Integrated model of textile composite reinforcements

S.V. Lomov, I. Verpoest
Department of Metallurgy and Material Engineering, Katholieke Universiteit Leuven, Belgium

Abstract

Textile materials are characterised by the distinct hierarchy of structure: fibre – yarn – fabric – ready product (preform), which should be represented by a model of textile geometry and mechanical behaviour. In spite of a profound investigation of textile materials and a number of theoretical models existing in the textile literature for different structures, the model covering all structures typical for composite reinforcements is not available. Hence the challenge addressed in the present work is to take a full advantage of the hierarchical principle of textile modelling, creating a truly integrated modelling and design tool. The architecture of the code implementing the model corresponds to the hierarchical structure of the textile material, which is represented as a library of generic C++ classes describing subsequent levels of it. The generic functionality of these classes, interface features and tools employing this functionality provides a framework for implementation of models of geometry and mechanical behaviour of different types of textiles. These are implemented as descendants of the generic classes using the inheritance mechanism of C++.

1 Introduction

Textiles are hierarchically structured fibrous materials. As it was discussed in the classical paper of Hearle et al. [5], this description of the nature of textiles defines an efficient approach to the construction of mathematical models of the geometry and the mechanical behaviour of textile structures. In spite of the generally recognised usefulness and even necessity of such a hierarchical approach, it was never employed in its full strength for the creation of textile structure models – the direction of textile science, which developed itself for
more than 60 years. The state-of-art of textile mechanics in the beginning of the 21st century includes models of the internal geometry of the basic textile structures, such as continuous-filament and staple yarns, random fibre mats, and woven and knitted structures.

The hierarchical approach of a geometry model architecture is naturally implemented via the minimum energy principle (MEP), introduced by Hearle and Shanahan [6] and de Jong and Postle [1]. This principle allows the decomposition of a problem into a set of problems for structural elements, leading to physically sound and computationally feasible models.

This paper discusses a generalised technique for the construction of a geometrical model of a textile structure. The principle is applied to the construction of a model, which predicts the internal geometry of a multi-layered woven fabric. This sample application has been described in some previous publications Lomov et al.[4, 9-11] and can serve as a demonstration of the general approach.

2 The problem

We will consider here a fabric composed of yarns. Non-wovens, containing random fibre mats, will therefore be excluded from the discussion. A particular reference will be made to multi-layered woven fabrics.

2.1 Geometry of yarns in a fabric

Consider a single repeat of the fabric. Assume further as given:
- all the necessary yarn properties;
- the topology of the yarn interlacing pattern within the fabric repeat;
- the yarn spacing within the repeat (i.e. the mean distance between warp/weft yarns in a woven fabric or the course/wale spacing in weft-knitted fabrics).

The problem is now to compute the spatial placement of all yarns in the repeat. In more practical terms, this means:
- determine all the yarn heart-lines within the repeat;
- define the yarn cross-sectional shape and its dimensions normal to the yarn heart-line for each point along the yarn heart-lines.

This problem will be formulated in accordance with the hierarchy of a textile structure: considering the sequence of hierarchical levels “fibres – yarns – fabric”, the focus is on the highest level (i.e. the “fabric”). The properties of the elements from the preceding level (i.e. the “yarns”) together with their interlacing pattern (the “topology”) will enter the formulation.

2.2 Geometry of fibres in a fabric

The solution of the problem formulated in the previous section will be able to answer the following question: consider a point P within the fabric repeat. Does the point P lie inside a yarn or not? This question can be further generalised: what is the fibrous content in the vicinity of point P and what is the fibre orientation near to it? In order to answer the latter question, we must descend to
a lower hierarchical level, namely the “fibre – yarn” level, and add to the corresponding input data:

- the fibre orientation distribution within the yarn induced by twist;
- the fibre distribution over the yarn cross-section;
- the change of these distributions during yarn deformation (see Grishanov and Lomov [2]).

