SOLID MECHANICS DRAPING SIMULATIONS OF WOVEN FABRICS

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SUMMARY: In the RTM processing, fibre reinforcement is draped over complex mould surface, resulting local variations in the fibre volume fraction and fibre orientation, which have significant effects on the permeability of the reinforcement during resin infiltration and on the properties of the composite product. This paper presents draping simulations of fabrics by following a mechanical approach. In this approach, an explicit dynamic FEA was employed. The fabric was considered as a solid continuum with mechanical properties and friction properties at interfaces. To incorporate large shear deformation of fabric during draping, an up-dated material behaviour law was adopted. Simulations were focused on the draping of a fabric into a hemisphere. The predictions were compared with the results from non-updated material, experimental data and those from a "fishnet" algorithm. $\boldsymbol{V_f}$ and mechanical properties of the composite product can be predicted from the results of draping.

KEYWORDS: drapability, modelling, simulation, fabrics, resin transfer moulding.

INTRODUCTION

In manufacture processes of composite components such as resin transfer moulding (RTM), an important stage is the draping of the reinforcement onto the mould surface. The prediction of the distortion of the reinforcement during draping and the changes in fibre orientation and fibre fraction are essential for the understanding of the manufacture process, the prediction of permeability and the evaluation of the mechanical properties of the composite products.

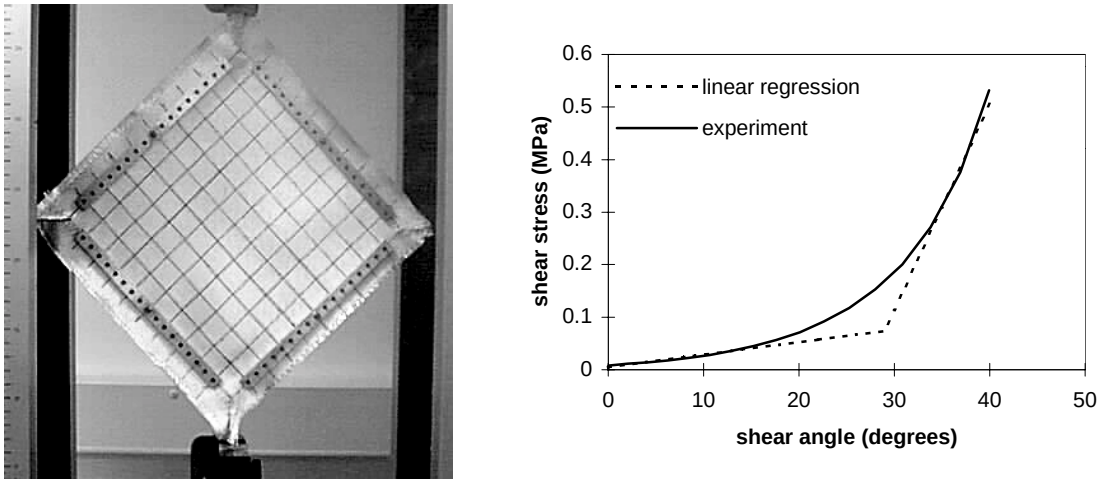
There are two different approaches for the simulation of the draping of woven fabrics onto complex geometries, the geometrical fitting and the solid mechanics drawing. In the geometrical fitting [1-6], in particular the "fishnet" model, the effect of material properties is not included, while the solid mechanics [7-12] represents a physical process which takes into account the mechanical properties of the fabric. The fabric is considered as a continuum sheet and the analysis of the draping of fabrics is essentially an extension of the deep drawing or diaphragm forming simulations of metal forming processes. The difference is that the dominant mode of deformation in the metal forming process is related to plasticity whereas in the woven fabric draping the dominant mode of deformation is shear.

This paper includes computer simulations of the draping of woven fabrics over a hemispherical surface adjusted to a flat surface. A mechanical approach of deep drawing typically employed to simulate metal forming is investigated and adopted in the simulations by using finite elements analysis (FEA) methodology. The analyses are carried out using the

ABACUS FEA code with linear elastic, anisotropic material properties. The predictions of the structure of the draped fabrics are compared with experimental data and the "fishnet" predictions.

