MATHEMATICAL MODELLING OF THE DRAPING OF FIBRE CLOTHS IN COMPOSITE PROCESSES AND NUMERICAL PREDICTION OF LOCAL POROSITY AND FIBRE ORIENTATION

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Abstract

This study focuses on the application of the solid mechanics finite element approach on the draping of fibre cloths in composite processes. This technique is compared to mapping methodologies and is found to offer the major advantage of being able to model non-linear material properties and interfacial friction properties. An example of prediction of local fibre fraction and fibre orientation is also given.

1. Introduction

The extended use of fabrics in the design and manufacturing of three-dimensional composite products has pointed to the need of optimizing the draping of cloths onto surfaces of varying geometry, most especially in the light of common problems in draping of cloths such as the occurrence of wrinkling, kinks, cuts, etc. Potter [1976] defined 'draping' as the ability of a material to form over three dimensional surfaces without first having to be cut or having to use undue force. Heisey and Haller [1988] were of the opinion that draping is difficult to define explicitly and, hence, they used the term 'fit' instead which originally [Mack and Taylor, 1956] was regarded as the ability of some fabrics to be in contact everywhere with the surface. Heisey and Haller [1988] used the term 'fit' to denote that a specific relationship exists between the fabric and the underlying surface and that, although various fabrics may be fitted to the same surface, each is fitted according to a different relationship. 'Fitting' has been therefore portrayed by a mapping procedure between points of the fabric and the surface.

Various investigators have adopted different mapping procedures in which the fabric is considered either as a network of fibres or as a continuum solid surface [Tiu et al, 1995]. The approach of fibre network is used most frequently where the basic cell of network might well be much larger than the basic unit in the actual fibre network of cloth. The popular approximation is a pin-joined net allowing for fibre shear and fibre slip at joints [Potter 1979, Long et al, 1996]. The network is then draped onto a solid surface following the constraints of geodesic paths intersecting at the point of initial contact between the fabric and the surface.

However, in practice draping is much more complex than the limited number of ideal mechanisms of free fibre shear and slip at joints would allow. The alternative is a continuum solid mechanics approach which has also been recently employed by researchers [Gelin et al, 1994]. The purpose of the current study is to address this approach, including its advantages and sources of complexity, as well as the range of evaluated variables especially the procedure to calculate local fibre volume fraction and fibre orientation after draping.

