MODELLING AND SIMULATION OF THE MECHANICAL BEHAVIOUR OF WEFT-KNITTED FABRICS FOR TECHNICAL APPLICATIONS

Part IV: 3D FEA model with a mesh of tetrahedric elements

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Abstract

This paper is in four parts. The first is related to general considerations and experimental analyses, and each of the others is related to different approaches to the theoretical analyses of the mechanical behaviour of weft-knitted fabrics and weft-knitted reinforced composites made of glass fibre. The objective is to find ways of improving the mechanical properties and simulating the mechanical behaviour of knitted fabrics and knitted reinforced composites so that the engineering design of such materials and structures may be improved.
In Part IV the technologies for weft-knitted 3D complex shape preform development are surveyed and a third model is presented. This a 3D model based on FEA (finite element analyses). A solid representation of a 2D yarn is built up, and an MES (mechanical event simulation) is applied to obtain a 3D-shaped loop. The final knitted fabric geometry is obtained by interacting this loop with the adjacent loops, according to the dimensional properties of the knitted fabrics and using an MES. Finally, the geometry of the reinforcement inside the composite is built up, and the composite material is divided into small tetrahedric elements to obtain a mesh of finite tetrahedric elements (FEA). The average values of the mechanical properties are obtained with FEA and compared with the experimental ones.

Key words:

knitted fabric, load-extension curve, technical textiles, modelling, mechanical properties, composite materials, FEA (finite element analyses), resin moulding

1. INTRODUCTION

The application of textile fabrics in engineering designs is a very important and interesting development. This type of fabric, known as technical textiles, has been widely used for protective clothing, transportation, geosynthetics, building construction, road construction, packing materials, military, medicine, sports, and so on.

Technical textiles include woven, non-woven, knitted and braided fabrics. Among these, knitted fabrics are a small percentage; according to the information available, knitted technical textiles represent about 9% of the total fibre consumption used for technical textiles. However, due to the flexibility of knitting technology, more knitted structures have been developed for technical applications in recent years.

The advantages of the knitting technologies used for the production of technical textiles can be summarised as follows:

- very flexible, especially in the case of weft-knitting;
- additional yarn preparation is not required;
- electronic needle selection and CAD also contribute greatly to the design capability, as well as to the quick set-up of the knitting machines;

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- due to the structural nature of knitted fabrics, properties such as axial strength (in various directions) may be achieved by introducing straight in-laid yarns or by other novel techniques (i.e. pre-tensioning);
- knitting to shape enables the formation of shaped fabrics in 2D and 3D, thus contributing to waste reduction and improved garment fit;
- the ability to conform to shapes and the improved drapeability of the knitted structures make them ideal for making complex parts or conforming to complex shapes in the manufacture of composite materials.

This paper presents some of the recent research work taking place in the development of weft-knitted fabrics for technical applications, especially for the reinforcement of composite materials. Modelling of the mechanical behaviour of knitted structures and the corresponding composites is also presented.

In weft-knitted fabrics, axial strength is normally achieved by the introduction of straight yarns. Various techniques have been used for the introduction of straight yarns, as described by Marvin [21], Saturnia [22], Cebulla [1] and Araújo *et al.* [9,10]. In practice, however, these techniques seem to be successful, principally with unshaped 2D fabrics.

Due to geometrical and process characteristics, the strengthening of shaped fabrics in various directions is far more complex, and the yarns need to be anchored to the ground structure at desired/convenient points. In this context, various techniques are used by the authors to overcome these problems, which include the use of:

- tuck and miss stitches;
- wrap striping;
- pre-tensioning of the fabric.

Tuck and miss stitches can be useful in introducing straight high-performance yarns in the weft direction. With the wrap striping technique, it is possible to introduce straight high-performance yarns in the warp and diagonal directions. In the latter case, racking of the needle beds may be required. Pre-tensioning the fabric is also useful for removing the effect of the loop deformation in the initial part of the load-extension curve of the knitted fabric (usually non-linear), so that the applied loads bear mainly on the yarns, after most yarn slippage has occurred (jamming).

