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

Part III: 2D hexagonal FEA model with non-linear truss elements

M. de Araújo, R. Fangueiro and H. Hong[1]

University of Minho, Guimarães, Portugal
Phone: +351 253 510 280 Fax: +351 253 510293
maraujo@det.uminho.pt; rfang@det.uminho.pt

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 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 III the second model is presented, and this is a 2D model based on FEA (finite element analyses).

A plain weft-knitted fabric, based on the simple loop structure, is simplified and represented by a 2D hexagonal structure constructed by non-linear truss elements. The characteristics of the truss elements for FEA simulation are obtained from experimental results through an analytical method when a loop is converted to a FEA model. The elongation deformation is simulated in one, two and multiple directions. The model can also be used to calculate a planar knitted fabric for deformation to fit a 3D spherical mould.

Key words:

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

1. INTRODUCTION

In recent years, knitted fabrics have received great attention in the composites industry for structural reinforcement [1-10]. This is attributed to their unique properties when compared with other reinforcement fabric structures such as woven and braided fabrics. Due to their loop structure, knitted fabrics may develop a high degree of deformability. This deformability provides drapeability, which makes them ideal for the reinforcement of complex-shaped preforms for liquid moulding in the production of composite components. Moreover, some important mechanical properties of composites, such as resistance against impact and delamination, can be improved due to the energy absorption capacity of loop structures. There is however no doubt that the loop structure will result in a reduction of the modulus of the resulting composites. However, this disadvantage may be overcome by inserting straight reinforcement yarns in the knitted structures. The directionally oriented structures (DOS) are examples of this, and yarn reinforcements [11-12] may be inserted in one, two, three or multiple directions. If necessary, a pre-tension can also be applied to the knitted fabric reinforcements in order to improve the stiffness of the composite.

Knowledge of the deformation behaviour of a knitted fabric is very important in the design of knitted reinforced composites. Two cases may be considered. The first case concerns pre-tension, and in this case the value of pre-tension required must be defined in order to produce a composite material with

---

[1] Currently at Dong Hua Textile University, Shanghai, China

the desired mechanical properties. The second case concerns the deformation of a planar knitted fabric to fit a mould in an RTM process. In this case, it is necessary to know whether the desired shape can be obtained after a given knitted structure has been deformed to fit the mould.

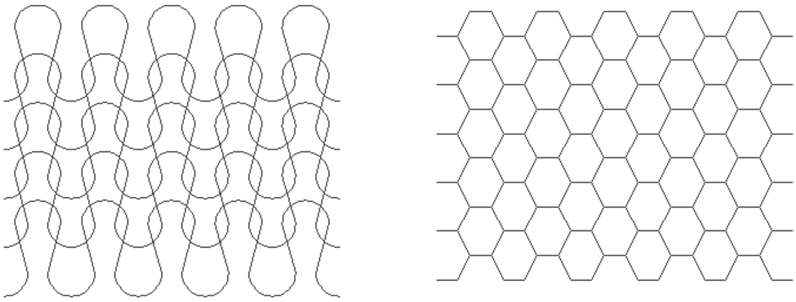
The deformation behaviour of a knitted fabric is directly related to its tensile properties. Different models [13-20] have been proposed for the prediction of these properties. They are mostly based on the plain weft-knitted structure using micro-mechanical analyses of the knitted loop. However, due to the complexity of the analyses, the application of these models for the prediction of the deformation behaviour of knitted fabric for composite reinforcements is very limited, especially in the case where the deformation of a knitted fabric is multidirectional.

In this paper, a FEA model has been developed to predict the deformation behaviour and the related mechanical properties of the fundamental weft-knitted structure. Besides the simulation of the elongation deformation in one, two and multiple directions, the model is also used to calculate the deformation of a planar knitted fabric to fit a 3D mould with a spherical form [21-22].

