behaviour for example, cannot be defined by simple expressions akin to Von Mises' criterion. Failure envelopes may be obtained experimentally but generating these envelopes for any combination of reinforcements, lay-ups, part thicknesses & curvature and any state of static, dynamic and hydrothermal stresses is impractical even for simple parts. Modelling stresses and identifying failure points in a structure requires simulations conducted interactively at the scales of the part and material; seeking a better design requires the introduction of manufacturing simulations in the loop. Such work generally is not done.

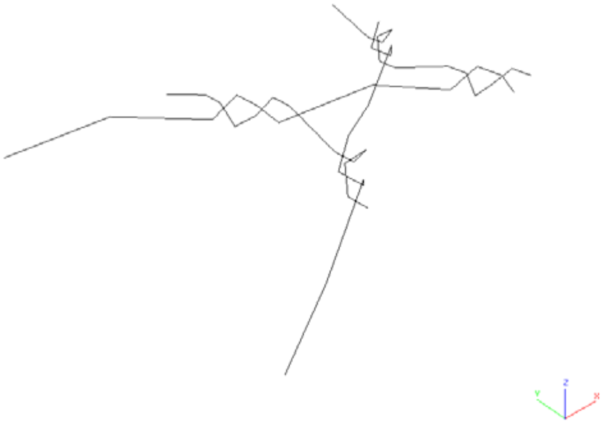
The fourth reason is variability. Textile reinforcements as well as their structural, flow and heat transfer properties are inherently variable. In the past, textile composites have been viewed as somewhat unpredictable and confined to low-volume, labour-intensive production. The current consensus is that that whilst the variability cannot be overlooked, as it is with metals, it can be modelled into simulations. The inherent risk can be managed, but this requires changes in the methods used to model materials and to conduct simulations.

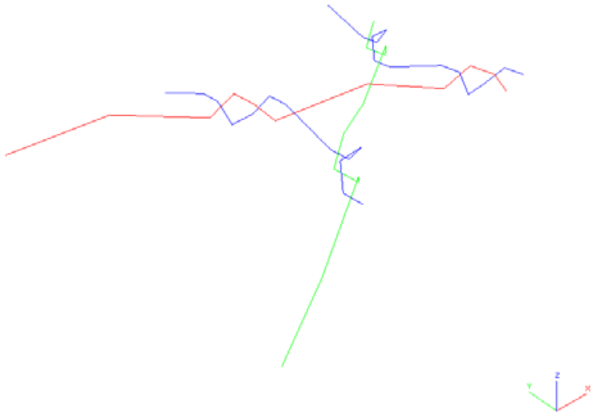
The above problems have long been identified and large amounts of usable information pertaining to numerous aspects of textile composites processing and performance can be found in the scientific literature as analytical equations, semi-empirical models and computer codes. However, in most cases the information only applies to very specific cases and it is generally difficult to extrapolate it to other materials or processes. There is a strong need for a methodology that allows such information to be applied to any textile reinforcement, real or virtual. Such a methodology has been developed by the authors. Current work focuses on predicting processing and performance properties systematically for a number of textile architectures, and on integrating simulations performed at different scales. The main aspects of the methodology are illustrated. The ability to work with any textile, to use and cross-validate different calculation methods for a given property, and to investigate different properties and phenomena in the same framework are discussed.

2. MODELLING TEXTILES

The methodology is implemented in a geometric textile modeller, TexGen. TexGen provides quick geometric modelling of textile unit cells under a single format. The software can model any textile in the same way regardless of its architecture, opening the possibility of using any downstream calculation method in the exact same way with any textile.

Architectures are defined by a series of vectors, which start and end at crossover points. An example is shown in Fig. 1 for a Swisstulle™ textile. At this stage the textile is defined by 44 3D vectors only; the amount of information is limited hence the definition is portable and easily generated. At this stage the geometry of the textile is difficult to perceive visually but some published models, say of the mechanical properties of dry textiles, use such information.



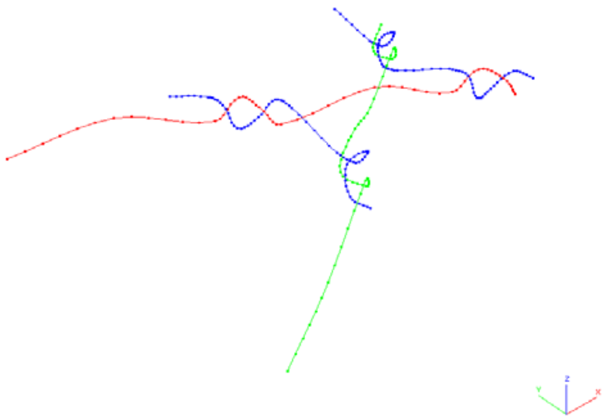


"**Fig. 1.** Vector definition of a Swisstulle™ textile."