MODELLING OF THE MECHANICAL BEHAVIOUR OF WOVEN FABRICS

Picture frame shear results



(a)) (b)

Fig.1. (a) *Picture-frame shear test set up; (b) test results for glass woven fabric*.

In the metal forming process the dominant feature of deformation is plasticity because of the isotropic nature for metals. In the woven fabric draping, however, the shear deformation is dominant because of the large difference between the stiffness in fibre direction and in-plane shear ($\boldsymbol{E}_{11}/\boldsymbol{G}_{12}\sim10^6$ in the simulations of this study). Therefore, it is important to determine the shear behaviour of the woven fabrics. An experimental technique called picture-frame shear method shown in Fig. 1(a) has been applied for that purpose[11,13].

Typical results of shear stress versus shear angle are shown in Fig. 1(b). Two straight lines can be fitted by linear regression analysis in the initial and last section of the experimental data. The corresponding shear angle at the intersection point was defined as the shear locking angle and was very close to the shear angle after which bukling or non-uniform deformation was developed in the picture-frame shear test. The initial slop of the straight regression line was used as the shear modulus, G_{12}, in the draping simulations.

The algorithm for up-dating material behaviour

The need for up-dating the material law [14] in FEA originated from the fact that the local, orthogonal, material coordinate system at each node of the finite element mesh does not generally coincide with the local fibre directions after the fibres have been sheared during draping [15]. Hence, an up-dated material behaviour law was formulated on the basis of changing directions of the unidirectional fibre laminates corresponding to the warp and weft directions of the woven fabric. The basic idea of up-dating material properties was to treat the woven fabrics with warp and weft yarns as two-ply laminates, where one ply comprises fibres in the warp direction and the other in the weft. This laminate is initially oriented as [0°/90°] in an (M_1, M_2) global coordinate system(see Fig. 2). It becomes [(γ/2)/(γ/2+α)] in the (m_1, m_2) local material coordinates which are rotated with the material points during deformation. This results in the local orientation of fibres varying at each material point and at each time increment of the draping simulation. The detailed formulations are described elsewhere [15].

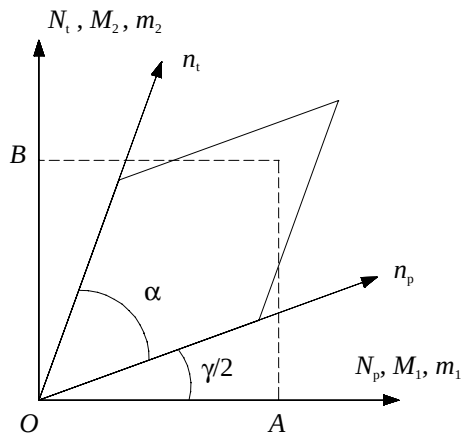
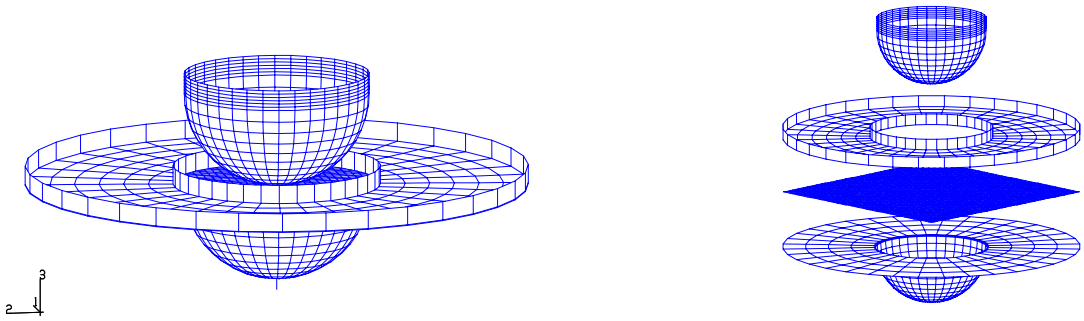


Fig.2. *Pure shear deformation of woven fabric.*

NUMERICAL DRAPING SIMULATIONS

The basic assumptions for the mechanical draping are: the woven fabric is considered as a solid continuum sheet with linear elastic, anisotropic properties. The thickness of the fabric is small compared to the other dimensions so that the plane stress option can be used.

