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TWO COMPONENT FINITE ELEMENT MODEL FOR THE SIMULATION OF SHAPING OF PREPREG WOVEN FABRIC

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1. INTRODUCTION

Continuous fibre reinforced composites are now firmly established engineering materials for the manufacture of components in the automotive and aerospace industries. They offer design engineers enormous opportunities for introducing new design concepts whilst reducing costs. In this respect, prepreg gives flexibility in the composite shaping and is already playing an important role in increasing the use of advanced composites. The ability to define, in advance, the ply shapes and material orientation allows engineers to optimize the composite structural properties of the part for maximum strength, maximum material utilization and maximum lay-up efficiency.

The formulation of the new efficiency numerical models for the simulation of the composite shaping processes should make it possible to reduce the time needed to manufacture of complex pieces and to optimize costs in an integrated design approach. Actually, the prepreg composite corresponds to a structure composed of the combination of the yarn network and resin membrane.

Some models are proposed to homogenize elastic properties of a composite material and to simulate the deformation of these materials by forming process. Geometrical and micro-macro mechanical approaches are proposed in the literature to simulate the transformation of fabrics during the draping process Cherouat (1994), Gelin (1996) and Blanlot (1996). It is difficult to globally characterise, by homogeneous methods, the behaviour of this fabric without losing mechanical characteristics. The new numerical finite element model developed at a mesostructural level permits to take into account the various mechanics of physics of the mechanical transformation of prepreg fabrics during the shaping process, namely large angular variations of yarns, viscoelasticity of resin and evolution of possible damages in yarns. The different advantages of this modelling is first to give the ability to obtain a very good material orientation of yarns and consequently to introduce good data in the pre-processing of the calculation of the

final piece after polymerization, secondly to give the mechanical limits of the fabric during the forming process and to limit the falls of the fabric thanks to a better definition of the flat form. The forming process of prepreg woven fabric usually includes complex mechanisms which can have a significant effect on mechanical properties of the finished product.

The overall behaviour of prepreg composite is based on a finite strain membrane model and must take fabric weaving (geometrical undulation of yarns), fibre properties and resin behaviour into account. The development of a numerical model for prepreg woven fabric behaviour can be defined as :

1. the most appropriate weaving of the reinforcements for the forming process,
2. fibre positions in the composite structure,
3. the holding force of the composite during the forming deformation, and
4. the state of impregnated fabric (wrinkling, folding, fibre damage and resin strains).

The proposed model is described by meso-structural approach for finite strains and geometrical non linearities. The bi-component finite elements for modelling prepreg fabric behaviour are based on an association of 3D membrane finite elements representative of resin behaviour and truss finite elements representative of warp and weft fibres behaviour. The efficiency of the proposed model resides in the simplicity of its numerical formulation and the performance of its mechanical approach.

2. MESO-STRUCTURAL FINITE ELEMENT APPROACH

It is easily shown that a large rotation of the fibres is followed by straightening phenomena which intervene in the kinematic transformation of fabrics during the shaping deformation and determine the aptitude of prepreg woven fabrics to make up complex shapes. The shaping operation is strongly affected by the fabric behaviour, which is different from that of a conventional sheet metal.

The simulation of the shaping process is based on the numerical and mechanical approaches specific to the composite reinforced fabric behaviour. The meso-structural model is a 'biphase model' in which the elastic fibre and viscous resin components are treated separately. The fibres are assumed to be embedded in the resin and move with inter-fibre shear deformation. The proposed finite element makes it possible to model the deformation of composite fabrics by taking into account the various dominating mechanisms in the physics of the mechanical transformation of fabrics such as geometrical non linearity (large displacements and finite rotations of fibres), material non linearity (viscoelastic behaviour of resin in shearing, variation of fibres due to weaving of fabric) and contact with friction between tools and prepreg material.