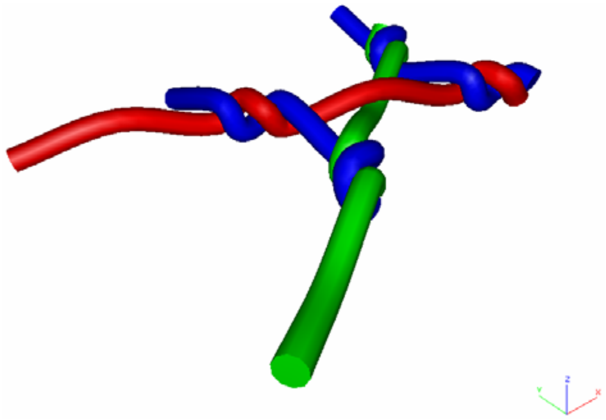
"**Fig. 2.** Assembled vectors."

The next processing step is to assemble the vectors in continuous chains as indicated by the colours on Fig. 2. This important step is fairly trivial but for practical reasons it is best to have the software performing it rather than to embed the information in the vector file. Following this, the next step consists in defining smooth paths for the tows, Fig. 3. Here Bezier functions were used, allowing fast generation of credible paths. TexGen offers different tools for doing this; ultimately the points on each path can be located individually. Whatever method is used, at the present time the locations are prescribed rather than calculated. The idea is to create geometric models for textiles and to use these together with adequate constitutive models in order to calculate a likely configuration for the dry textile. Complete, universal 3D constitutive models that can withstand very large deformations are being developed.

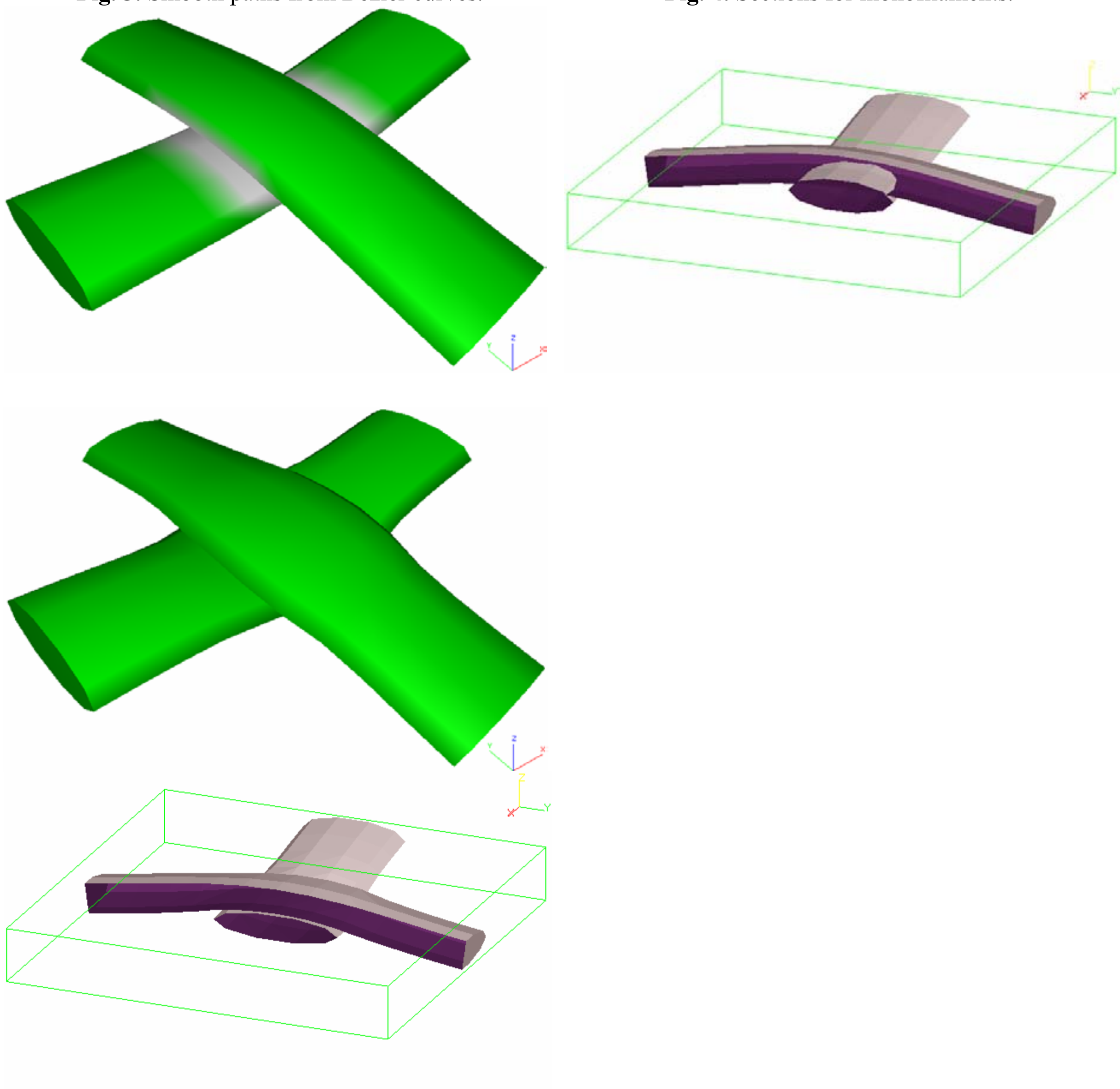
The same approach is used to define tow sections. Sections such as those illustrated in Fig. 4, where the textile is made of monofilaments, are easily measured and modelled. In cases where tows are made of multiple fibres, as for composite reinforcements, tow sections will vary along their length. At the present time TexGen supports this and includes functions detecting and correcting any interferences resulting from the generation process, Fig. 5. In this figure the upper left image shows detail of a crossover from a plain weave; detected interference is shown in grey. The upper right image shows a section through the same detail, viewed with DeskArtes View Expert™. The same detail, corrected by TexGen, appears in the lower left corner. The section of this latter version, shown at the lower right, highlights that the local sections were pushed apart, compressed and widened in arbitrary proportions. Ultimately local tow sections will be calculated from large deformation constitutive models. Models featuring multiple unit cells and representative, non-identifying colours appear in Fig. 6.