3 Architecture of the yarn data in the software

The modern Object Oriented Programming (OOP) technique is ideally suited to implement the hierarchical nature of textiles. The three main features of the OOP are encapsulation, inheritance, and polymorphism.

Consider as an example a Yarn object. The geometry of a textile structure in the relaxed state (i.e. in absence of external forces) is determined by the equilibrium of the yarn interaction forces, which naturally arise to accommodate the topology of the yarn contacts within the textile. Bending of the yarns – necessary to maintain the topology – creates transversal forces at the yarn contacts. These forces lead to yarn compression and flattening and – in case of non-symmetrical contact conditions – to local deflections of the yarn path from the ideal directions, which are in turn resisted by friction between the yarns). In the relaxed state the yarns are free of tension. The weaving process does not imply torsion of the yarns; for knitted fabrics however torsion takes place. These considerations determine the nomenclature of data fields and methods (procedures describing the object behaviour) necessary to fully characterise the yarn.

Encapsulation means that the object holds not only data, but also the behaviour. Wherever the Yarn object will be encountered in the software, all these data fields and methods will be accessible, and the model can instruct the yarn, say to Compress under the force $Q$. One can say that the Yarn object virtually represents the actual yarn. Note that the Yarn object does not contain fibre data. It is designed to be sufficient for geometrical calculations on the “yarn – fabric” level of the textile hierarchy.

Inheritance means that one can construct another object, say YarnWithFibreData, which will inherit all the data and the behaviour of the parent Yarn object, but adds fibre data and behaviour, which in its turn is encapsulated in the Fibre object, placed on the lower level of the structural hierarchy. Now it is possible not only to evaluate the yarn properties using the fibre data and a structural model of the yarn, but also to determine properties lying on a lower hierarchical level (i.e. the fibrous structure of the yarn). The new object virtually represents the actual yarn with some added knowledge of it. The inheritance feature of the OOP provides therefore a logical basis for the gradual improvement of the model.

Polymorphism gives the developer the possibility to take full advantage of this gradual improvement process. Consider a method Compress, which for the Yarn object simply computes the cross-sectional dimensions in the compressed configuration, but which for the YarnWithFibreData object additionally computes the fibre distribution in the compressed state. When used inside the
software in reference to a certain Yarn object, the method will be applied in the former style if the object does not contain fibre data, and in the latter style, if fibre data are present. The Yarn object will be polymorph, changing its behaviour according to its actual contents.

The OOP approach provides a powerful tool for the construction of “virtual textiles”.

4 Structural elements and minimum energy principle

A natural structural unit of a fabric is its repeat. It consists of a number of yarns \{Y\}, which are in contact one with another. The contact regions occupy certain zones on the yarns; characteristic points on the yarns provide the natural boundaries for structural elements of the repeat. For example, in a woven fabric the structural elements consist of intervals of warp and weft yarns located between subsequent intersections. A yarn Y consists of a set of structural elements \{e\}_Y. Consider a structural element e on yarn Y. It is characterised by:

- the co-ordinates of its end points – points \(A_{Ye}\) and \(B_{Ye}\);
- the dimensions of the contact regions near the end points;
- forces acting on the contact regions.

The exact shape and the dimensions of the contact regions on a structural element and the forces acting on them are determined by the nature of the yarn interactions within the structure. The basic assumption of the theory, which will be developed here, is the principal role of the spatial positions of the end points of a structural element in the geometry of the structural element. Suppose that the end positions of the structural elements for all the yarns in the fabric repeat are given and fixed. Near the end points, contact regions will develop due to yarn interactions and internal forces will be present in the contact zones. Geometrical constraints imposed on the structure by the end point positions of the structural elements will determine the local deformations of the yarns within the contact regions – and hence the shape and dimensions of these regions – which in turn will determine the required forces to produce these deformations. In the general case we will designate a set of parameters \(q_j, q_k, q_5...,\) that will determine the mechanical properties of the structural elements. Related to the assumption formulated in previous paragraph, this set of parameters consists of the positions of end points of the structural elements, \(\{q_j\} = \{A, B\}\).