The draping simulations are performed using the FEA computer code—ABAQUS/Explicit v5.7. The finite element model is shown in Fig. 3 and includes a punch, a die and a holder and the woven fabric blank. The punch is a hemispherical male mould with a radius of 98.6 mm joined with a cylindrical flange at the upper end. The die is a hemispherical hat shape female mould with a radius of 100.4 mm in the hemisphere. The holder is a flat ring to hold the fabric during draping. The blank material is a glass fibre, 8 harness satin woven fabric.



(a) (b)

Fig.3. (a) *Finite Element model for draping*; (b) *punch, holder, blank and die.*

Rigid surface elements are used to model the punch, die and holder. Shell elements are used to model the woven fabric. The material directions of the woven fabric coincide with the gridlines directions of the initial mesh, so that the finite element mesh is used to represent the fibre yarns on the woven fabric blank. The unidirectional fibre material data used in the simulation with the up-dating material law algorithm are shown in Table 1.

In the explicit, dynamic FEA draping simulations [12], the punch speed is 3 m/s. The friction coefficient is 0.2 at the interface of punch/fabric, 0.5 at die/fabric, consistently with the experimental measurements [12], and 0.0 at holder/fabric. A mass of 0.64 kg is attached to the holder and a force 22.87 kN is applied to the holder. 2500 elements were used for meshing the fabric blank. Automatic time increments were adopted in the ABACUS runs.