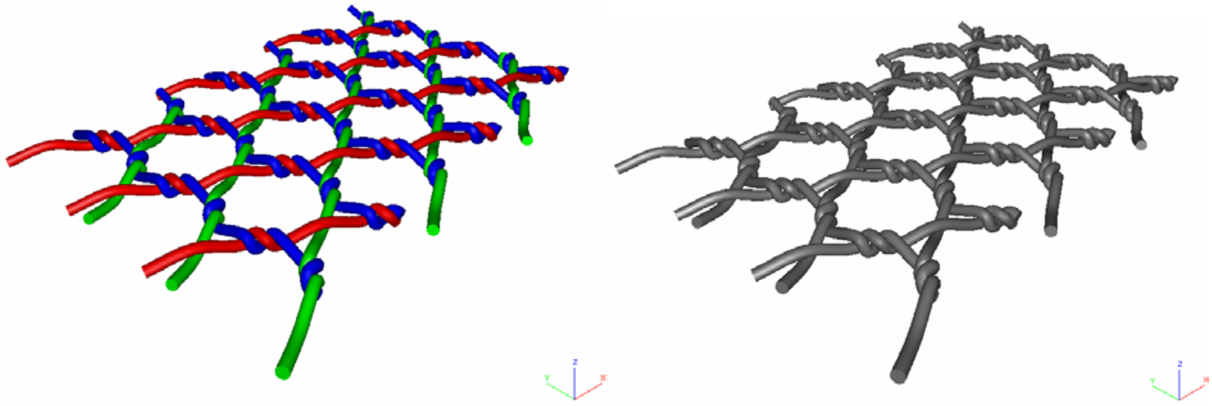
“**Fig. 3.** Smooth paths from Bezier curves.”



“**Fig. 4.** Sections for monofilaments.”



“**Fig. 5.** Automated interference detection and correction for detail of a plain weave.”

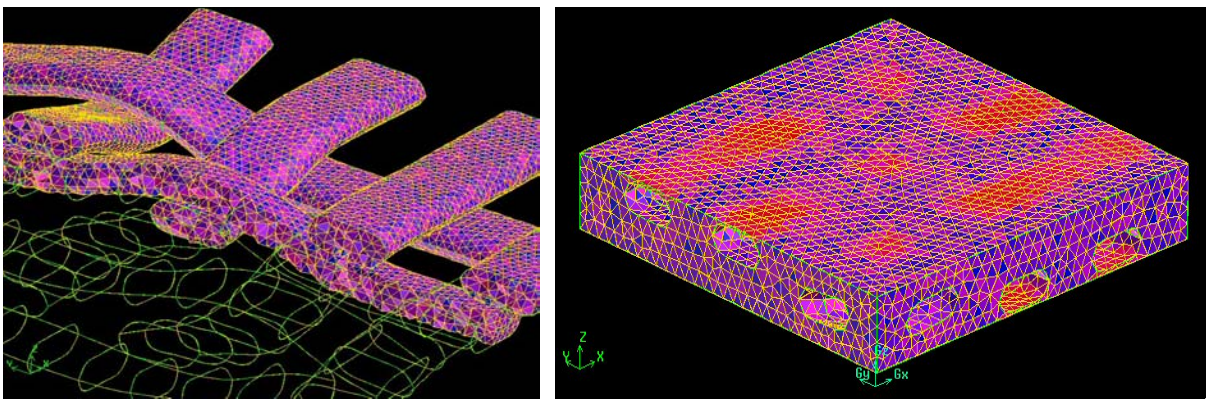


“**Fig. 6.** Models of a Swisstulle™ textile featuring multiple unit cells, and realistic colours (right). ″