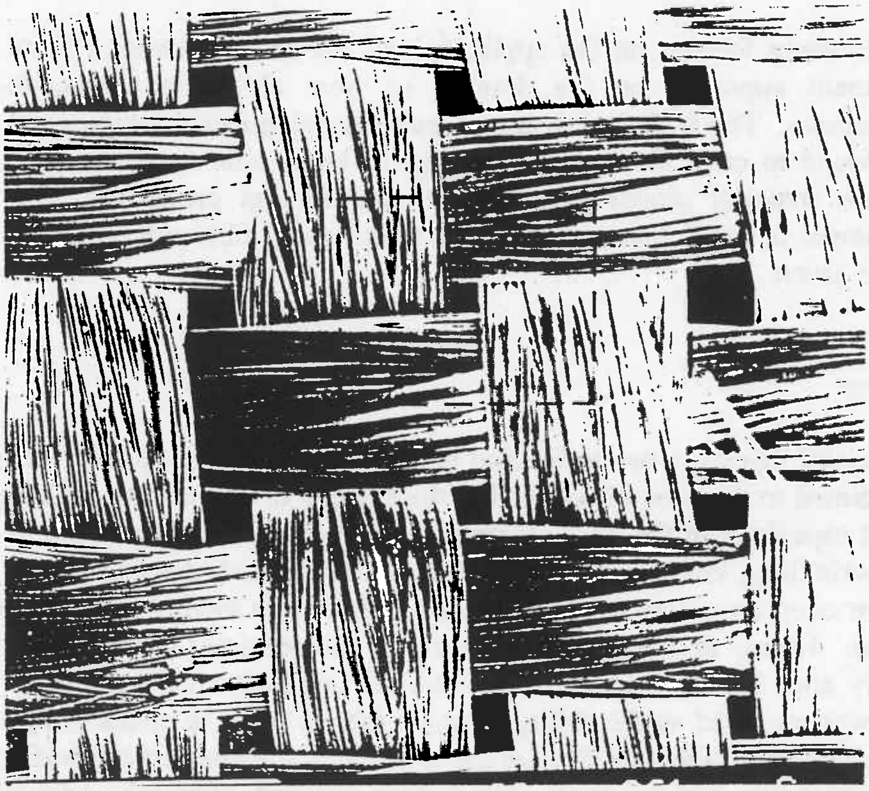


Fig.1. The basic micro-unit of the fibre network of a typical orthogonal woven cloth.

2. Finite element continuum solid mechanics of draping

In this approach the fabric is represented by a solid surface or a thin solid body with a numerical finite element mesh. The mesh should be sufficiently fine to model accurately local features of draping, such as wrinkles, but may not reach the fabric micro-scale. Macro-elements can be related to the basic micro-unit of the actual fibre network regarding fibre volume fraction, porosity and fibre orientation. This could be easily demonstrated in the case of an orthogonal woven cloth (see Fig.1) but may need more complex geometric and micro-mechanical modelling in three dimensional non-orthogonal and knitted fabrics.

The finite element analysis for static or quasi-static cases is based on the principle of conservation of virtual work which includes body forces, concentrated loads and surface forces. The displacement in each element, $\underset{\sim}{u}^{(e)}$, is derived from the interpolation of the nodal element displacements, $\underset{\sim}{a}^{(e)}$, by using the shape function matrix, $\underset{\approx}{N}^{(e)}$.

$$\underset{\sim}{u}^{(e)}=\underset{\approx}{N}^{(e)}\underset{\sim}{a}^{(e)} \tag{1}$$

The strains in each element, $\underset{\sim}{\varepsilon}^{(e)}$, are related to $\underset{\sim}{a}^{(e)}$ via the strain-displacement matrix:

$$\underset{\sim}{\epsilon}^{(e)}=\underset{\approx}{B}^{(e)}\underset{\sim}{a}^{(e)} \tag{2}$$

Constitutive relationships are used between stress and strain where the mechanical/viscous material properties feature. By using the virtual displacement theorem, the equilibrium equations of the assembly of elements are derived:

$$\underset{\sim}{R}=\underset{\approx}{K}\underset{\sim}{a} \tag{3}$$

where $\underset{\approx}{K}$ is the structure stiffness matrix and $\underset{\sim}{R}$ is the structure force vector including element body forces, element surface forces, initial stresses and strains and concentrated loads.

The deformation behaviour of the fabric under tension, shear and transverse compression needs to be known. This in reality would be viscoelastic (see Fig.2 and Fig.3) with a non-linear elastic component (see Fig.4). Yu et al [1994] carried out characterisation tests concerning small deformations of various types of textiles in in-plane tension, in-plane shear, transverse compression and out-of-plane bending. Non-linear constitutive models are needed for larger deformations. The complexity of modelling increases if draping takes place in the presence of a viscous liquid or viscoelastic matrix which may flow and infiltrate the fibre bundles. Numerical continuum mechanics simulations in the presence of a flowing matrix have been carried out in several recent studies [McGuinness and O Bradaigh, 1995, Pickett et al, 1995, Wheeler and Jones, 1995]. However the matrix infiltration process is not considered in these studies.