2. FEA MODEL

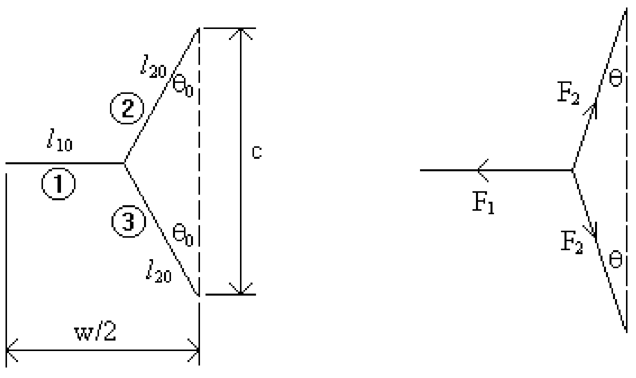
2.1. Description of the model

In order to simulate the deformation behaviour of a knitted fabric using Finite Element Analysis (FEA), it is necessary to set up a FEA model which can represent the characteristic structure of the fabric. As shown in Fig. 1, a plain weft-knitted fabric, based on the simple loop structure, is simplified and represented by a 2D hexagonal structure. The hexagonal structure is a FEA model constructed by non-linear truss elements. Fig. 2 (a) shows a minimum representative unit of the model. It includes three truss elements 1, 2 and 3. Elements 2 and 3 are symmetrical. By considering different deformation behaviour of the knitted fabric in the wales and courses directions, it is assumed that element 1 has different material properties than elements 2 and 3. From this consideration, all truss elements in the model can be divided into two material groups, I and II. As shown in Fig. 2 (a), element 1 belongs to group I, and elements 2 and 3 belong to group II.



(a) (b)

Fig. 1. Plain weft-knitted fabric structure (a) and corresponding FEA model (b)



(a) (b)

Fig. 2. Minimum representative unit of the FEA model: initial state (b) extended state (a)

2.2. Determination of the element parameters

When a plain weft-knitted fabric is represented by the above FEA model, the geometrical parameters and load extension properties of the knitted fabric must be converted to the characteristics of the truss elements in order to perform a simulation. In the present model, two kinds of element parameters must be determined. These are the elements of dimensions and material parameters. For a truss element, the cross section area and length are the two main dimensional parameters. In order to simplify the simulation, the cross-section area is assumed to be equal to 1 mm^2 for all elements. However, the length of the elements in groups I and II are different. By analysing the geometrical configuration shown in Fig. 2, the following relations are obtained:

$$l_{10} = 0.5\ c \cos\theta_0 \quad (1)$$

$$l_{20} = 0.5\ (w - c \tan\theta_0) \quad (2)$$

where:

l_{10}, l_{20} = lengths of the elements in group I (element 1) and II (elements 2 and 3) at the initial state;
c, w = course spacing and wale spacing of the knitted fabric;
θ_0 = angle formed by elements 2 or 3 with the vertical line.

It is necessary to point out that the lengths of the elements depend not only on the geometrical dimensions of the loop, c and w, but also on the angle θ_0. This is different from the model proposed by Wu et al. [19]. In the present model, θ_0 is determined by considering a force equilibrium state at a near-initial state (0.01% deformation).

To determine the element material parameters, it is assumed that the elements for each group obey the following non-linear relations when they are extended:

$$F_1 = M_1\ \varepsilon_1^{n_1} \quad (3)$$

$$F_2 = M_2\ \varepsilon_2^{n_2} \quad (4)$$

where:

F_1, F_2 = axis tensile forces of the elements in group I and II at the extended state;
ε_1, ε_2 = axis elongation of the elements in group I and II;
M_1, M_1, n_1, n_2 = material parameters to be determined from experimental data.

M_1, M_2, n_1 and n_2 have been determined by statistical analysis. The idea is that the total error between the tensile forces calculated from the FEA model and those obtained from the experimental results, for all deformation states, must be minimised. As shown in Fig. 2(b), the axial elongation of the elements 1, 2 and 3 (ε_1 and ε_2) can be calculated by the following relations:

$$\varepsilon_1 = \varepsilon_x \quad (5)$$

$$\varepsilon_2 = \{(1 + \varepsilon_x) \sin^2\theta_0 + (1 + \varepsilon_y) \cos^2\theta_0\}^{1/2} - 1 \quad (6)$$

where:

ε_x, ε_y = elongation of the knitted fabric in the coursewise and walewise directions.

By using the least square method, the total error between the values of the tensile forces calculated from the model and experimental data can be calculated from the following error function:

$$F(M_1, M_2, n_1, n_2) = \sum_{i=1}^{N} \{(T_{xi} - F_{1i})^2 + (T_{yi} - \cos\theta_i\ F_{2i})^2\} \quad (7)$$

where T_{xi} T_{yi} are the tensile forces of the knitted fabric, respectively in the coursewise and walewise directions, obtained from biaxial tensile testing results.