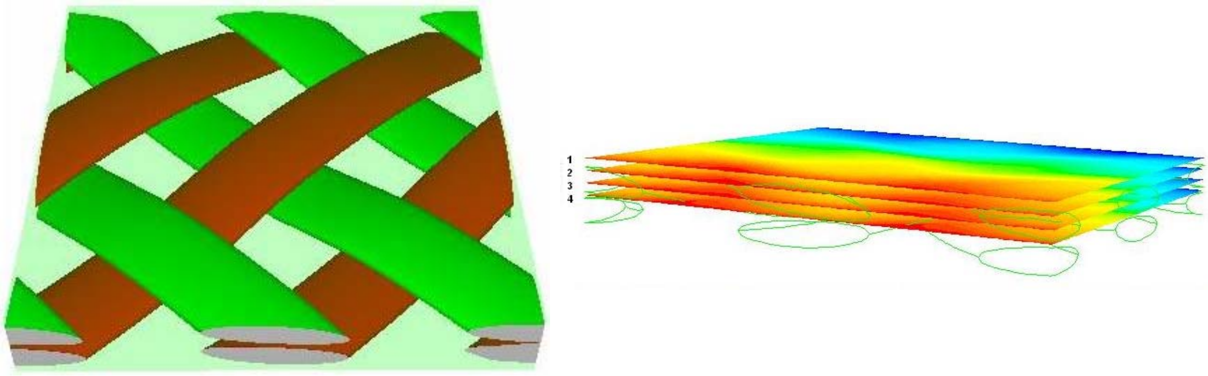
3. PREDICTING PERMEABILITY

The purpose of the methodology, and of the above geometric models, is to predict diverse processing and performance properties for textile composites. Numerous methods are readily available to predict a large number of properties. The models, which are independent of these methods, should offer equal support for all. This section discusses the implementation of a number of methods for the calculation of the directional in-plane permeability of textiles.

The permeability is calculated over 3D domains of arbitrary extents containing porous tows separated by gaps. The presence of these gaps has a major influence on permeability; textiles especially engineered with such gaps are used in manufacturing, in order to enhance flow for processes such as vacuum infusion. On the other hand, most preforms for structural parts feature high fibre volume fractions and flow through the porous tows cannot be neglected. Pressure and flow fields can be calculated in 3D over such domains, using CFD software such as Fluent™. This and other commercial software require meshes that model the tows and the gaps between them. TexGen writes journal files for Gambit™, the pre-processor to Fluent™, allowing autonomous creation of such meshes. An example is presented in Fig. 7 for a satin weave; inter-tow spacing was enlarged and tow sections were simplified to ease visualisation. A more realistic twill weave appears in Fig. 8, with pressure values calculated in 3D and represented over four slices. Flow proceeds from high (red) to low (blue) pressure.



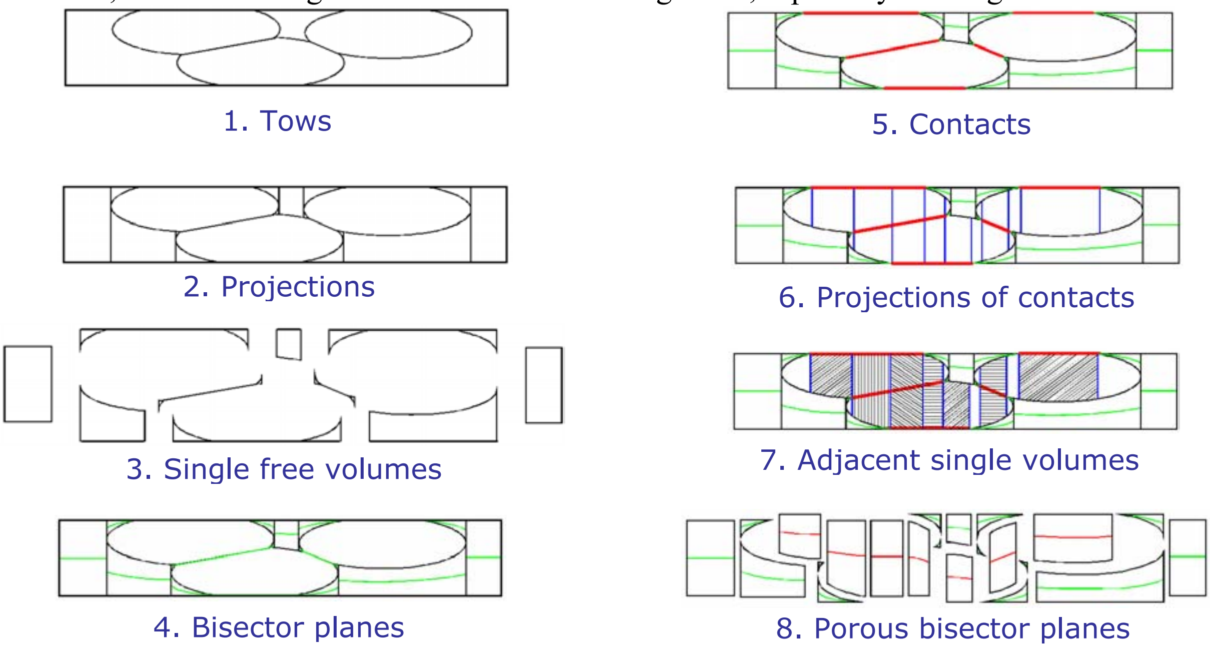
“**Fig. 7.** Meshes of the tows and gaps for an open, simplified satin weave. ″



"**Fig. 8.** Twill weave and 3D pressure distribution."