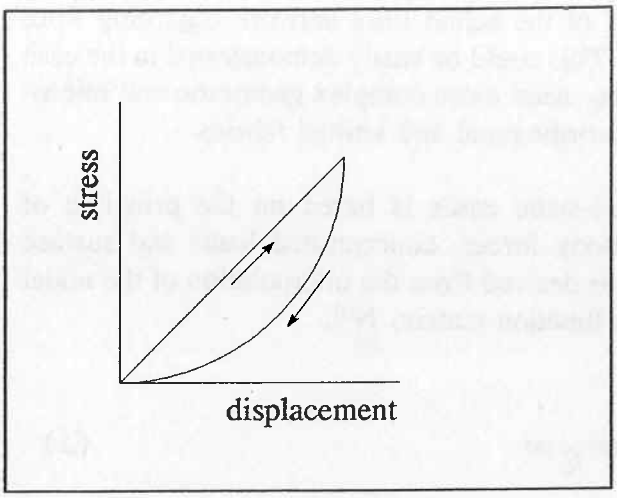


Fig.2. A hysteresis loop for small deformations of a typical fabric under tension.

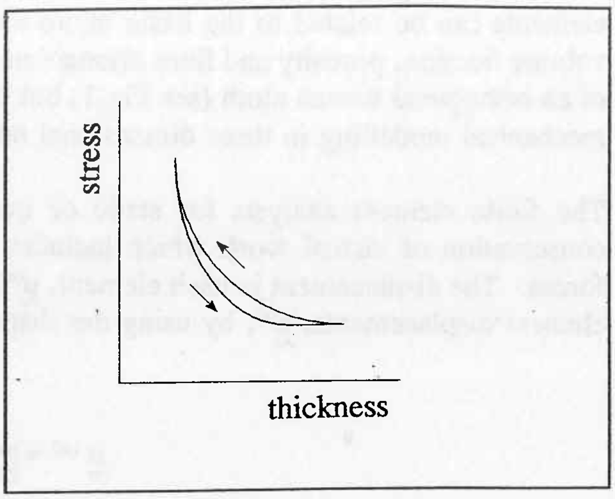


Fig.3. A hysteresis loop for the compression of a typical fabric.

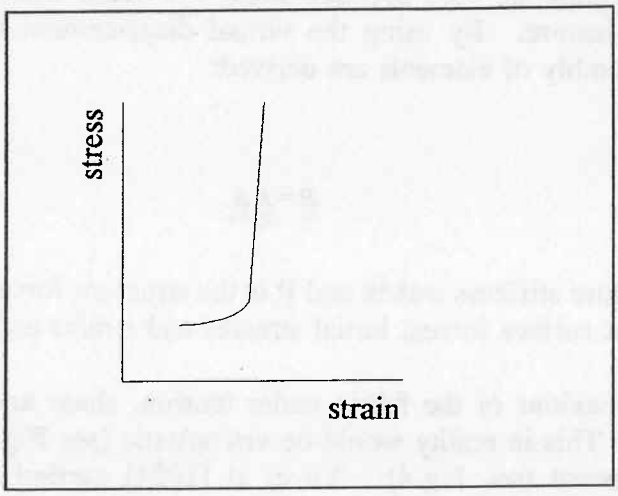


Fig.4. Non-linear elastic deformation of a fabric under tension.

The continuum mechanics approach offers the possibility of defining interface properties between the fabric and the surface as well as between various layers of fabrics. On the other hand it also poses the need to measure these properties unless certain assumptions and approximations are made.

3. Computer simulations

Model geometries of single curvature and double curvature are commonly used in draping to test the different modes of fabric deformation. An example of draping over a cylindrical surface is presented in this study as displayed in Fig.5. The fabric is modelled as a thin, flat, solid sheet which is meshed numerically using a regular grid of quadrilateral, orthotropic, solid elements. As a first approximation, orthotropic, elastic properties have been given to the sheet. The volume between the sheet and the solid surface is modelled by flexible solid elements of a modulus of 0.1 MPa.