In the numerical model, the behaviour of the fabric is represented by structural truss finite elements corresponding to the behaviour of warp and weft fibres and the resin is modelled by 2D membrane finite elements (Figure 1). The interaction effects and friction phenomena between fibres are negligible. The proposed bi-component finite elements can take into account geometrical non linearities such as large displacements and finite rotations of fibres, material non linearities such as viscoelastic behaviour of

resin in shearing and undulation of fibres due to the weaving of fabric. A co-rotational formulation associated with rigid body rotation, derived from the polar decomposition, is used to describe the kinematic motion and the deformation mechanism that woven material undergo during shaping process.

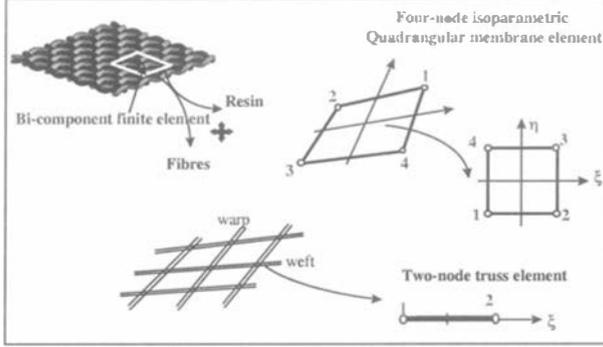


Figure 1. Two-component finite element for the simulation of mechanical behaviour of woven fabric

3. MODELLING OF PREPREG WOVEN FABRIC BEHAVIOUR

Large angular variations of yarns, viscoelasticity of resin and evolution of damage in yarns are the main mechanical mechanisms which control the shaping process of impregnated fabric. The kinematic transformation of impregnated material in large displacements and finite strains is based on the following assumptions :

A1 : Non-sliding inter-fibre during the shaping process can be experimentally observed by the following transformation of aligned straight lines drawn on the fabric. For each point of continuum material the current position is defined in current configuration by

$$\vec{x}^{fibres} = \vec{x}^{re sin} = F\vec{X}^{fibres} = F\vec{X}^{re sin} \quad (1)$$

F describes the deformation gradient of the composite fabric.

A2 : The current longitudinal orientation of each fibre $\vec{n}_L^f(F, \theta_0)$ is calculated from the geometrical transformation defined by the linear application

$$\vec{n}_L^f(F, \theta_0) = \frac{F\vec{N}_L^f(\theta_0)}{\sqrt{\vec{N}_L^f(\theta_0)^T F^T F \vec{N}_L^f(\theta_0)}} \quad (2)$$

A3 : The shear angle deformation of fibres can be associated with the rotation of the rigid body of the fibre. This assumption can be written using the following kinematic relation

$$\vec{N}_L^f(\theta_0) \cdot \vec{N}_T^f(\theta_0) = \vec{0} \Rightarrow \vec{n}_L^f(F, \theta_0) \cdot \vec{n}_T^f(F, \theta_0) = \vec{0} \quad (3)$$

Considering the previous assumptions in the proposed model, we introduce a new pseudo-gradient of transformation **F'** as a function of the gradient of transformation of composite fabric **F** (Figure 3). The motion of different material points of fibres are defined in the current configuration by

$$\begin{cases} F^f = \lambda_i^f n_i^f \otimes N_i^f & \text{fibres} \\ F^m = F = RU^m & \text{re sin} \end{cases} \quad (4)$$

The non linearity of the shaping problem imposes the use of incremental formulation. The spatial velocity gradient in the current configuration, is expressed in a reference frame by

$$\begin{cases} L^f = \dot{F}^f F^{f-1} = \frac{\dot{\lambda}_i^f}{\lambda_i^f} n_i^f \otimes n_i^f + \dot{n}_i^f \otimes n_i^f & \text{fibres} \\ L = FF = D + W & \text{re sin} \end{cases} \quad (5)$$

and in the rigid body rotation frame as

$$\begin{cases} \bar{L}^{fR} = \frac{\dot{\lambda}_i^f}{\lambda_i^f} N_i^f \otimes N_i^f = \bar{D}^{fR} + \bar{W}^{fR} & \text{fibres} \\ \bar{L}^R = R^T L R + \dot{R}^T R = \dot{U} U^{-1} = \bar{D} + \bar{W} & \text{re sin} \end{cases} \quad (6)$$