Table 1. *The unidirectional glass fibre material data*

E_{11}(GPa)	E_{22} (MPa)	ν_{12}	G_{12} (MPa)
19.0	76	0.1	0.02

NUMERICAL RESULTS AND EXPERIMENTAL DATA

Effect of the force acting on the holder

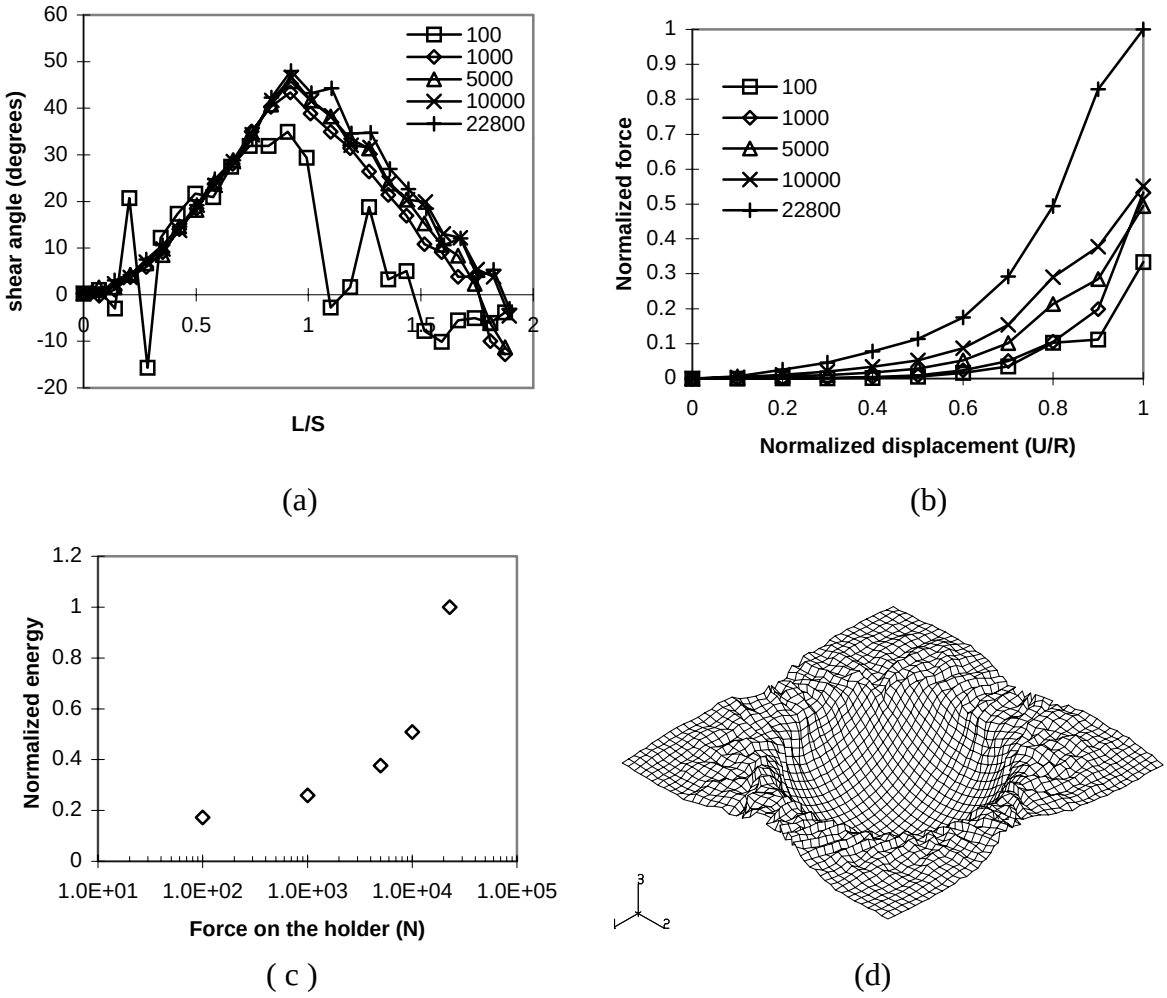
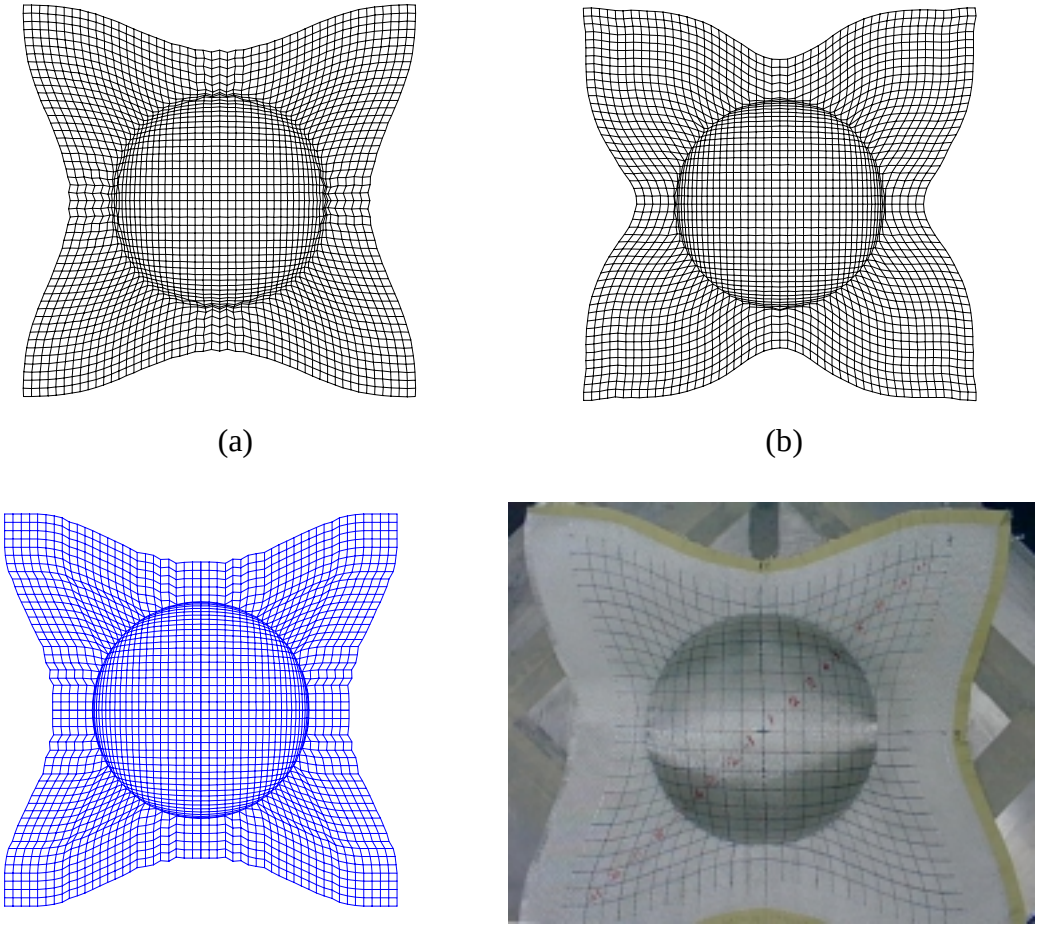