In order to obtain the minimum error, the partial differentiations of the function $F(M_1, M_2, n_1, n_2)$ should be zero, thus:

$$\partial F(M_1, M_2, n_1, n_2)/\partial M_1 = 0 \quad (8)$$

$$\partial F(M_1, M_2, n_1, n_2)/\partial M_2 = 0 \quad (9)$$

$$\partial F(M_1, M_2, n_1, n_2)/\partial n_1 = 0 \quad (10)$$

$$\partial F(M_1, M_2, n_1, n_2)/\partial n_2 = 0 \quad (11)$$

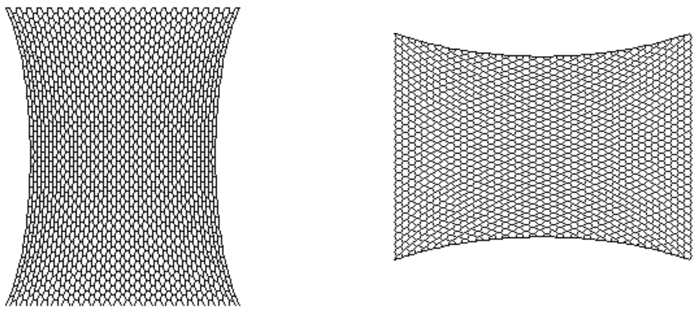
Solving these non-linear simultaneous equations will give the values of M_1, M_2, n_1 and n_2 for a given knitted fabric.

3. RESULTS OF THE SIMULATION

As an example, the geometrical parameters and biaxial testing results of a cotton plain weft-knitted fabric have been used to calculate the truss element parameters. The course spacing (c) and wale spacing (w) of the fabric are 0.877 mm and 1.204 mm respectively. The biaxial tensile tests were performed at equal elongation conditions in the coursewise and walewise directions, i.e., $\varepsilon_x = \varepsilon_y$. From the geometrical parameters and tensile testing results of the knitted fabric, the values of the truss element parameters are calculated and shown in Table I.

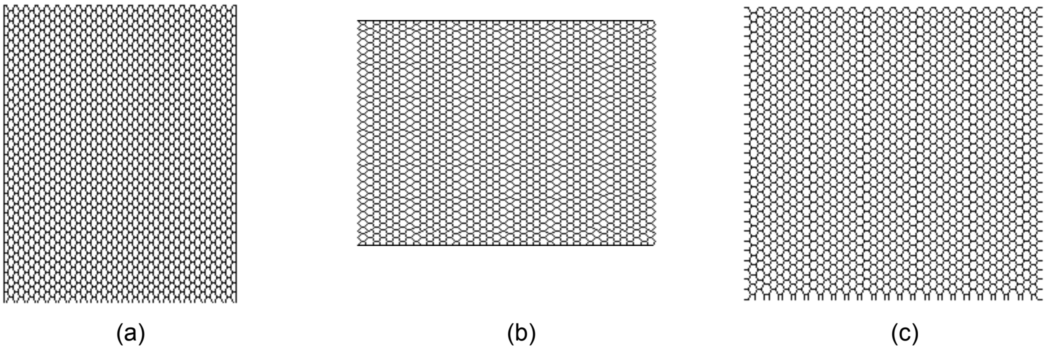
Table I. Truss element parameters used for the simulation

Group I (element 1)			Group II (elements 2 and 3)		
l_{10} (mm)	M_1(N)	n_1	l_{20} (mm)	M_1(N)	n_2
0.379	69.423	2.844	0.492	77.92	2.844



(a) (b)

Fig. 3. State of deformation of the model for a uniaxial elongation in the walewise direction (a) and in the coursewise direction (b)



(a) (b) (c)

Fig. 4. State of deformation of the model for a biaxial elongation in (a) the walewise direction (restrained coursewise),in (b) the coursewise direction (restrained walewise) and (c) equal biaxial elongation

With these values, it is possible to perform a simulation of the elongation of the knitted fabric in one, two and multiple directions, using the FEA model. The calculated deformation states of the FEA model, at an elongation of 30%, in these cases, are shown in Figs. 3 to 5. The corresponding theoretical tensile curves are also shown in Figs. 6 to 8.

