

Simulations of one-layer and multi-layer composite forming

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Abstract. The use of composite materials is strongly increasing in aeronautics industry. Consequently there is a need for numerical analysis of these composite components. To perform accurately the service live analyses, it is necessary to know the direction and the density of the fibres at any point of the part. These directions are mainly depending of the forming of the composite. Because they are woven, textile reinforcements can reach very large in-plane shear strain during manufacturing. A numerical tool that simulates this forming process permits to envisage the feasibility of a process without defect but also to know the directions of the reinforcements after shaping. These directions condition strongly the mechanical behaviour of the final textile composite structure. In addition, the angles between warp and weft yarns influence the permeability of the reinforcement and thus the filling of the resin in the case of a liquid moulding process. The forming of composite reinforcement can be made on a single ply or simultaneously on several plies. In this paper models for the single woven ply forming are compared. The extension to multiply forming simulation is then considered.

Keywords: Textile composites, Forming simulations, Finite element analysis

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INTRODUCTION

The simulation of a composite forming process needs a model of the mechanical behaviour woven reinforcement and usually a numerical method, within, for instance, the Finite Element Method. The mechanical behaviour of fabrics is complex due to the intricate interactions of the yarns. It is a multi-scale problem. The macroscopic behaviour is much dependent of the interactions of yarns at meso-scale (scale of the woven unit cell) and at the micro-scale (level of the fibres constituting yarns). Despite the lot of works in the field, there is no widely accepted model that describes accurately all the main aspects of a fabric mechanical behaviour. The main model families come from the multi-scale nature of the textile. A first family of models is obtained by homogenizing the mechanical behaviour of the underlying meso-structure and considers the fabric as an anisotropic continuum [1]. The next section will compare two

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of these approaches. If these models can easily be integrated in F.E. classical shell or membrane elements, the identification of homogenized material parameters is very difficult, especially because these parameters change when the fabric is strained and when, consequently, the directions of the yarns change. Currently, the continuum models proposed in the literature do not generally account for the interactions between warp and weft yarns (crimp change, locking....). At the opposite, some authors present fully discrete models of fabrics based on beams and springs [2]. A proposed approach associates a finite element method and a mesoscopic analysis of the woven unit cell. Specific finite elements are defined that are made of a discrete number of woven unit cells. The mechanical behaviour of these woven cells is obtained by experimental analyses [3] or from 3D F.E. computations of the woven cell [4-6]. The nodal interior loads are deduced from this local behaviour and the corresponding strain energy in the element deformation. The simple and consequently numerically efficient four and three node 3D membrane elements obtained in this way have given satisfactory results in some fabric forming simulations.

CONTINUOUS APPROACH FOR COMPOSITE FORMING

For finite strain analyses, FE codes widely use rate elastic constitutive equations (hypoelastic law):

$$\underline{\underline{\sigma}}^{\nabla} = \underline{\underline{C}} : \underline{\underline{D}} \quad \underline{\underline{\sigma}}^{\nabla} = \underline{\underline{Q}} \cdot \left(\frac{d}{dt} \underline{\underline{Q}}^T \cdot \underline{\underline{\sigma}} \cdot \underline{\underline{Q}} \right) \cdot \underline{\underline{Q}}^T = \dot{\underline{\underline{\sigma}}} + \underline{\underline{\sigma}} \cdot \underline{\underline{\Omega}} - \underline{\underline{\Omega}} \cdot \underline{\underline{\sigma}} \quad (1)$$