Consider now the main problem formulated above – the computation of the spatial placements of the yarns in the fabric repeat space. Let \(r_f(s)\) be the parametrical representation of the heart-line of yarn \(Y\), where \(r(s)\) is the position vector of the heart-line as a function of the scalar parameter \(s\). According to the minimum energy principle, the set of \(r_f(s)\) for all the yarns in the fabric repeat should satisfy:

\[
\sum_{(r_f)} W(r_f(s)) \rightarrow \text{min.} \tag{1}
\]

If we split the function \(r_f(s)\) into separate functions for each structural element \(e\) on yarn \(Y\), then Equation 1 will take the form:
which can be written as:

\[
\sum_{(f)} \sum_{(e)} W(r_e(s)) \rightarrow \text{min} ,
\]

The global minimisation problem of Equation 3 can be reformulated as a series of minimisation problems for the structural elements:

\[
\min_{r(s)} \sum_{(f)} \sum_{(e)} W(r_e(s; q_1, q_2, q_3, \ldots)) = \min_{q_1, q_2, q_3, \ldots} \sum_{(f)} \sum_{(e)} \min_{r(s)} W(r(s; q_1, q_2, q_3, \ldots)) ,
\]

where the minimisation problem for a structural element should be solved with the parameters \(q_j\) fixed. It yields the solution:

\[
\min_{r(s)} W(r(s; q_1, q_2, q_3, \ldots)) \Rightarrow r(s; q_1, q_2, q_3, \ldots) ,
\]

which is further used to calculate energy of the structural element:

\[
r(s; q_1, q_2, q_3, \ldots) \Rightarrow W(q_1, q_2, q_3, \ldots) .
\]

The function \(W\) only depends on the parameters of the structural element. We will call it the characteristic function of the structural element. Now the minimisation problem Equation 3, which has the functions \(r_f(s)\) as arguments, is reduced to the minimisation problem:

\[
\sum_{f} \sum_{e} W_{re}(q_1, q_2, q_3, \ldots) \rightarrow \text{min} ,
\]

where the arguments are a set of scalar parameters \(q_j\). Equation 7 leads to a system of non-linear algebraic equations.

5 Topology of a fabric

The logical division of the fabric unit cell into its structural elements is determined by the topology of the yarn interlacing pattern. Physical data such as the yarn dimensions or the yarn spacing do not enter in the topological description.
The topological coding of a multi-layered weave is based on the warp yarns paths (Fig. 1). The $i$-th warp path is coded by a sequence of intersection levels $w_{ij}$—denoting either the index number of the weft layer situated above the warp yarn in its intersection with the $jk$-th weft row, or 0, if the warp yarn lies on the face of the fabric. The weave coding for 3D fabrics is discussed more attentively elsewhere [7, 8].

6 A generic fabric description

Now we will use the OOP approach to create a generic fabric object to be used in geometric models of textile fabrics regardless of the fabric structure. The Fabric object should consist of the following data objects: Topology, Yarns and Spacing.

The Topology object describes the yarn interlacing structure. For example, for woven fabrics or 2D braids it contains the matrix of weave codes $w_{ij}$. The Topology object has the ability to create a set of structural elements of the fabric used in the energy minimisation algorithms. The Yarns object contains a list of Yarn objects, and references to their positions according to the Topology (for example, in a woven fabric references to a particular yarn description via warp or weft number). At last, parameters related to the yarn positions are stored in the Spacing object. For woven fabrics this can be the number of warp and weft yarns per unit length, for knitted fabric – the loop module (i.e. the ratio of the loop length to the yarn diameter).

Topology and Spacing objects are so-called abstract objects. As the common ancestor of all Fabric objects they play the role of placeholders. Using the OOP mechanisms of inheritance and polymorphism, the description of a particular structure is incorporated in the descending Fabric object.