2. DEVELOPMENT OF 3D PREFORMS FOR COMPOSITE MATERIALS BY KNITTING TO SHAPE

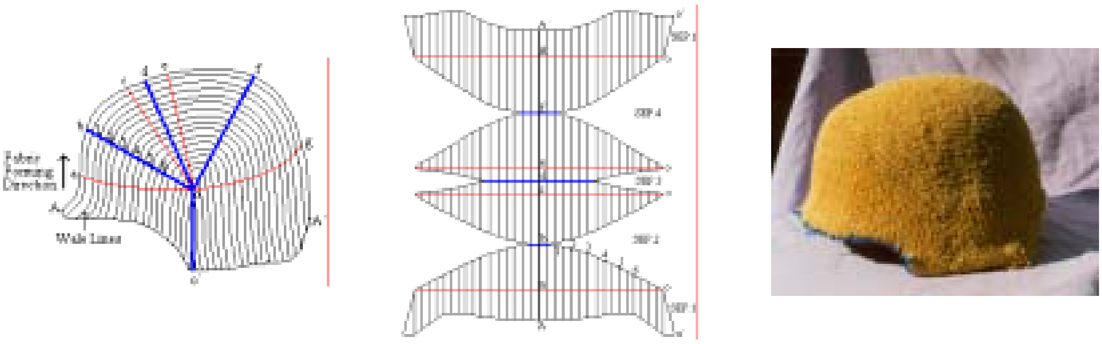
Knitting to shape is an important feature of knitting technology. Knitting to shape can be realised either by weft knitting or by warp knitting. In general, the weft knitting process is more flexible, due to the needle selection capability available and the variety of structural designs possible.

With the modern development of electronic V-bed flat knitting machines, the ability to knit to shape has been substantially enhanced. In a modern flat knitting machine, knitting to shape can be performed by using the following methods:

(1) using different structural combinations;
(2) using different stitch lengths;
(3) altering the number of operating needles from course to course;
(4) link-off.

The first and second methods are not suitable for the production of knitted pieces with homogeneous properties, since loop length variations lead to the production of knitted fabrics with different properties from place to place.

The third method is widely used in flat knitting for the production of fully-fashioned pieces. Two operations can be performed: increasing and decreasing the number of operating needles (widening and narrowing). The increasing and decreasing operations easily change the knitting width; this is why they are widely used for the production of knitted 2D-shaped panels. However, if suitable knitting procedures are used, this technique can also be used for the production of 3D-shaped pieces. For the production of a correct 3D form or shape, the decreasing operation always needs to be symmetrically combined with the increasing operation. When this method is extended to the production of more complicated 3D-shaped knitted pieces, the main technique consists in transferring 3D forms to 2D patterns, which can be formed by decreasing and increasing lines or curves (Fig. 1).



(1) 3D Theoretical form (2) 2D Pattern (3) Knitted Fabric

Fig. 1. Helmet form produced with aramid fibres

The fourth method is widely used in flat knitting to produce fully-fashioned panels such as sleeves or the back and front parts of a sweater. The different steps to close a tubular jersey knitted fabric from left to right are shown in Fig. 2.

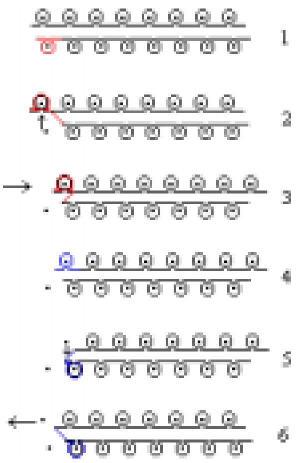


Fig. 2. Link-off process steps

This method is very complicated when applied to the production of weft-knitted fabrics made from high-performance fibres, which are very brittle and stiff. In order to prevent yarn rupture during the transferring and racking operations, the following aspects must be taken into consideration:

- use low speed;
- decrease the main take-down tension;
- use an auxiliary take-down system;
- slightly increase the transfer loops' length.

Fig. 3 shows an example of a glass fibre 3D-shaped weft-knitted fabric using this method.