$\underline{\underline{\sigma}}$ and $\underline{\underline{D}}$ are respectively the Cauchy stress tensor and the strain rate tensor. $\underline{\underline{\sigma}}^{\nabla}$ is the objective derivative of $\underline{\underline{\sigma}}$ associated to rotation $\underline{\underline{Q}}$. The classical Hughes and Winget incremental scheme is constructed from equation (1) for stress calculation:

$$\left[\underline{\underline{\sigma}}^{n+1} \right]_{\mathbf{e}_i^{n+1}} = \left[\underline{\underline{\sigma}}^n \right]_{\mathbf{e}_i^n} + \left[\underline{\underline{C}}^{n+1/2} \right]_{\mathbf{e}_i^{n+1/2}} \left[\Delta \underline{\underline{\epsilon}} \right]_{\mathbf{e}_i^{n+1/2}} \quad (2)$$

$$\left[\underline{\underline{\sigma}}^{n+1} \right]_{\mathbf{e}_i^{n+1}} = \left[\underline{\underline{\sigma}}^n \right]_{\mathbf{e}_i^n} + \left[\underline{\underline{C}}^{n+1/2} \right]_{\mathbf{e}_i^{n+1/2}} \left[\underline{\underline{D}}^{n+1/2} \right]_{\mathbf{e}_i^{n+1/2}} \Delta t \quad (3)$$

For a fibrous medium the constitutive tensor $\underline{\underline{C}}$ is oriented by $\underline{\underline{f}}$ the fibre direction. $\underline{\underline{f}}$ is a material direction. Let $\{\underline{\underline{e}}_i\}$ denotes the orthonormal frame formed by the initial basis vectors rotated by $\underline{\underline{Q}}$, consequently $\underline{\underline{f}}$ is in general not fixed in $\{\underline{\underline{e}}_i\}$ since it is a material direction. The initial fibre direction $\underline{\underline{f}}^0$ is transformed by $\underline{\underline{F}}$ (the gradient tensor) into $\underline{\underline{f}} = \underline{\underline{f}}_1$, while $\{\underline{\underline{e}}_i\}$ is rotated by $\underline{\underline{Q}}$ (figure 1). To solve this problem two approaches are developed for fibrous media within the hypoelastic formulation presented above. The first one [7,8] uses the classical Green Naghdi objective

derivative that is used in user-subroutine of codes such as ABAQUS. All the calculations are performed in the corresponding rotated frame (Green Naghdi's frame). The material behaviour operator is obtained in this frame from its specific form in the fibre frame by a basis change. The second approach [5] consists in using another objective derivative defined from the fibre rotation. It can be shown that in some case the second approach is preferable.

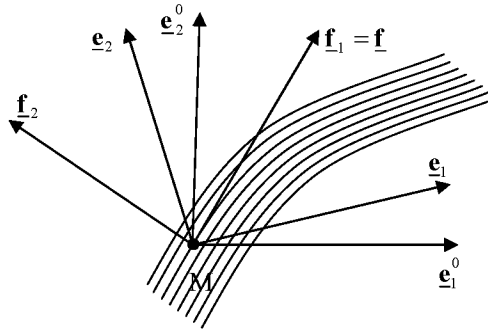


FIGURE 1. Initial frame $\{\underline{e}_i^0\}$, rotated frame $\{\underline{e}_i\}$ and fibre frame $\{\underline{f}_i\}$

SEMI-DISCRETE FINITE ELEMENTS

The approach associates a finite element method with a mesoscopic analysis of the woven unit cell. Specific finite elements are defined. They are made of a discrete number of woven unit cells.

This approach permits to describe the specificities of textile reinforcement mechanical behaviour, especially:

- the non-linear tensile behaviour due to crimp interchange
- shear locking angle and the very different in plane shear behaviour before and after this angle. The following global simplified dynamic equation is considered :

$$\sum_{p=1}^{ncell} ({}^p \varepsilon_{11}(\boldsymbol{\eta}) {}^p T^{11} L_1 + {}^p \varepsilon_{22}(\boldsymbol{\eta}) {}^p T^{22} L_2) + \sum_{p=1}^{ncell} {}^p C {}^p \gamma(\boldsymbol{\eta}) - W_{ext}(\boldsymbol{\eta}) = \int_{\Omega} \rho \ddot{\mathbf{u}} \cdot \boldsymbol{\eta} \, dV \quad (4)$$