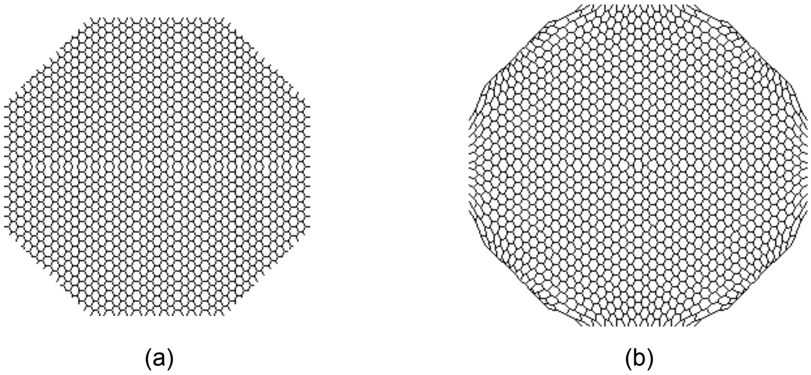


Fig. 5. State of deformation of the model for a multiaxial elongation (equal elongation in four directions, at 45º, at the same time): (a) initial relaxed state (b) final deformed state

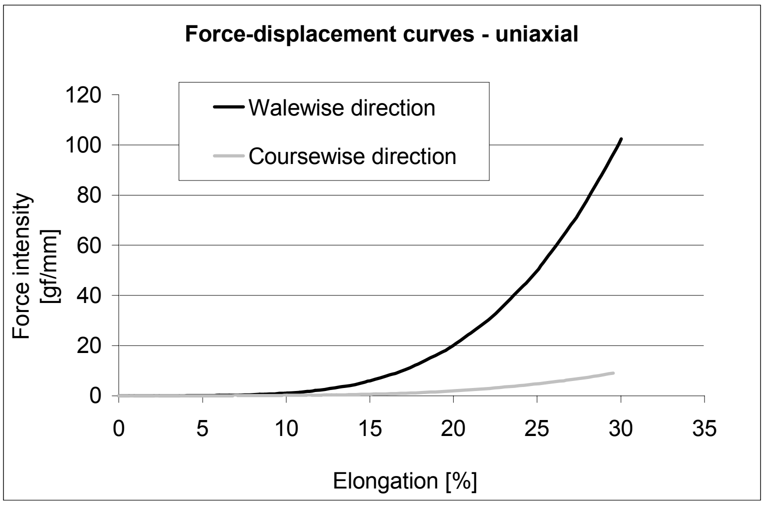
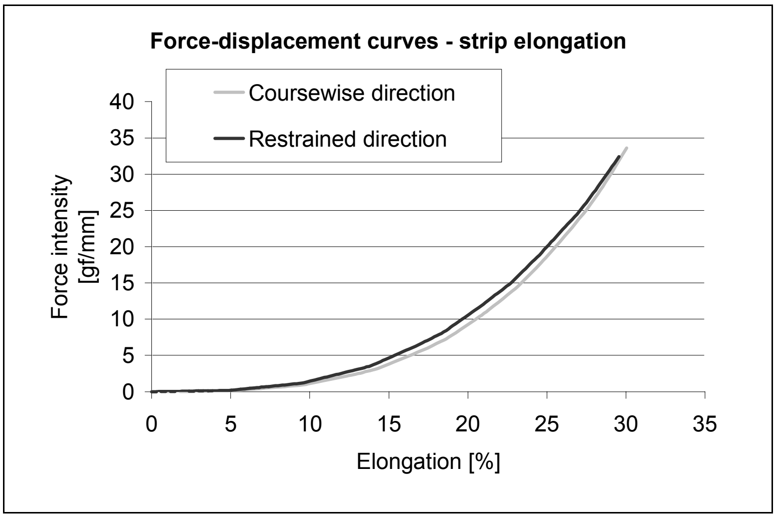
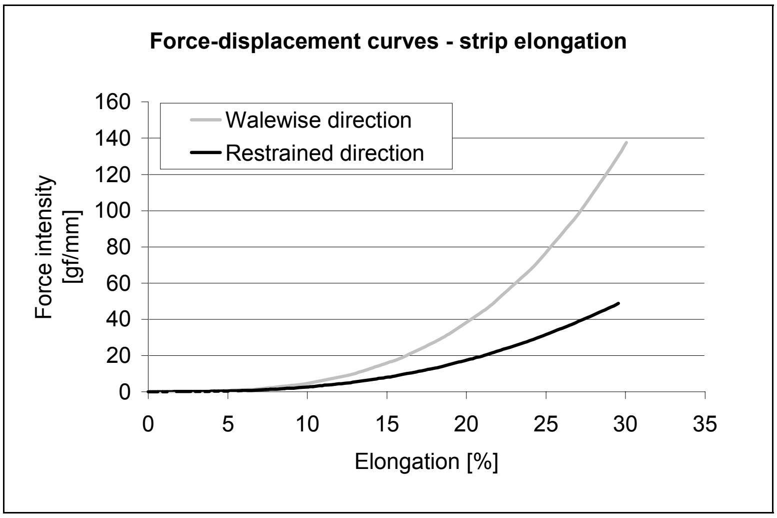