Fig. 3. T- tubular form with lateral reinforcement produced with glass fibre

3. WEFT-KNITTED SANDWICH FABRIC DESIGN

A sandwich fabric is made up of two separate fabrics, connected by yarns or knitted layers. Fig. 4 illustrates this concept. It can be seen that this is a 3D construction, with the thickness being determined by the length of the connection.

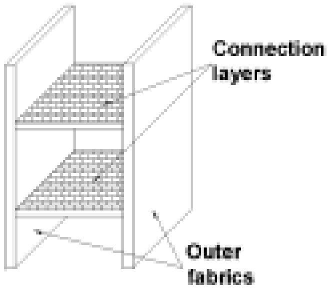


Fig. 4. Sandwich structure

The basic production principle includes knitting separately on the two needle beds, and at a certain point stopping knitting the separate layers and starting knitting the connection layer on selected needles, usually in a 1×1 rib. These needles can also be used to knit the separate fabrics (if the length of the connection layer is short), or can be used exclusively to produce the connection layer, if its length and/or shape complexity so require.
The construction of sandwich fabrics is limited to single jersey. In order to increase the mechanical behaviour, in-lay patterns (both miss and tuck and weft insertion) can also be used. There are two ways of knitting the connection layers:

- Single connection layers (Fig. 5.a) – the layer is produced on one needle bed (jersey) or on both needle beds (rib, interlock), and can be perpendicular or inclined in relation to the separate fabrics.
- Double connection layers (Fig. 5.b) – the two layers are knitted separately on the two needle beds and connected at a certain point by a row of rib. If at this stage, a specified amount of courses are produced in the outer fabrics, then the connection will be "X"-shaped. It is also possible to increase the number of rib joining courses, resulting in the geometry shown in Fig. 5. b. 2.

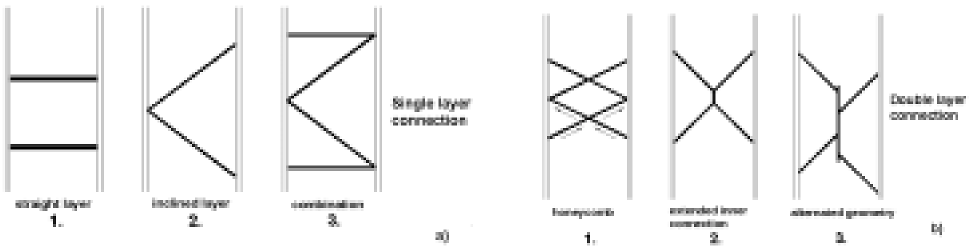


Fig. 5. Different types of layer connection

The length of the connection layers may be used as another criteria for classification, which is related to the thickness of the sandwich fabric:

- Up to 2 cm thickness - the fabrics are easy to produce, no special equipment is required for its production, and may be classed as standard fabrics.
- For thickness over 2 cm - the connection layers require special take-down systems (the main take-down is not used, due to the fact that knitting of the outer fabrics is stopped). The thickness of such fabrics can reach considerable values – as much as 10 cm.

3.1. Design directions for sandwich fabrics

The sandwich fabrics presented so far have been characterised by constant thickness and rectangular form. There are three major ways to design these fabrics in order to obtain structures with complex shapes:

- The use of connection layers of different lengths;
- The use of connection layers with variable form (the incomplete courses technique);
- The use of outer, separate fabrics with shape (fully-fashioned).

3.1.1 Sandwich fabrics with connection layers of different lengths

The simple variation of the connection layer length will modify the cross-section of the fabric. The shape is created by the positioning of the separate fabrics between the consecutive layers. Two possibilities can be considered. The first case consists of a specified sequence of connection layers with different lengths, as illustrated in Fig. 6.

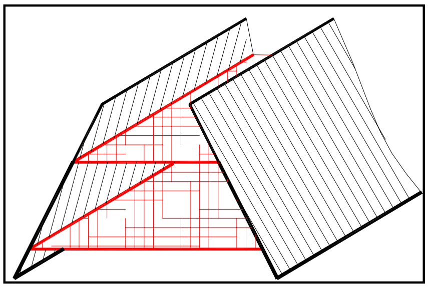


Fig. 6. Sandwich fabric with layers of different length

In the second case, a sequence of two layers with predetermined (different) lengths is combined with a given number of courses in the separate fabric(s), generating a corner effect (90^0 geometry). This is the case of fabrics with L or T cross-sections, presented in Fig. 7.