Fig.4. (a) *Predictions of the shear angle along the diagonal line of the fabric as a function of the normalised arc distance L/S: L/S = 0 represents the apex; L/S = 1 where the hemispherical dome ends and the flat rim starts; (b) the normalised reaction force on the punch against the normalised punch displacement; (c) the normalised processing energy against the force on the holder; (d) distorted woven fabric with wrinkles in draping (force on holder F= 100 N).*

The force applied on the holder is considered as one of the key process factors which is critical for wrinkle initiation and formation due to the shear locking effect of the woven fabric. The predicted shear angles under different force conditions are presented in the Fig. 4(a), in which values of the shear angle are presented along the diagonal line of the fabric. As it can be observed, the apex is not sheared due to symmetry whereas the maximum shear occurs around L/S = 1, where the hemispherical dome ends and the flat rim starts. For small load such as F = 100 N, wrinkles are formed in the draping simulation shown in Fig. 4(a and d) and when the force is raised over 1 kN no wrinkles are observed. However, when the force is at 22.8 kN the motion of the fabric is restricted, the shear angle is associated with small

oscillations and the maximum reaction force (Fig. 4(b)) and processing energy (Fig. 4(c)) on the punch are all increased substantially.

Comparison of different draping algorithms



(a) (b)

(c) (d)

Fig.5. *Comparison of predictions from different methods and experiment: (a) Draped shape predicted by solid mechanics FEA (updated material properties); (b) Draped shape predicted by solid mechanics FEA (non-updated material properties); (c) "fishnet" geometric draping; (d) Experimental draping of glass fibre woven fabric.*

Fig. 5((a)-(c)) illustrate the draped fabric shapes predicted following three different approaches, namely solid mechanics FEA with up-dated material law, with non-up-dated material law and the "fishnet" approach [16], respectively. Fig. 5(d) presents a glass woven fabric (8 harness satin) draped experimentally on the same type of mould as that used for the simulations.

Fig. 6 compares the experimental and predicted profiles of the draped fabric. The results demonstrate that the predictions from the "fishnet" simulations and the solid mechanics FEA with up-dated material law are very close and well fitted to the experimentally draped shape. The predictions from the solid mechanics FEA with non-up-dated material law do not fit so well to the experimental profile.