where $\varepsilon(\cdot) = \nabla^s \cdot = \varepsilon_{\alpha\beta}(\cdot) \otimes \beta$ is the symmetrical gradient in the virtual displacement $\boldsymbol{\eta}$ (α and β are indexes taking value 1 or 2). $\mathbf{h}^1, \mathbf{h}^2$ are the contravariant vectors related to $\mathbf{h}_1, \mathbf{h}_2$. L_1 and L_2 are the lengths of the warp and weft yarns in the mid-plane of the fabric. $\gamma(\boldsymbol{\eta})$ is the virtual relative rotation between warp and weft fibres (or virtual shear angle). $ncell$ is the number of woven unit cells of the textile structure, ${}^p Q$, means that

the quantity Q is considered for the woven unit cell number p . ρ is the mass per volume of the fabric Ω . $W_{\text{ext}}(\boldsymbol{\eta})$ is the virtual work of the exterior prescribed loads.

To make a finite element simulation of composite woven reinforcement forming based on the above approach, it is necessary to be able to know the tensions T^{11} and T^{22} and the shear couple C for a given strain field in the woven unit cell. It is assumed that the tension do not depend on the shear angle and that the shear couple do not depend on the axial strain i.e. $T^{11}(\epsilon_{11}, \epsilon_{22})$, $T^{22}(\epsilon_{11}, \epsilon_{22})$ and $C(\gamma)$. In [3], biaxial tensile tests performed for different angle between warp and weft yarns have shown that the influence of this angle is small and can be neglected. The second assumption (C only depending on γ) is probably less true [9]. Nevertheless, all the experimental results that are currently available give the shear load in function of the shear angle without any information on the tensions, so the assumption $C(\gamma)$ will be made by default.

The tension surfaces ($T^{11}(\epsilon_{11}, \epsilon_{22})$ and $T^{22}(\epsilon_{11}, \epsilon_{22})$) and of the shear curve ($C(\gamma)$) can be determined both by experiments or mesoscopic F.E. on the unit woven cell. From the simplified dynamic equation (4) a specific finite element for fabric forming is constructed (figure 2). The nodal interior load components ($\mathbf{F}_{\text{int}}^e$) are obtained from the strain interpolation matrix:

$$W_{\text{int}}^e(\boldsymbol{\eta}) = \eta_s \sum_{p=1}^{\text{ncell}^e} \left(\|\mathbf{g}_1\|^2 {}^p B_{11s} {}^p T^{11} + \|\mathbf{g}_2\|^2 {}^p B_{22s} {}^p T^{22} + {}^p C {}^p B_{\gamma s} \right) = \eta_s (\mathbf{F}_{\text{int}}^e)_s \quad (5)$$

The detailed formulation of the element can be found in [6].

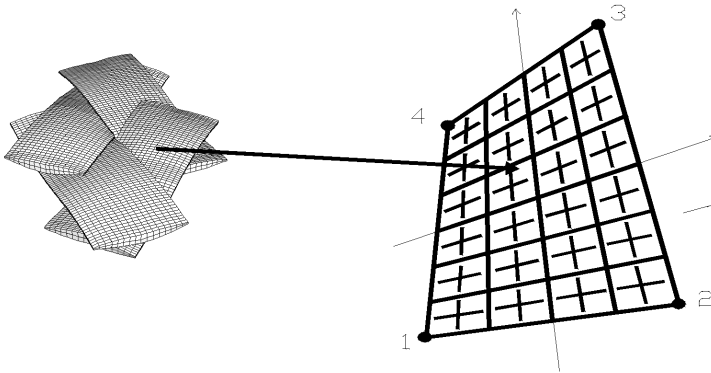


FIGURE 2. Semi discrete finite element

This classical square box benchmark test is performed using the semi-discrete finite element presented above. The geometry is strongly double curved, and asks very large angle variations between warp and weft yarns in the radius of the square box. The shear angles that are necessary to shape the part can be larger than the locking angle of the fabric depending on the radius values. The forming of a plain weave fabric is simulated. The locking angle of this fabric is 41° . The forming simulation is made with