Fig. 7. Sandwich fabrics' corner effects (different length of the layers): L-shaped, T-shaped

3.1.2 Sandwich fabrics with layers of variable shape

In this class of fabric, the form is determined directly by the shape of the connection layers, obtained through the incomplete courses technique. This technique consists in knitting certain rows with a selection (fraction) of the needles that are producing the connection layer, while the other needles (not selected) remain idle.
Two main types of shaped layers can be developed, i.e., integral shaped layers, where the yarn guide is feeding continuously on a variable number of needles (Fig. 8) and divided shaped layers, which involves knitting on distinct groups of needles (requires separate feeders).

(a) (b) (c)

Fig. 8. Sandwich fabrics with shaped layers

3.1.3 Sandwich fabrics with shaped outer fabrics

The fully-fashioned technique involves narrowing and widening the fabric width, by changing the number of knitting needles. This is done by stitch transfer and racking. Fig. 9 illustrates an example of this type of construction.

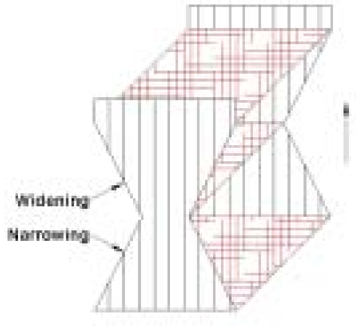
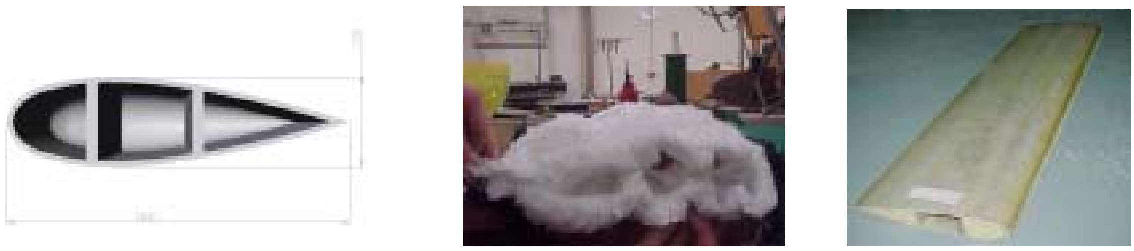


Fig. 9. Sandwich fabric with shaped outer fabrics

The combination of these three methods can be used to produce very complex shaped fabrics for applications such as preforms for composite materials. The design of these textile preforms is part of the total process of designing composite materials (material selection, structural design and production technique) and must be conducted in conformity with the requirements of the end user.

<u>**3.2. Example of application**</u>

An interesting application of varying section sandwich structures is an airplane wing. As shown in Fig. 10, a small simplified plane wing is constructed with an exterior wall and two connection layers. In this case, an integral knitted sandwich preform can be directly used as the reinforcement material. Due to the variation of the space between the exterior walls and the dimensions along the wing, the knitting to shape technique is also necessary in order to obtain the required dimension and form. The advantages of using sandwich structures as reinforcement in this case consist in the structural integrity and facility of applying resin during the RTM process.



(1) (2) (3)

Fig. 10. Application of a sandwich structure for aeroplane wing
(1) Wing section (2) Knitted preform (3) Composite