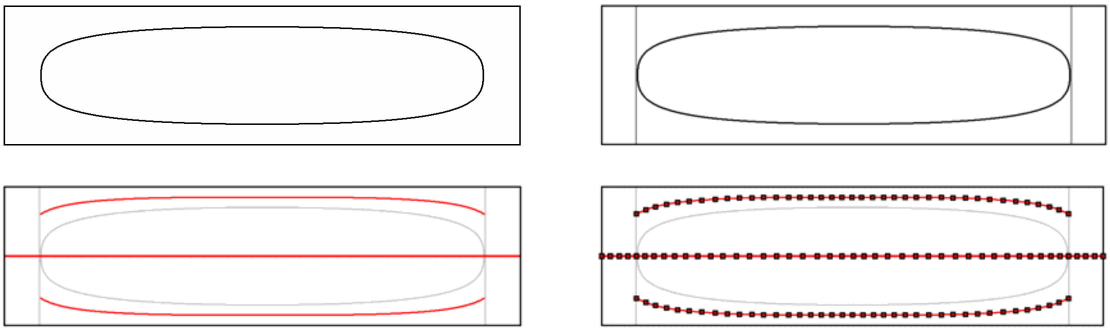
If conducted carefully such calculations are reliable and provide extensive detail about the flow field; however, they are time consuming. For this reason the authors have developed the alternative streamsurface and grid average methods which can both be applied over 3D domains, or over 2D slices of the domain to save further CPU time.

The basic principle of the streamsurface method is illustrated in Fig. 9 for a 2D slice of a domain featuring a number of tow sections (1). The edges of the tows are identified (2); these delimit the boundaries of single free volumes (3), which are volumes that are free of fibres, and through which the resin will flow. For each of these volumes a bisector line is identified (4) and a local channel height is associated to each point. These lines are identified to streamlines along which the resin flows, hence a curvilinear 1D mesh is generated over each. As the domain is made of numerous such curved lines it is referred to as a 1.5D domain. The method is also being implemented for the 2.5D solution of 3D domains as highlighted below. Whilst the 4 initial steps described above deal with 1.5D meshing for flow through the free volumes, the flow through the tows cannot be neglected, especially for high fibre volume

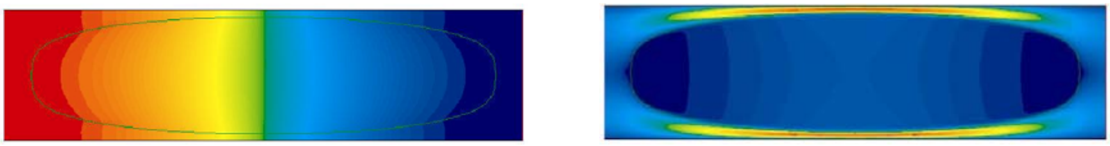


"**Fig. 9.** Principle of the streamsurface permeability calculation method, illustrated in 2D."

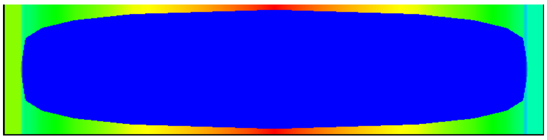
fractions. This is done in a very similar way by identifying zones of zero thickness in the free volumes, which are zones where the tows are in contact (5). Here again the boundaries of these zones (6) delimit single porous volumes (7). A bisector line is identified for each of these volumes (8), local permeability values are associated to each point, a mesh is created over each line and this is integrated to the mesh previously defined for the free volumes. Fig. 10 shows the creation by TexGen of a mesh that extends around the free volumes surrounding a single tow as well as through the porous volume of that tow, whilst Fig. 11 shows a pressure and a velocity field obtained over the same domain using CFD. Fig. 12 shows a velocity field obtained in the same case from the 1.5D streamsurface solution (the colour scheme is different). Despite the absence of through-thickness pressure gradients in the latter case both methods lead to virtually equal permeability values; streamsurface is about 300 times faster.



"**Fig. 10.** 1.5D streamsurface mesh generated in the free and porous zones of a single tow domain. "