The constitutive equations for finite-strains use objective derivatives. In a above equations the rotation rate of the local frame in which a simple derivative would give objective derivative is defined by Green-Naghdi's co-rotational formulation. To characterise the objective behaviour of the fabric, the stretching tensors are written in the rigid body rotation frame as

$$\begin{cases} \bar{D}_L^f = \begin{pmatrix} \dot{\lambda}_L^f \\ \lambda_L^f \end{pmatrix} & \text{fibres} \\ \bar{D}^R = \bar{L}^R & \text{re sin} \end{cases} \quad (7)$$

Using Kirchhoff's and Green-Naghdi's tensor stress, the stress rate in the fibre and the resin can be written at any time by :

$$\begin{cases} \left(\bar{\sigma}_L^{fR} \right)_{n+1} = \left(\bar{\sigma}_L^{fR} \right)_n + \int_{t_n}^{t_{n+1}} E_L^f(\lambda_L^f) \frac{\dot{\lambda}_L^f(\tau)}{\lambda_L^f(\tau)} d\tau & \text{fibres} \\ \left(\bar{\sigma}^{mR} \right)_{n+1} = \left(\bar{\sigma}^{mR} \right)_n + \int_{t_n}^{t_{n+1}} C^m(\tau) \bar{D}^R d\tau & \text{re sin} \end{cases} \quad (8)$$

The internal vector load is defined by summation of elementary forces which are function of Cauchy's stresses, material surface area S and normal vector to the surface \vec{n}_S

$$\begin{cases} \vec{f}^{fibres} = \sum_{fibres} \int_{S^f} \bar{\sigma}^{fR} \vec{n}_S dS & \text{fibres} \\ \vec{f}^{resin} = \int_{S^m} \bar{\sigma}^{mR} \vec{n}_S dS & \text{re sin} \end{cases} \quad (9)$$

The behaviour of prepreg woven fabric in a non-polymerized phase is obtained by superimposing the membrane behaviour of the resin and the behaviour of each fibre in the material frame :

$$\bar{f}^{comp} = \sum_{elts \ S^m} \int \bar{\sigma}^{mR} \bar{n}_s dS + \sum_{warp \ S^f} \int \bar{\sigma}_{warp}^{fR} \bar{n}_s dS + \sum_{weft \ S^f} \int \bar{\sigma}_{weft}^{fR} \bar{n}_s dS \quad (10)$$

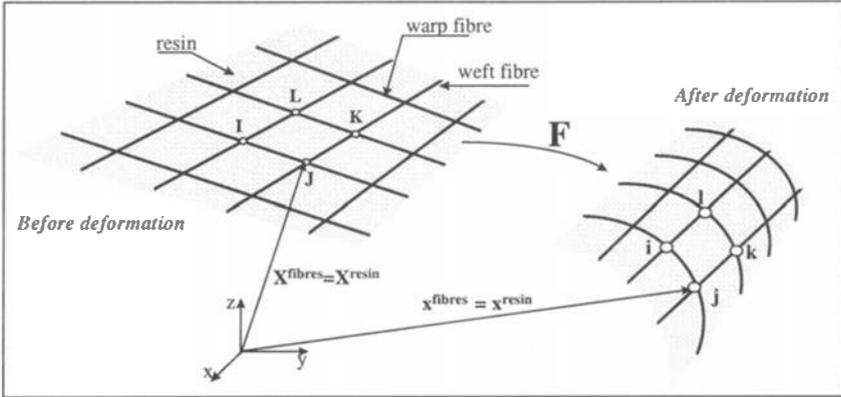


Figure 2. Geometrical transformation of fibre-resin linkage points

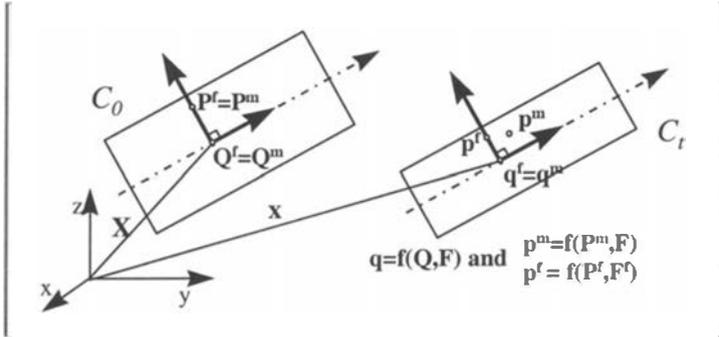


Figure 3. Geometrical transformation of the woven fabric and-resin material point