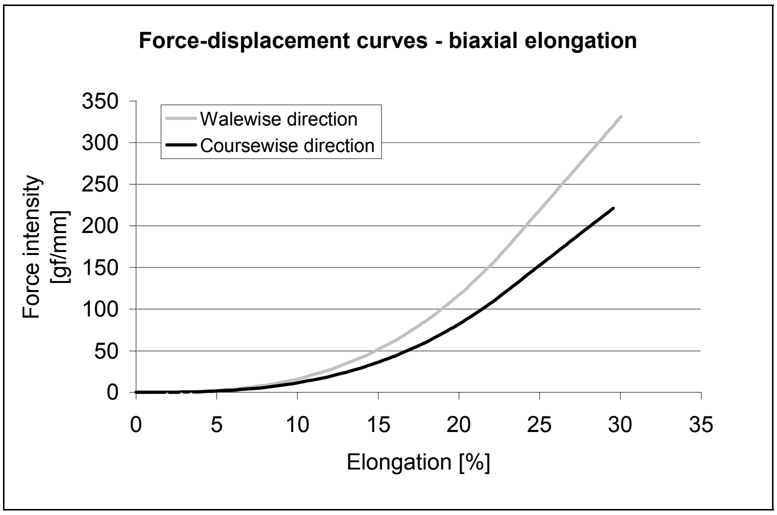
Fig. 6. Load-extension curves for the uniaxial elongation

a)





b)



c)

Fig. 7. Load extension curves for the biaxial elongation:
(a) strip elongation in the walewise direction (restrained coursewise)
(b) strip elongation in the coursewise direction (restrained walewise)
(c) equal biaxial elongation

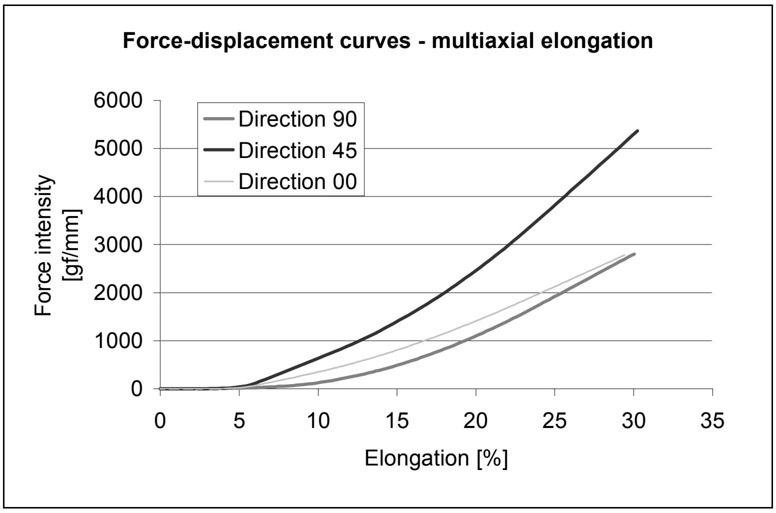


Fig. 8. Load extension curves in the multiaxial elongation
(equal elongation in the four directions at the same time)

In order to validate the current model, the theoretical results were compared with experimental ones, from Kawabata [18] (Fig. 9) in the case of equal biaxial elongation. The results show that there is very good agreement between the theoretical and experimental results.