4. MODELLING THE MECHANICAL BEHAVIOUR OF COMPOSITE MATERIALS REINFORCED WITH A PLAIN WEFT KNITTED STRUCTURE

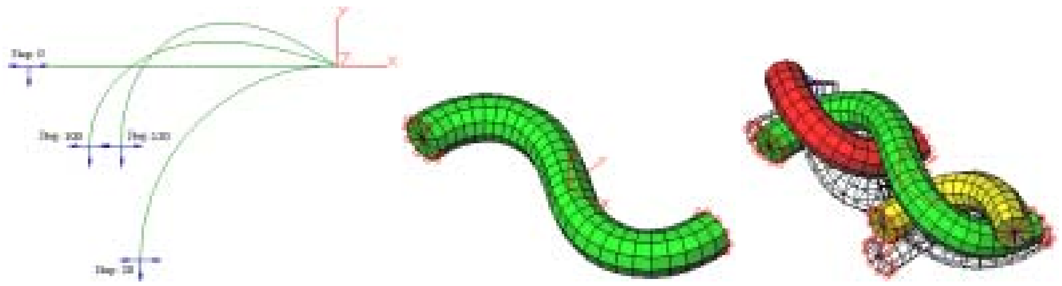
The characterisation and prediction of the mechanical properties of a composite material are much more complex than those of isotropic and homogeneous materials, like metals. Since a composite material generally consists of two or more constituents, the approach followed to analyse their mechanical behaviour is to replace the material itself by an equivalent or effective material, based on the averaging technique.

The elastic properties of the glass fibre used to knit the weft knitted fabric and those of the polyester resin used to impregnate it are shown in Table I.

The 2D shape of a loop unit cell inside a plain weft-knitted fabric has been established by using a finite element analysis. In this case, a straight yarn has been forced to acquire the loop shape by imposing prescribed rotations and displacements defined according to the dimensional properties of the knitted fabric. Due to the loop unit cell symmetry, only a quarter of the loop has been analysed. Fig. 11 (1) shows the final shape of the loop thus obtained (Step 150) and Fig. 11 (2) illustrates the 3D loop shape obtained, taking the yarn diameter into account. The final knitted fabric geometry obtained by interacting this loop with the adjacent loops, according to the dimensional properties of the knitted fabrics and using a Mechanical Event Simulation, is shown in Fig. 11 (3).

Table I. Tensile properties of the composite constituents

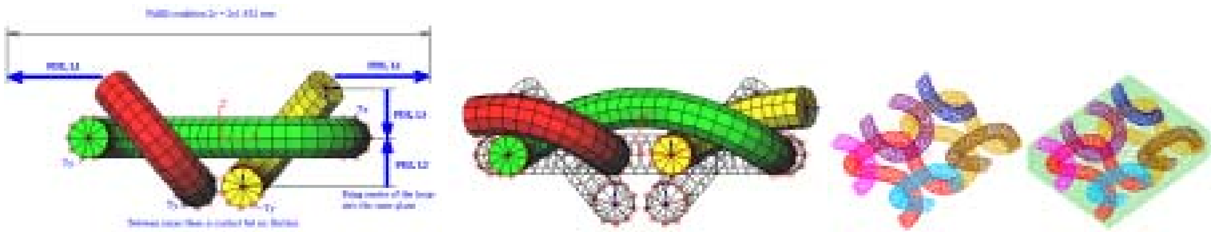
Constituent	Young´s Modulus [MPa]	Poisson ratio
Glass fibre	73000	0.24
Resin (polyester)	2412	0.35
Glass fibre strand embedded in resin	68770	0.245



(1) (2) (3)

Fig. 11. Establishment of the reinforcement geometry by using Finite Element Analysis

In order to define the final configuration (3D) of the loop, as a result of the interaction with the adjacent loops, another finite element non-linear simulation (involving large displacements and contact without friction between yarns) was done in 100 steps. Fig. 12 (1) presents the initial configuration of the loops, together with some dimensional conditions to be achieved at the end of the simulation. Fig. 12 (2) illustrates the final configuration of the loops obtained during the analysis. Finally, the geometry of the reinforcement inside the composite is built as shown in Fig. 12(3).



(1) (2) (3)

Fig. 12. Final configuration of the loop

The dimensions of the composite Unit Cell (UC) depicted in Fig. 12 (3) are 4.88×3.92×1.2 mm. The volume is divided (meshed) in FE, each one containing only one material. In the case of an orthotropic material, it is necessary to introduce 9 independent engineering constants, such as three distinct Young´s moduli (E_1, E_2, E_3) (1–wales direction, 2–courses direction, 3–thickness direction), three distinct shear moduli (G_{12}, G_{13}, G_{23}) and three distinct Poisson ratios (υ_{12}, υ_{13}, υ_{23}). In addition, three distinct coefficients of thermal expansion (α_1, α_2, α_3) have to be introduced in order to fully characterise the material.