4. NUMERICAL SIMULATION OF SHAPING PROCESS

To validate the proposed approach for the mechanical behaviour of the prepreg woven fabric and the computational finite element modelling, some numerical simulations were carried out . The laying-up of prepreg fabric on a non developable surface was built inside our laboratory in order to cover hemispherical surface (Figure 4) Blanlot (1996). The numerical simulation is carried out with Abaqus software using an explicit formulation. With the numerical simulation, we can visualize fibre orientations and ply shapes after the forming process and predict manufacturing problems.

4.1. SIMULATION OF LAYING-UP SHAPING PROCESS

An initially square non polymerized woven fabric made of carbon fibre (350 x 350 mm) is draped on a hemispherical surface ($r = 120$ mm). Eight loaded springs are used to maintain the fabric during the shaping transformation. The formability of composite fabric during the laying-up process is tested by using two directions of fibres $\pm 45^\circ$ (Figure 5a) and 0° (Figure 5b). The final experimental shapes for a 300 mm displacement of the mould are shown in Figure 6a for $(-45^\circ, +45^\circ)$ fabric deformation and in Figure 6b for $(0^\circ, 90^\circ)$ fabric deformation. We can notice that these shear angles values are very large ($>40^\circ$) along the diagonal line for the $(0^\circ, 90^\circ)$ fabric on Figure 8 and along the median line for the $(-45^\circ, +45^\circ)$ fabric Figure 7. These numerical results show that the proposed finite element model takes into account the highly anisotropy of fabric behaviour.

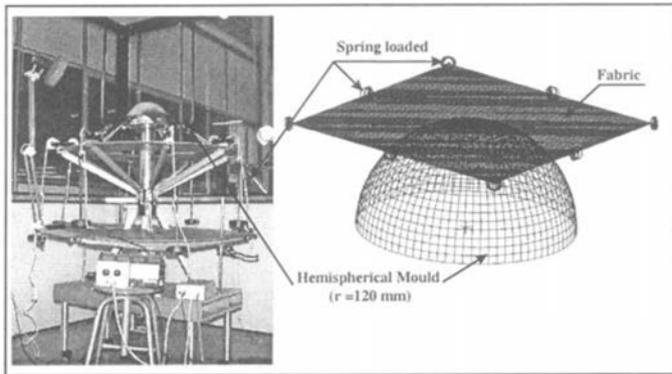


Figure 4. Laying up on the hemisphere



Figure 5. Experimental shape obtained with woven fabric $\pm 45^\circ$ (a) and 0° (b)



Figure 6. Simulation shape obtained with woven fabric $\pm 45^\circ$ (a) and 0° (b)