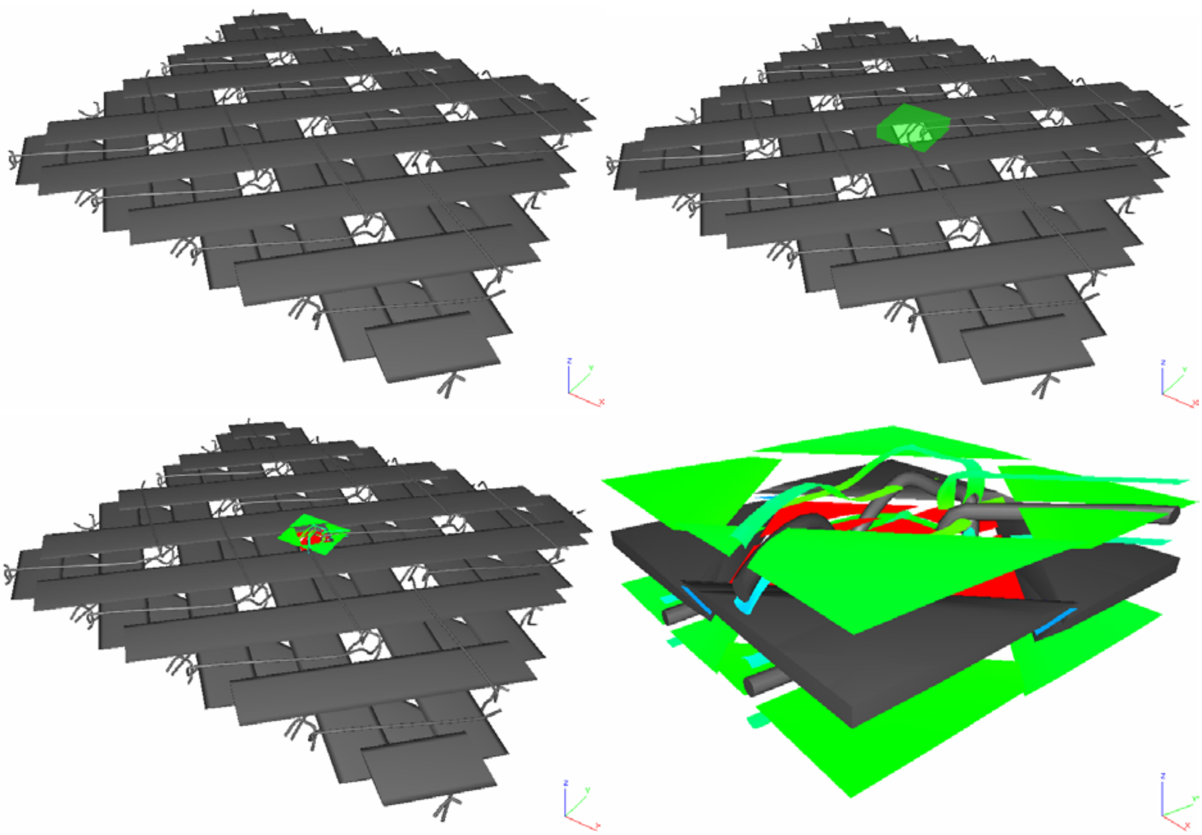


"**Fig. 11.** Pressure (left) and velocity (right) fields obtained from 2D CFD. "

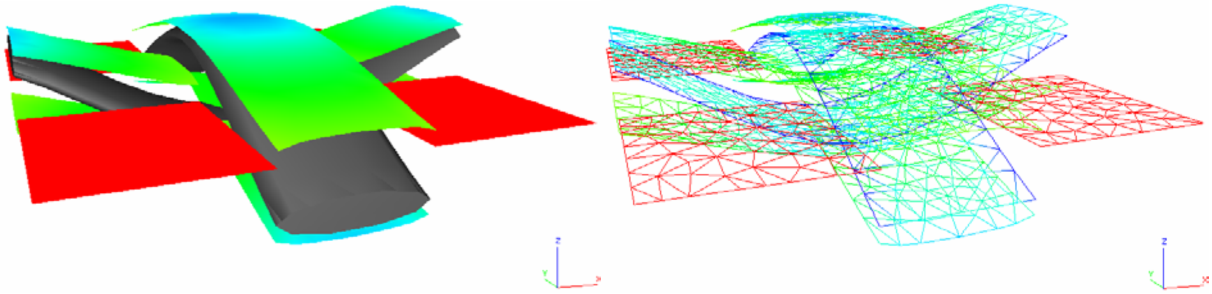


"**Fig. 12.** Velocity field obtained from 1.5D streamsurface. "

Streamsurface is fully implemented for 1.5D slices, and currently being implemented for 2.5D calculations over volumes. Fig. 13 shows an example where a 2.5D streamsurface domain is generated automatically by TexGen for a relatively complex textile, here a stitched 45/0/45° non-crimp reinforcement. The upper left part of the figure shows the textile, with the tows and stitch coloured grey. The upper right corner shows the domain over which permeability is to be calculated, in green. The lower right figure shows the streamsurface generated over that domain. The same portion of the textile is magnified on the lower right. The tows and stitch still appear in grey whilst the surfaces bisecting each free volume appear in different colours, indicative of the local channel height. The red surfaces in the centre of the domain are the thickest ones, as in these locations the free volumes extend throughout the thickness of the domain. Most green surfaces correspond to free volumes that are defined between a tow and one of the lower or upper boundaries of the domain. Finally, the blue surfaces are the thinnest as they extend between two tows, or between a tow and a stitch. All surfaces feature variable thickness, as shown by the colours changing over some surfaces in this example. A simpler example appears in Fig. 14 for a plain weave. The left part of this figure shows the tows and the associated streamsurface; note the presence of a separate surface in the centre of the domain, between the two tows. The right part of the figure shows the associated mesh, including elements defined at the centre of each tow and representing the porous volumes. In such cases the pressure and flow fields over the domain will be determined using Darcy flow software such as LIMS™ or PAM-RTM™; implementation is on-going.