Because the internal geometry of the composite is highly irregular, the mesh is also expected to be highly distorted and irregular, and it is therefore necessary to have strict control over the precision of the results. One method used to qualify as a percentage coefficient, the imprecision of a particular mesh, is the use of the same mesh to analyse a similar problem, but with the theoretical or experimental solutions already known. The mesh imprecision coefficient (IC) is defined as the ratio between the theoretical solution and the FEA one. In order to define the IC, a mesh was used for an UC completely made from aluminium in order to 'predict' the elastic parameters. The mesh had the following isotropic properties: E=69637 MPa, υ=0.36, G=25602 MPa, $\alpha = 23.58 \cdot 10^{-6}$ 1/°C.

Table II shows the predicted and corrected values for the knitted structure reinforced composite.

Table II – Predict values for the knitted structure composite

Predicted	IC	Corrected
E_1=6808 MPa	+ 1.37%	E_1=6715 MPa
E_2=5990 MPa	+ 3.77%	E_2=5764 MPa
E_3=4986 MPa	+ 0.57%	E_3=4986 MPa
υ_{12}= 0.110	- 10.43%	υ_{12}=0.121
υ_{13}= 0.474	+ 5.01%	υ_{13}=0.450
υ_{23}= 0.374	+ 12.62%	υ_{23}=0.327
G_{12}= 1659 MPa	0%	G_{12}=1659 MPa
G_{13}= 3200 MPa	0%	G_{13}=3200 MPa
G_{23}= 1186 MPa	0%	G_{23}=1186 MPa
$\alpha_{12}=47.98 \cdot 10^{-6}$ 1/°C	0%	$\alpha_{12}=47.98 \cdot 10^{-6}$ 1/°C
$\alpha_{13}=70.63 \cdot 10^{-6}$ 1/°C	0%	$\alpha_{13}=70.63 \cdot 10^{-6}$ 1/°C
$\alpha_{23}=99.92 \cdot 10^{-6}$ 1/°C	0%	$\alpha_{23}=99.92 \cdot 10^{-6}$ 1/°C

A comparison between the experimental and FEA predicted values for E_1 and E_2, is presented in Table III.

Table III – Comparison between experimental and FEM for E_1 and E_2

Experimental	Predicted	Error
E_1 = 6447 MPa	E_1 = 6715 MPa	4.2%
E_2 = 3448 MPa	E_2 = 5764 MPa	40%

This comparison shows that the theoretically predicted values for the walewise direction are good, but the ones for the coursewise direction are poor. This may be due to the fact that frictional constraints, which were not taken into account in this model, are more relevant in the coursewise direction. This agrees with the experimental findings by Araújo [24], comparing the tensile and recovery behaviour of interlock and half-gauge 1x1 rib fabrics, which found that the SIF[2] (structure interference factor) was mainly a coursewise direction property, and that its value depended to some extension on the yarn coefficient of friction, machine tightness factor and the level of strain developed.

5. CONCLUSIONS

Weft-knitted fabrics made of high performance yarns have great potential for use in textile reinforced composites. Complex structures can be engineered to meet performance requirements. However, much development has yet to take place in order to be able to introduce straight non-knitting yarns to increase stiffness in various directions. These developments are taking place now, and there are some interesting structures, such as fleece and others, that are now being adapted for application in complex shape preform development. The 3D FEA model developed has shown great value for the prediction of properties in the walewise direction, but requires a provision for introducing frictional forces into the model in order to be able to improve predictions, especially in the coursewise direction.

[2] Interlock is a double 1×1 rib fabric with crossed sinker wales; when the stress required to extend one rib unit by a given amount in the coursewise and walewise direction differs between a 1×1 rib half-gauge fabric and an interlock fabric (both knitted from the same yarn and at the same machine settings), this difference in stress, not being randomly distributed, but following some particular law or trend, may be termed the SIF (structure interference factor).

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