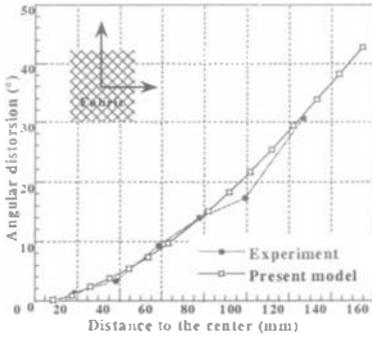


Figure 7. Angles between yarns on the median $\pm 45^\circ$

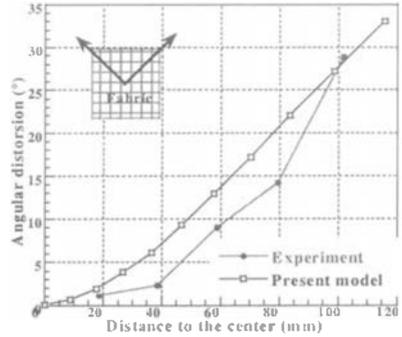


Figure 8. Angles between yarns on the median 0°

4.2. SIMULATION OF DEEP DRAWING PROCESS

An initially square blank (280 x 280 mm) and a circular blank ($r = 140$ mm) made of a glass fibre are shaped into a square box (Figure 9). The forming process of composite fabric usually includes large angular variation of the warp and the weft directions which can have a significant effect on the mechanical properties of the finished product. Results of simulations of the shaping operation are shown in Figure 10. Figures 11 and 12 show the shear angles of the fibres for three sets of radius (5, 10 and 15 mm) for the punch. These radii mainly influence the maximum values of the angular variations of the fibre directions. The square blank leads to shear angles greater than 80° which values cannot be used for the fabric. On the contrary, the circular blank leads to shear angles smaller than 60° and the shaping operation appears to be possible.

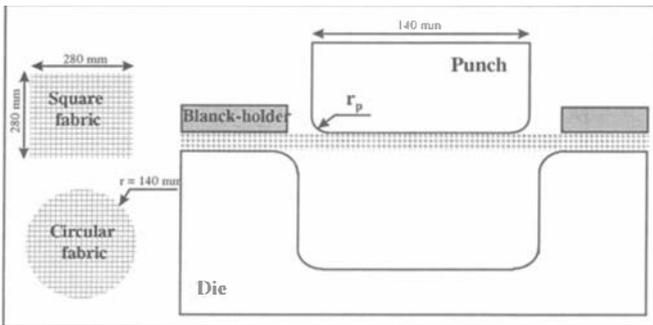


Figure 9. Trial of punch-drawing

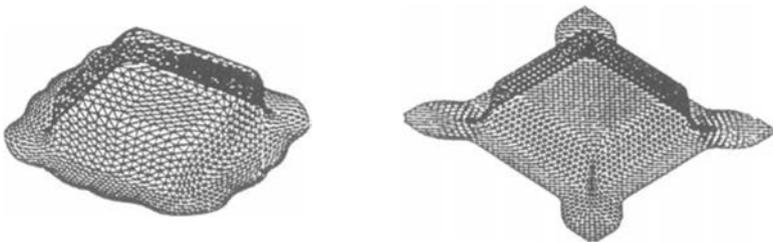


Figure 10. Simulation shape obtained with circular (a) and square woven fabric 0° (b)

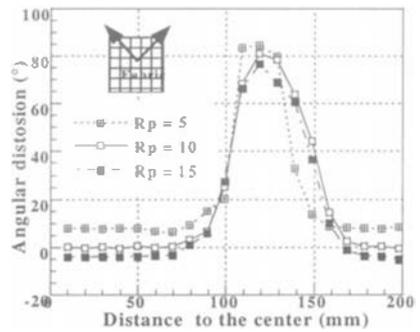
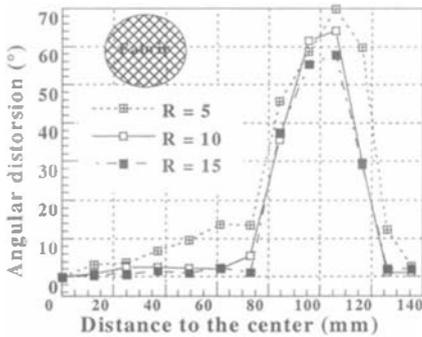


Figure 11. Angles between yarns on the circular diagonal Figure 12. Angles between yarns on the diagonal square

5. CONCLUSION

A numerical mesostructural approach is proposed for modelling the behaviour of the preimpregnated composite fabric. Numerical examples show the concordance of the computed final shapes and relative distortions between fibres with experimental ones. The numerical results of shaping processes (deep drawing and laying-up) prove the validity of the proposed formulation. The numerical tool is an efficient means of evaluating factors related to manufacturing process and an efficient help to design a preforming sequence for manufacturing fabric reinforced composites. It is possible to detect the main defects occurring during the shaping deformation in order to obtain good, quantitative information on the forming process and to pre-determine the mechanical properties of the composite parts and tool shapes.

Extensions of the numerical model have been carried out with a view to take the viscoelasticity of the resin and the undulation of fibres into account.

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