The Fabric object contains a full description of the fabric geometry. Using the functionality of the contained Yarns objects, the Fabric object generates the following output:

- Overall geometrical characteristics: unit cell dimensions (including thickness), mass per unit surface area, average porosity/fibrous content and yarn lengths in the unit cell.
- For any point within the unit cell: the fibrous content, the average orientation and an identification of the fibre material in the vicinity of the point.
- A 3D array storing the previous data over the unit cell (where the grid spacing is chosen by the user).
- Yarn path geometry, position and size of the yarn cross-sections, fibre density and orientation distribution over the yarn cross-section for arbitrary points on any yarn within the fabric repeat.

The description of the internal fabric geometry can be used for various purposes:

- Visualisation: creation of a 3D picture of the unit cell with rotating, zooming and sectioning capabilities;
- Preprocessing for finite element codes;

Advances in Composite Materials and Structures VII

6.1 Examples of woven geometry simulations

Here examples from the area of woven reinforcements for composites will be given. Examples of simulations for other fabric types are given elsewhere [10].

6.1.1 2D glass fabrics

Results of computations for plain glass (rovings) fabrics are shown in Fig. 2. It can be concluded that the model correctly predicts fibre volume fraction and the change of the yarn cross-sectional dimensions in a fabric (yarns are compressed to 80% of their initial thickness) and hence also interaction forces between warp and weft yarns. The ability of the model to characterise a wide range of 2D woven structures is illustrated by Fig. 3, which shows 3D images of the computed fabric geometry for different types of glass reinforcement. These 3D images are constructed with the help of a visualisation module included within the software.

Figure 2: Computer tomography (left) and computed (right) sections of glass rovings fabric (sections on different positions in the unit cell)
Figure 3: Photographs (left) and computed images (right) of different types of 2D glass reinforcements: (a-c) glass multi-filaments, different weave density; (d) glass rovings; (e) unidirectional weave.

6.1.2 3D carbon fabric

A 3D carbon fabric studied by Pu Gu [3] was chosen as an example for comparison of computed and experimental data. Fig. 4 shows the weave structure and a comparison between measured and computed values for fabric thickness and fibrous content. Note that for these computations virgin yarn data were not available, and the dimensions of the compressed yarn are based on values measured in [3] on fabric cross-sections.
Fibrous content, %

Figure 4: Weave structure and fibrous content of 3D carbon reinforcement for different thickness of Z warp yarn (white: computed, black: measured)

7 Conclusion

A hierarchical description of textile fabric geometry is implemented in algorithms and software using the Object Oriented Programming technology. The OOP provides a framework for the implementation of decomposition models, which use in full the Minimum Energy Principle in textile mechanics. As it has been shown on the multi-layered woven fabric examples, this approach results in physically sound and computationally effective algorithms, which provide a 3D description of the internal fabric geometry, including the fibrous structure of the contained yarns. The description can be used to create 3D images of the fabrics that can be manipulated via standard 3D imaging tools (e.g. OpenGL). It also provides a basis for the creation preprocessing tools for finite elements, micro-mechanical and hydrodynamic codes. An implementation of these tools will be a subject of our subsequent publications.

8 Acknowledgements

This work was done in the framework of the project "Development of unified models for the mechanical behaviour of textile composites" (GOA/98/05), funded by the Flemish Government through the Research Council of K.U.Leuven. S.V.Lomov’s work on this project was supported by grants for Senior Fellowship by the Research Council of K.U.Leuven (F/98/108, F/99/096). Samples of woven reinforcements were supplied by Syncoglas, Belgium and TISSA, Switzerland. KES-F measurements were done in laboratories of Centexbel, Belgium, with kind permission and help of Dr. E.Baetens and Dr. D.Verstraete. Authors would also like to thank Prof.N.N.Truevtzev (St.-Petersburg State University of Technology and Design) for his constant support of international collaboration in the field of textile mechanics.
9 References


11. Lomov, S.V. and N.N. Truevtzev, A software package for the prediction of woven fabrics geometrical and mechanical properties. Fibres & Textiles in Eastern Europe. 3(2) pp. 49-52, 1995