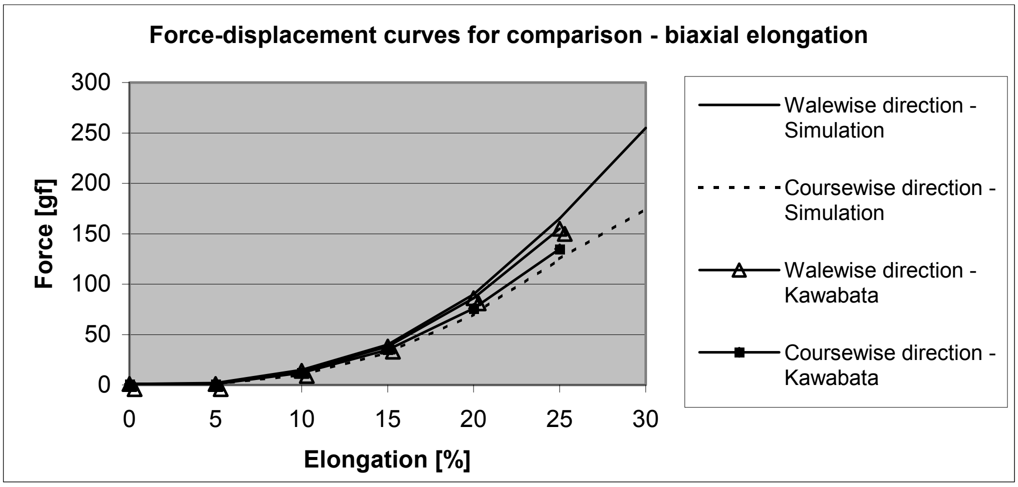
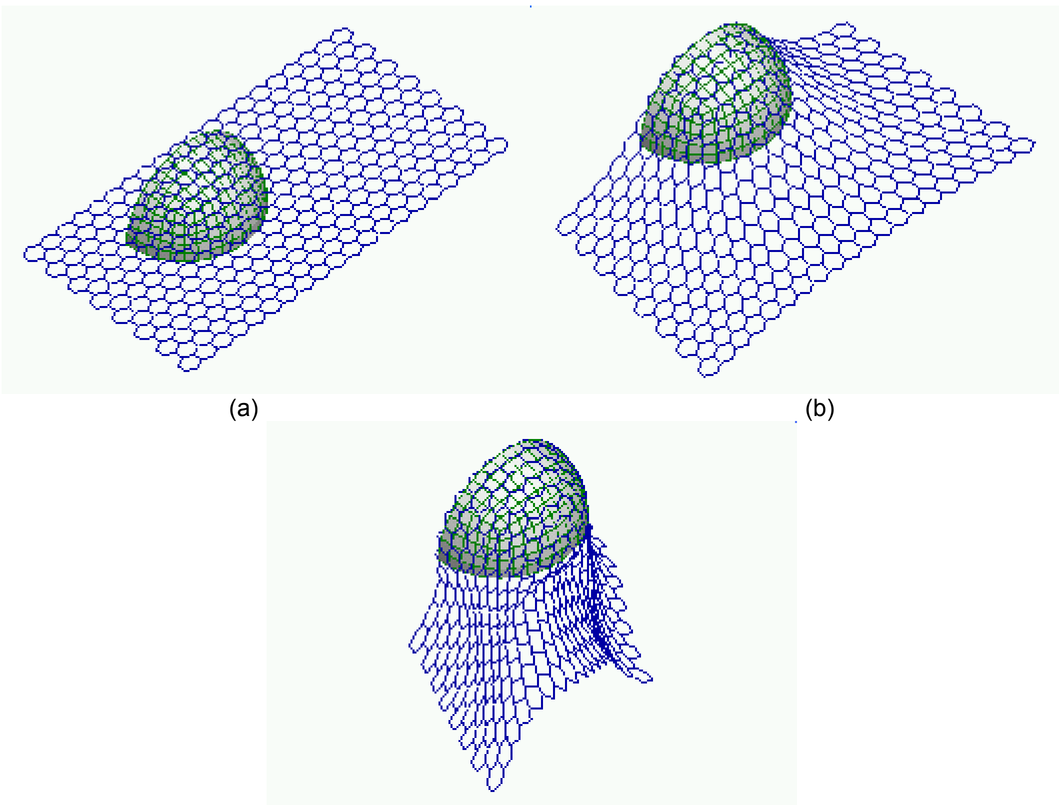


Fig. 9. Comparison between simulated and experimental results for the equal biaxial elongation

Besides the simulation of the deformation behaviour of a knitted fabric in one plane, the present FEA model can also be used for the simulation of a planar knitted fabric when deformed to fit a 3D mould in the RTM (resin transfer moulding) process. As shown in Fig. 10, a planar knitted fabric can be deformed to fit a spherical form without any problems. This example clearly shows the high deformability of knitted structures.