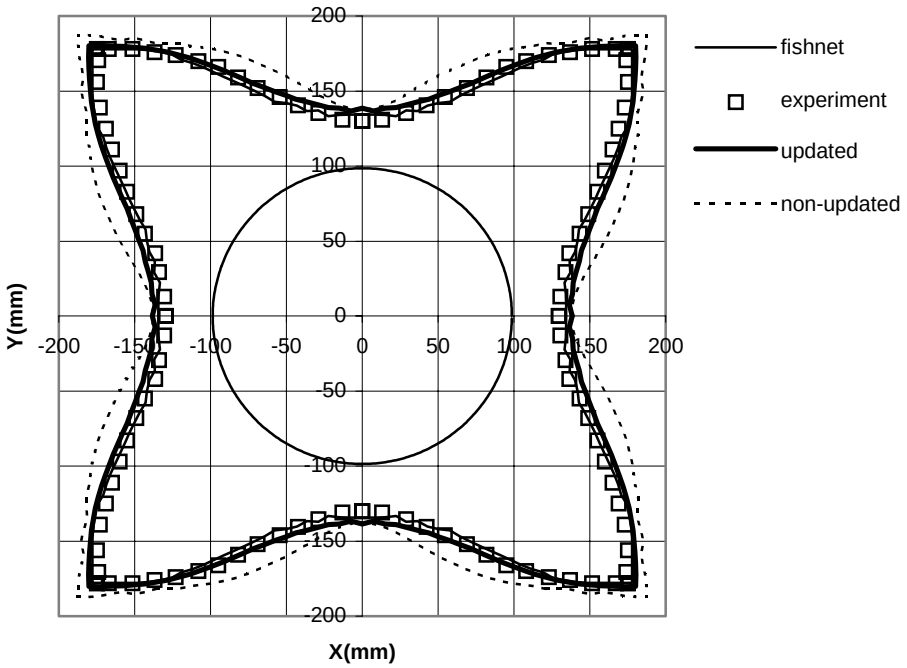


Fig.6. *Experimental and predicted profiles of draped fabric*

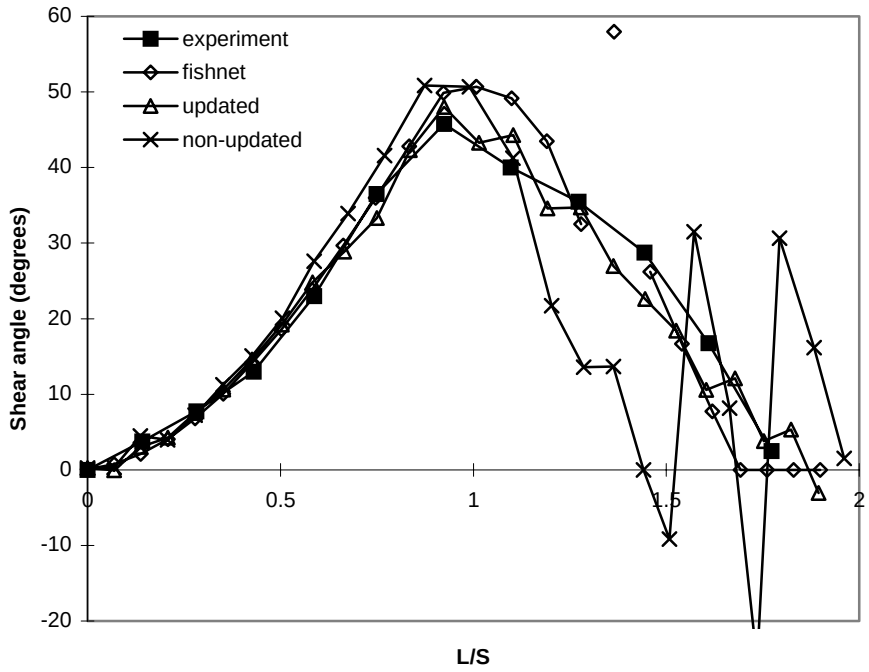


Fig.7. *Shear angle along the diagonal line of the fabric as a function of the normalised arc distance*

Fig. 7 presents the shear angle along the diagonal line of the fabric as a function of the normalised arc distance L/S. The four curves in Fig. 7 are almost identical well within the spherical part (L/S < 1) and start diverging at about L/S > 0.6. The solid mechanics FEA predictions with non-updated material law are the least accurate in comparison with the experimental data.

From a computational point of view, the “fishnet” approach yields quick predictions of the local fabric distortion, the fibre directions and the fibre volume fraction. However, it cannot

provide parameters which are vital for the design of moulding tools for deep drawing processing such as force values on the holder, the effects of different mould materials or lubricants and stress and energy requirements, and cannot predict wrinkles caused by shear locking effects.