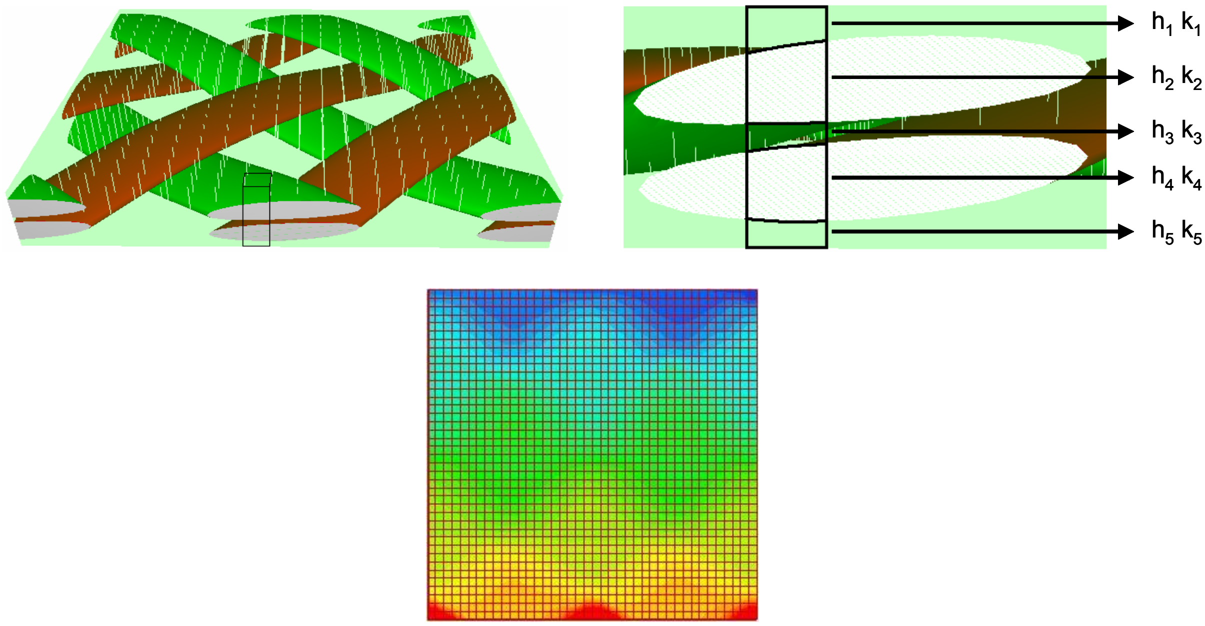
"**Fig. 13.** 2.5D streamsurface for domain defined over a stitched non-crimp reinforcement. "



"**Fig. 14.** 2.5D streamsurface for domain defined over a plain woven reinforcement. "

As mentioned in the introduction, many models and computational methods can be found in the scientific literature for each property or phenomenon associated to textile composites. The models are distinguished by the hypotheses and simplifications used in their development; some will provide more thorough answers at the cost of longer computational times. This diversity in possible solutions should be welcome as it allows the possibility of cross-validating them. Simpler methods may be perfectly acceptable and provide answers much more rapidly, making them usable in industrial practice. The two methods presented above for permeability calculation are an example of this. Whilst both methods are equally general and applicable, streamsurface provide less detailed information about the flow field but is much faster. For all practical purposes the important information is the directional permeability, and it is very useful to have the possibility of validating streamsurface using CFD.

With this in mind the authors are developing and evaluating various methods for permeability prediction. Grid average is another example where the problem is further simplified than with streamsurface, Fig. 15. In this case a grid which is regular along the *x* and *y* axes is generated over the flow domain, allowing the use of a regular mesh in solving the pressure and velocity fields. Properties associated to each element are generated by combining the thickness and permeability characteristics of the free and porous channels found locally. Consequently, the resulting domain is defined in 2D. The method has shown promising results. The pressure field shown in the lower part of the figure, obtained using LIMS™, compared well with the field generated CFD, Fig. 8. Full cross-evaluation of the three methods is under way.



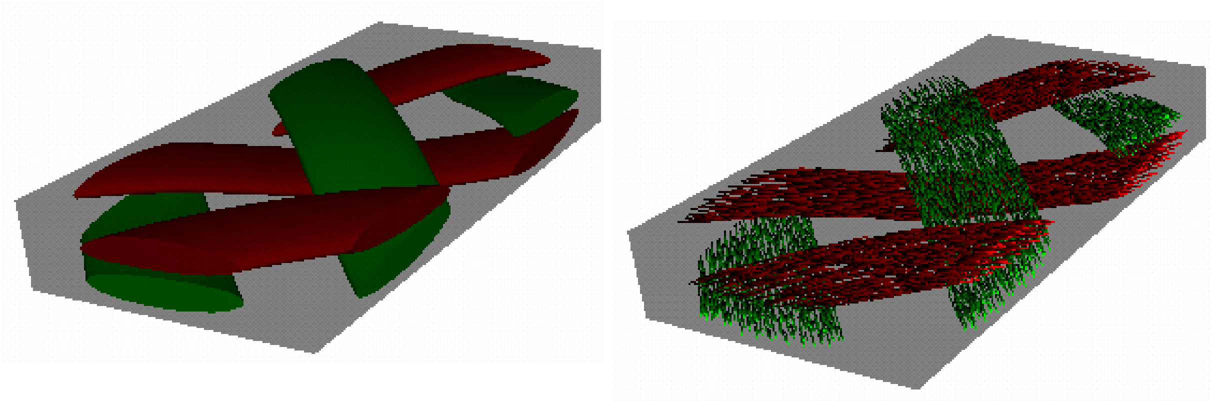
"**Fig. 15.** Twill weave and 2D pressure distribution obtained from grid average method."

Whilst this paper presents an overview of the current state of development of geometric and properties modelling for textile unit cells, further analysis of the results generated so far by the authors for permeability can be found in references [1-3].