(a) (b)

(c)

Fig. 10. Simulation of the deformability of the model fabric
(a) initial position (b) intermediate position (c) final position

CONCLUSION

A hexagonal FEA model, constructed by non-linear truss elements, has been proposed. In order to perform the simulation, the geometrical parameters and tensile properties of the knitted fabric must be converted to the truss element parameters. The method used to do this conversion has proven to be effective. The simulation was performed for 2D in plane elongations in one, two and multiple directions, as well as for a 3D case, where a planar knitted fabric is deformed to fit a semi-spherical shape. The work shows the efficiency of the Finite Element Method for the complex analyses of textile structures such as knitted fabrics.

REFERENCES

1. *Ramakrishna. S., et al.(1993) in Pro. of 3rd Japan International SAMPLE Symposium, Tokyo, pp. 312-317.*
2. *Horstine, K., Wulhorst, B., Franzke, G. and Offermann, P. (1993), SAMPE J., 29, 7-12.*
3. *Dewalt, P:L. and Reichard, B.P. (1994), J. Reinf. Plast. Comp., 13, 908-917.*
4. *Mayer, J., Ruffieux, K., Tognini, R. and Whintermantel, E. (1993) in Proc. of ECCM6, Bordeaux, 1993, pp. 219-224.*
5. *Ramakrishna, S., Hamada, H., Rydin, R. and Chow, T.W. (1995), Sci. Eng. Comp. Mater., 4(2), 61-72, 1995.*
6. *Ramakrishna, S. and Hull, D. (1993), Comp. Sci. Technol., 49, 349-356.*
7. *Ramakrishna, S. (1995), J. Reinf. Plast. Comp., 14, 1121-1141.*
8. *Ramakrishna, S., Hamada, H. and Hull, D. (1995), in Impact and Dynamic Fracture of Polymers and Composites (ESIS19), Willianms, J.G. and Pavan, A., eds, Mechanical Engineering Publications, London, pp. 453-464.*
9. *Rudd, C.D., Owen, M.J. and Middleton, V. (1990), Comp. Sci. Technol., 39, 261-277.*
10. *Gommers, B., Verpoest, I. And Houtte, P.V. (1966), Comp. Sci. Technol., 56, 685-694.*
11. *Raz, S. (1988), The Karl Mayer Guide to Technical Textile, Karl Mayer Textilmaschinenfabrik GmbH.*
12. *Araújo, M.D., Hong, H. and Fangueiro, R. (1995), ITB Nonwovens, Industrial Textiles, 1, 44.*
13. *Popper, P. (1966), Text. Res. J., 36, 148.*
14. *Whiteney, J.M. and Epting, J.L. (1966), Text. Res. J., 36, 143.*
15. *MacRory, B.M. and McNamara, A.B. (1967), Text. Res. J., 37, 908.*
16. *Shanahan W.J. and Postle R. (1974), Text. Res. J., 65, 200.*
17. *Hepworth, B. (1978), J. Text. Inst., 4, 101.*
18. *Kawabata, S., Nonlinear Mechanics of Woven and knitted materials, Chapter 3 in Textile Structural Composites, Chou T.W. and Ko F.K. (1989), eds., Elsevier.*
19. *Wu, W.L., Hamada, H. and Maekava, Z.I. (1994), J. Text. Inst., 85, 199.*
20. *Hong H.. de Araújo, M.D. and Fangueiro, R. (2002), ICCE/7, July 2-8, Denver, Colorado, USA, 335.*
21. *Araújo, M. de, Hong, H., Fangueiro, R., Ciobanu, O., Ciobanu, L. and Moscathou, (2002), The design of complex shaped fibre based preforms for composite materials, 2nd AUTEX Conference, Belgium, 1-3 July.*
22. *Araújo, M. de, Hong, H., Fangueiro, R. and Ciobanu, O. (2002), Simulation of the Deformation Behaviour of Weft-knitted Fabrics for Composites Reinforcement Using Finite Element Analysis (FEA), October, UMIST, Manchester, U.K.*