Solid mechanics FEA with non-up-dated material law is less accurate in predicting draped shapes, but it can provide the parameters needed in a deep drawing process for the design of the moulding tools (although not accurately).

Solid mechanics FEA with up-dated material law is much more accurate in predicting draped fabric shapes, local fibre directions and fibre volume fraction, and can take into account the "shear locking" effect yielding wrinkling. It can also provide design parameters for draping. However, it consumes much more computer time than the other two methods.

APPLICATIONS USING DRAPING SIMULATION RESULTS

Predictions of the fibre volume fraction and material properties of the composite product can be achieved along with the draping simulation.

Predictions of fibre volume fraction

If matched-die moulding tools such as in this paper are used, then the thickness $\boldsymbol{t}$ of the composite component is constant and the fibre volume fraction, $\boldsymbol{V_f}$, is variable. For pure shear deformation (see Fig. 2), the amount of material in a small initially square element would remain the same after shear deformation, i.e.

$$V_{f0} abt_0 = V_f abt \sin\alpha \tag{1}$$

where a and b are the lengths of the element sides which would not change in pure shear deformation. The variables with subscript "0" represent the value before deformation. From equation (1) the ratio of the volume fraction after and before deformation is:

$$\frac{V_f}{V_{f0}} = \frac{t_0 ab}{tab \sin\alpha} = \frac{1}{\sin\alpha} \tag{2}$$

The distribution of the local element angle α in the composite product can be determined from the draping simulation. Fig.8 displays predicted contours of $1/\sin\alpha$ which represent the normalised fibre volume fraction after draping. Fig. 9(a) presents the fibre volume fraction along the diagonal line of the moulding as a function of the normalised arc distance L/S. It has been taken that $\boldsymbol{V_{fo}}$ = 0.46 (see Table 2) which at the apex remains the same after draping. The maximum $\boldsymbol{V_f}$ after draping is predicted as 0.67 at the point on the diagonal line between the hemisphere and the flat surface.

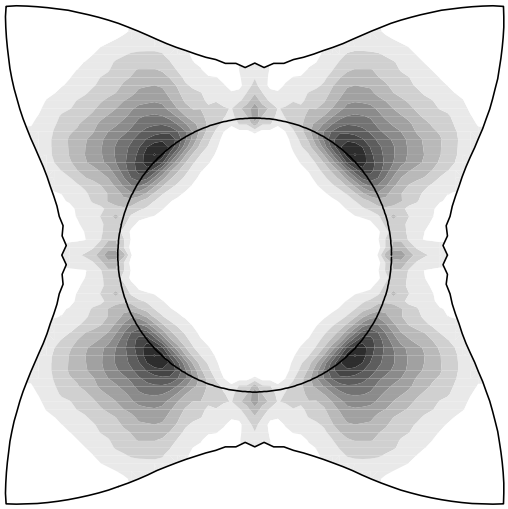
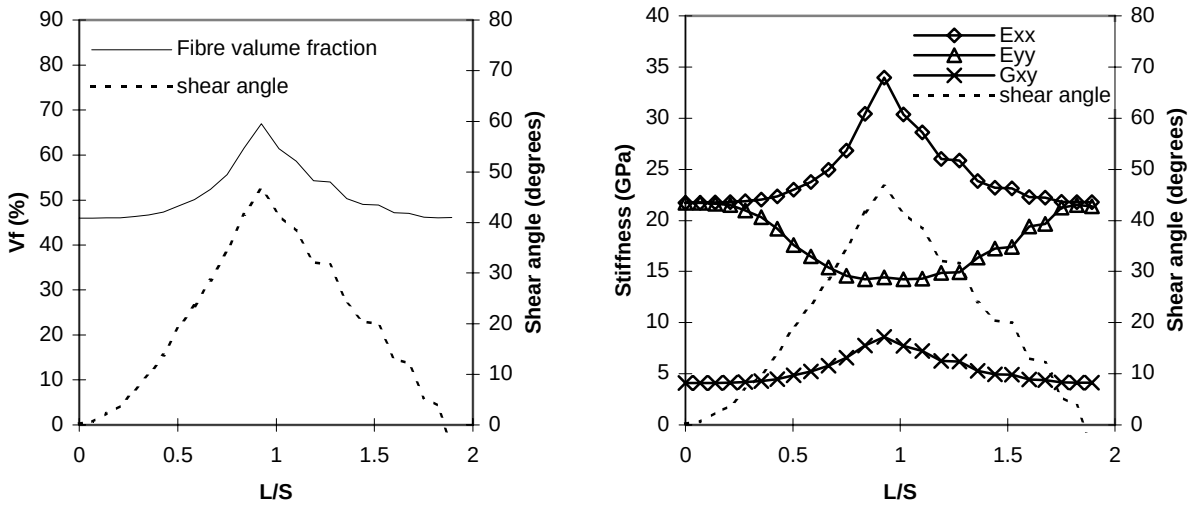