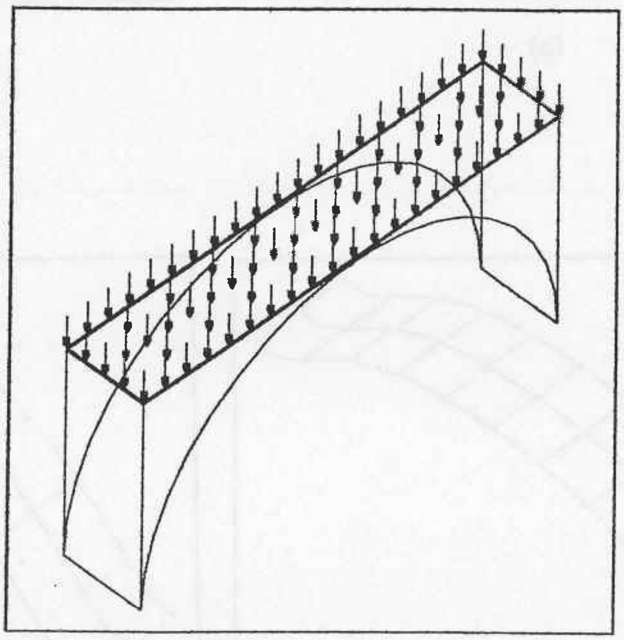
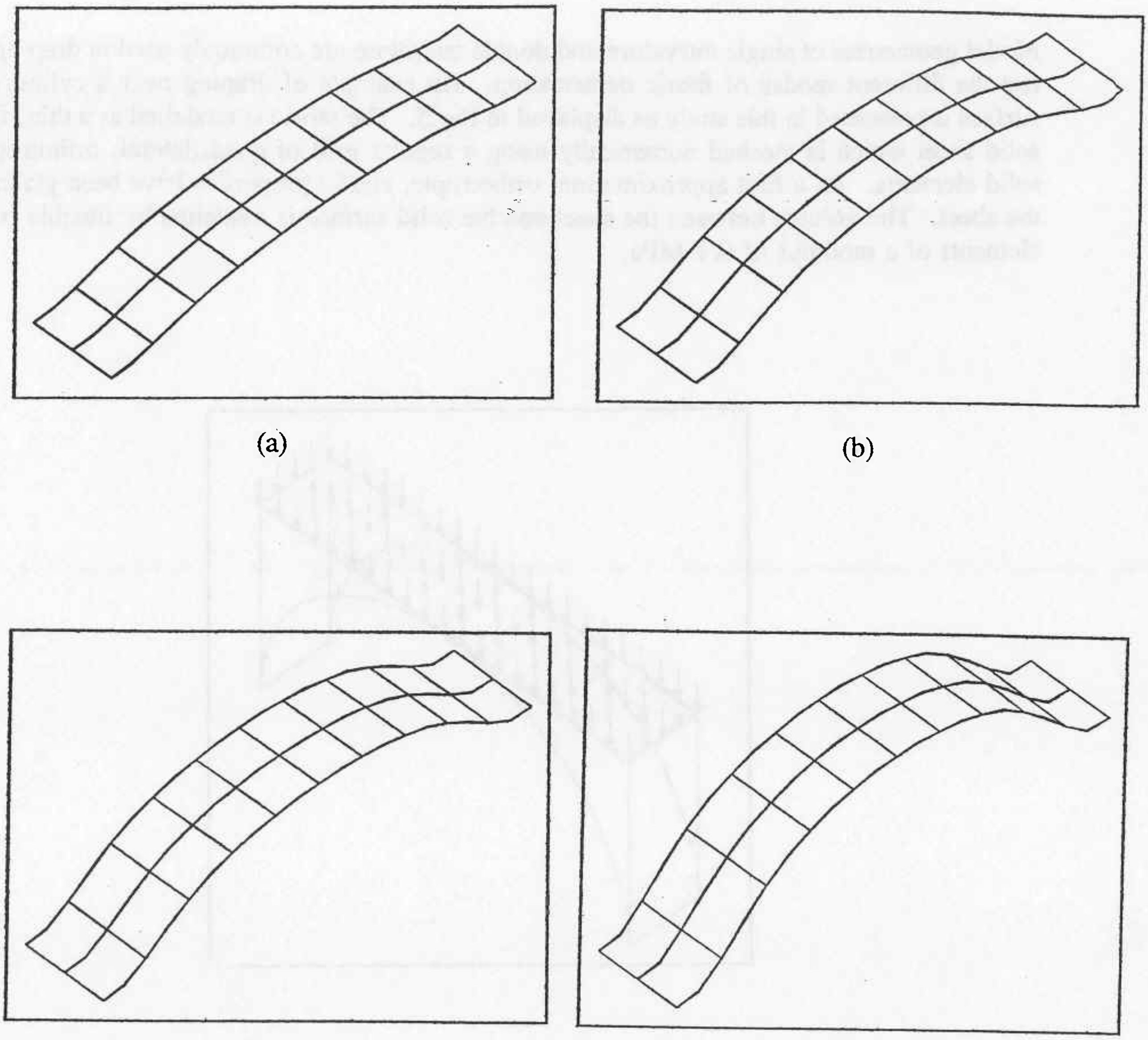