the dynamic equation presented in (4) (tensile and in plane shear energy) but also neglecting the in-plane shear term (tensile energy only). Figures 3 and 4 present in both cases the computed deformed shape after forming. Because of the geometry (strongly double curved) the locking angle of the plain weave fabric is exceeded. This leads to rather different results for both approaches. There is no wrinkle when using the approach based only on the tension because there is no source of instability (figure 3). On the contrary, the computed solution obtained when taking shear into account shows some wrinkles (figure 4). Those are due to shear locking that leads to out-of plane solutions in order to reduce this shear. The rotation angles are clearly reduced when the shear stiffness is taken into account. This example (as others [6]) shows that the contribution of the in-plane shear term is important in the description of the deformed shape after the appearance of wrinkles.

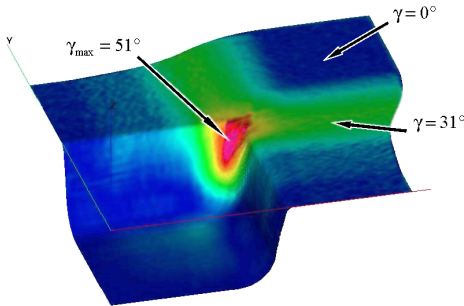


FIGURE 3. Deformed shape and shear angle (Tensile energy only)

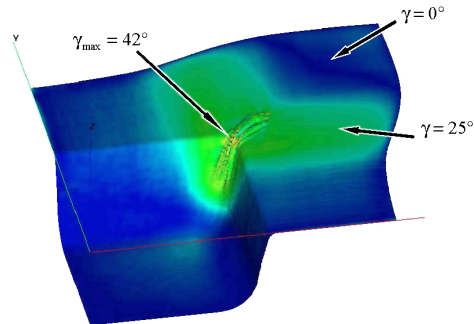


FIGURE 4. Deformed shape and shear angle (Tensile + in plane shear energy)

SIMULTANEOUS FORMING OF SEVERAL LAYERS

The difficulty of modeling simultaneous forming of several layers mainly comes from the relative motion of the different plies during forming. It can be important if the formed shape is double curved and if the layers do not have the same orientation which is usually the case (Figure 5 and 6). Because of this relative displacement, the laminate shell elements used to model the total stack of plies for strength analyses of composite cannot be used here.

Two approaches are considered. In the first one, each ply is modeled by a set of finite elements and the contact/friction between the plies is taken into account. A forward Lagrange multipliers technique is used. The edge-edge contact is an important point in multiple forming and must be taken into account.

In the second approach, a single element is used for all the plies through the thickness and an ALE scheme is used to take the motion of the plies relatively to the element.

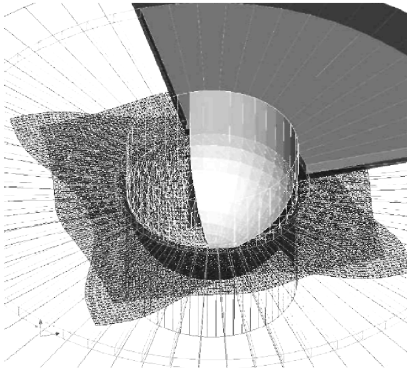


FIGURE 5. Simultaneous forming of a 0-90 layer and a $\pm 45^\circ$ layer.

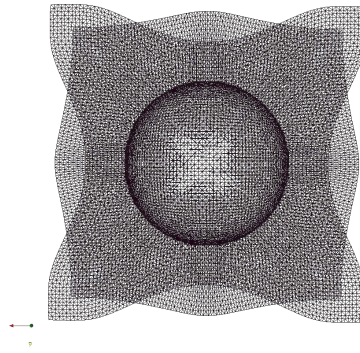


FIGURE 6. Simultaneous forming of a 0-90 layer and a $\pm 45^\circ$ layer.
Deformed shape of the two plies

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