Fig.8. *Predicted contours of fibre volume fraction of the composite product. The value for the darkest area is V_f/V_{f0} = 1.46, and the brightest is 1.0* (apex).



(a) (b)

Fig.9. P*redictions along the diagonal line: (a) predictions of fibre volume fraction and (b) predictions of moduli of the composite product*.

Predictions of material properties of the composite component

The material properties of the composite product can also be predicted from the local fibre volume fraction and the element angle which represents the angle between the local fibre directions. If the local axis ***x*** is taken as the warp, then the woven fabric is a two ply laminate of [0°/α°] in (***x, y***) coordinates. Fig. 9(b) displays the predicted variation of the moduli of each unidirectional ply along the diagonal line of the draped moulding. Fig.10 shows predicted contours for E_{yy}. Table 2 presents the data used for the undeformed unidirectional GFRP (E-glass fibre) ply.

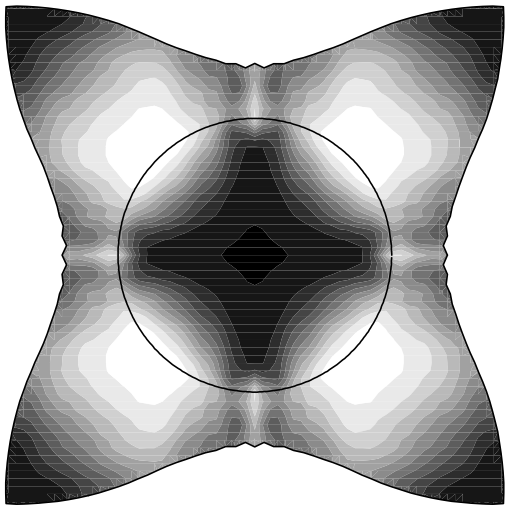


Fig.10 *Predicted contours of E_{yy} of the composite product. The value for the darkest area is* $\boldsymbol{E}_{yy}$ *= 22 GPa and for the brightest is 14 GPa.*

Table 2. *The unidirectional GFRP (E-glass fibre) material data[22]*

V_f	E_{11}*(GPa)*	E_{22} *(GPa)*	v_{12}	G_{12} (GPa)
0.46	35.0	8.22	0.26	4.10

CONCLUSIONS

- Updating of the material law due to the large shear deformation provided a promising way to incorporate part of the "shear locking" effects.
- Computer simulations of the draping of a fabric over a hemispherical hat combined with a flat rim showed that the shear angle predictions from the three algorithms, i.e. "fishnet" and solid mechanics FEA with non-up-dated and up-dated material properties, are close to the experimental measurements well within the spherical part.
- Solid mechanics FEA with up-dated material law appeared to be most accurate and appropriate for feasibility studies aiming to provide parameters needed for the design of the moulding tools and optimisation of the draping process.
- Solid mechanics FEA with non-updated material law was less accurate but also less expensive in terms of computer time.
- "Fishnet" simulations may provide quick and accurate predictions for wrinkle free draping problems, but have several restrictions in feasibility studies and in the design of moulding tools for deep drawing processing.

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