Fig.5. Considered model for the draping of a cloth onto a single-curvature cylindrical surface.



(a)

(b)

(c)

(d)

Fig.6. Finite element simulations of the draping of a cloth over a cylindrical surface for increasing loads.

The finite element simulations were performed using LUSAS 11, (FEA Ltd.) software package. Fig.6 illustrates the draping of a fabric in slow motion as the load is gradually increased. Step-wise increase of load is a useful methodology employed in finite element simulations of large deformations. In comparison, mapping techniques cannot offer this possibility which is linked with the determination of intermediate deformation states of the cloth as is being draped that give an insight into the sources and development of various problems during draping.

The orientation of the local axes of coordinates at the finite element nodes after draping can be linked to the local fibre orientation in orthogonal cloths (see Fig.7). Changes in the local fibre volume fraction, V_f, during draping can be determined from volume changes of the deformed elements, according to the following relation:

$$V_f = V_{f,o} \frac{h_o A_o}{hA} \tag{4}$$

where h and A are the thickness and mid-crossection of the deformed elements.

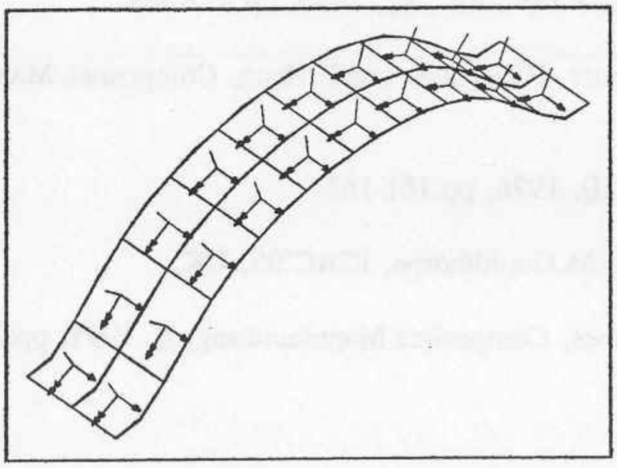


Fig.7. Representation of local fibre orientation in orthogonal cloths.

4. Conclusions

This study has focused on the application of the approach of continuum solid mechanics to the modelling and finite element simulation of the draping of cloths in the processing of composites. In comparison with mapping techniques, this approach offers clear advantages in dealing with the complexity of the problem of draping, regarding the areas of non-linear mechanical properties of cloth, interactions between the cloth and the solid surface, as well as between assembled cloths, and intermediate stages of draping as the load is increased gradually. It is also possible to evaluate local fibre orientation and fibre volume fraction from the orientation of local axes at nodes and the deformation of elements, respectively. On the other hand, in order to take proper advantage of the improvements suggested in the continuum mechanics approach, it is necessary to supply a set of data for the mechanical properties of the fabric and the friction properties between layers of fabric and the fabric and the solid surface over which it is draped.

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