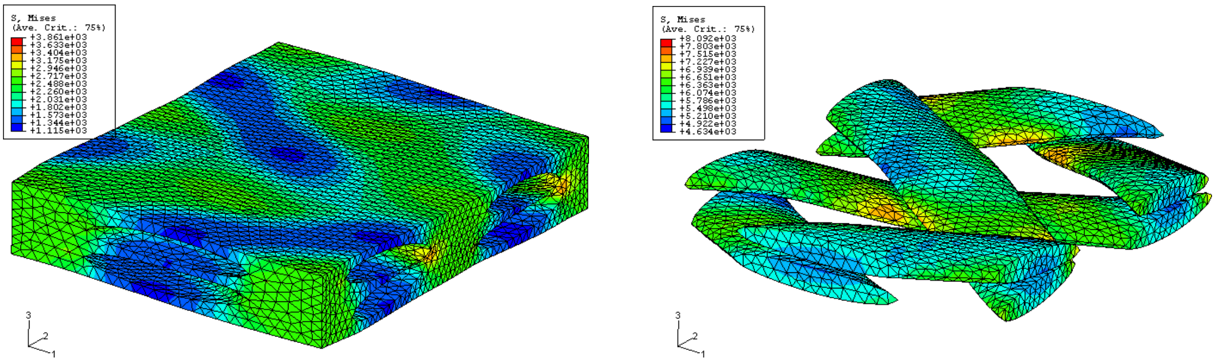
4. PREDICTING STRUCTURAL PROPERTIES

An essential part of the methodology is the capability to model various properties of the textile unit cells in the same framework. The authors are presently pursuing similar development of faster, simplified property prediction methods for heat transfer, large deformations of dry textiles, and crashworthiness/post-failure mechanical behaviour of composites. In this section the prediction of failure in composites is briefly discussed.

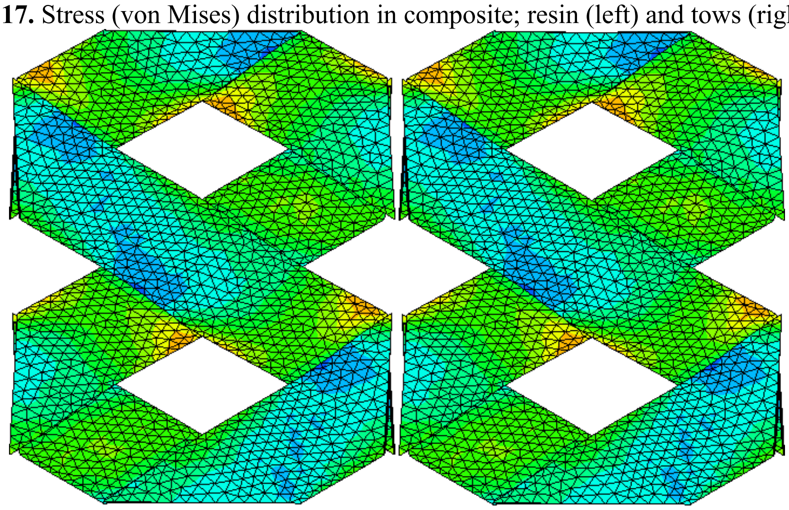
Consider the braided material discussed above. The left image in Fig. 16 shows the domain over which stresses are to be calculated, and the right image shows the fibre orientation on each of the tow elements; this is obviously required in any calculation where the anisotropy of the tows must be considered. Fig. 17 shows the stress distributions in the resin (maximum value: 3.86×10^3 Pa) and in the tows (maximum value: 8.09×10^3 Pa) resulting from an elongation of the domain applied along axis 1. The calculations were conducted in 3D with small deformations, using ABAQUS™. TexGen automatically write input decks for this software. The mesh is produced in Gambit™, re-important within TexGen for assignment of the tow orientations, and then exported to ABAQUS™ in the form of a simple input deck. Such input decks generally have to be refined, mostly for boundary conditions. The stress map shown on the right side of Fig. 17 is repeated twice, viewed from top, in Fig. 18. The centre of the figure shows that tow deformations at the boundaries are compatible. Stress levels at the boundaries are consistent with those observed at the horizontal centre of each cell, indicating correct boundary conditions given the symmetry of the material.



"**Fig. 16.** Geometric model of twill weave and fibre orientations in tows. "



"**Fig. 17.** Stress (von Mises) distribution in composite; resin (left) and tows (right). "



"**Fig. 18.** Stress distribution in tows of braided composite submitted to axial extension. "

Here again this calculation, performed using proven commercial software, provides extensive information about the stress field; this information is obtained at the expense of time and CPU power. The authors are continuing the development of alternative calculation methods for stresses and for other properties. The integration of models developed by other groups within the formalism represents another, potentially very powerful avenue for progress.

3. CONCLUSIONS

The formalism proposed by the authors allows the geometric modelling of virtually any textile under the same, simple format. Precise tow paths and tow sections are currently prescribed; development of complete 3D, large-deformation constitutive models for multi-fibre tows is ongoing. The formalism is designed to support multiple calculation methods for any given processing or performance property. For example the different permeability calculation methods discussed in this paper use different hypotheses, and the extent of detail contained in the data they require and in the information they yield varies. The formalism also allows calculation of different properties for the same domain in the same framework. This will lead to concurrent optimisation of diverse properties for different textiles. The authors are pursuing the development and implementation of various calculation methods to be used with the TexGen. Implementation of methods developed by other teams offers strong potential for further progress.

ACKNOWLEDGEMENTS

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