SIMULATION OF THE MECHANICAL BEHAVIOUR OF THICK INTERLOCK COMPOSITE REINFORCEMENTS DURING FORMING

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Abstract

Numerical analysis of interlock composite preforming allows to determine conditions for feasibility of the process and above all to know the position of fibres in the final composite part. For this forming simulation, specific hexahedral finite elements made of segment yarns are proposed. Position of each yarn segment within the element is taken into account. This avoids determination of a homogenized equivalent continuous law that would be very difficult considering the complexity of the weaving. Transverse properties of fabric are taken into account within a hypoelastic constitutive law. A set of 3D interlock fabric forming simulations shows the efficiency of the proposed approach.
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1 Introduction

Laminated composites with 2D layered reinforcements have been used with outstanding success for several decades in aircraft and others top ranking applications. Nevertheless, when the thickness of a composite part is large, the use of these laminated composites is restricted by manufacturing problems and their low resistance to delamination cracking. To overcome these difficulties composites with 3D fibre architecture called ply to ply interlock fabric have been proposed [1-3]. This material is not fully 3D since there is no third yarn set in the transverse direction but the properties through the thickness are much improved. Above all, the possible delaminations of the 2D laminated composites are overcome. Recent advances in the field of computer controlled Jacquard looms allow obtaining much more complicated interlock weavings. The sections of yarns can be different in various places of the reinforcement. Finally the number of weft yarns can vary along the part. The resulting preform is a complex 3D assembly of yarns Figure 1. These complex architectures of interlock fabrics have great benefits. First thickness of the preform can be large. Above all, design of the weaving can be optimized in order to obtain optimal mechanical properties. These advantages added to the fact that interlock fabrics are damage tolerant due to the resistance offered by interlacing tows to crack propagation, lead to use this technology for some aeronautical applications such as motor blades.

From the interlock fabric preform, composite parts are obtained by R.T.M. process (Resin Transfer Moulding) [4]. This process is composed of two main stages. First, the interlock fabric is formed in order to obtain the geometry of the final part that can be complex. In particular when this geometry is double curved, shear strains are necessary to reach the shape. Analysis and simulation of this preforming stage in case of the interlock 3D reinforcements is the purpose of this present paper. Subsequently, resin (usually thermoset) is injected within porous fibrous reinforcement. The composite structure obtained in this way can be thick, without layer stacking and with complex shapes. They have improved mechanical properties especially resistance to crack propagation. Furthermore the finishing is good.

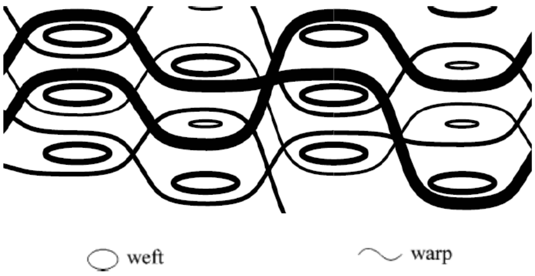

Figure. 1. Interlock used in thick preforms

2 3D Interlock fabrics preforming simulation

The preforming stage has important consequences on the following. First it conditions injection stage. Strains change the permeability of the interlock fabric. Shear strains tend to “close” channels of the flow and compression of the reinforcement in the mould are necessary to avoid flows between the fabric and the tools and to set prescribed thickness of the part. Above all, preforming stage determines the position of yarns in the final composite part. This position and especially direction of fibers plays a predominant role in the mechanical properties of the composite structure. It must be taken very accurately into account in structural analyses (rigidity, damage, fracture, vibrations….) that must be performed on the composite part especially if it is a critical structure. Thus simulation of the preforming stage has two main goals. First it aims to determine if the preforming process is possible or what are the manufacturing conditions that make it possible. In particular, strains of the reinforcement must not exceed some limits. Angle variations between warp and weft yarns are limited (30 to 50° depending on the reinforcement). Tensile strain of yarns must remain very small. All strains and especially compressive strain must insure that there is no local or global buckling. Secondly it is necessary to provide fiber directions and densities after the preforming in order to be able to simulate resin injection and structural behavior of the final composite part.
Within the virtual work principle, the internal virtual work of tension and the other internal virtual works are distinguished:

$$W_{int}^{t}\left(\underline{\eta}\right)+W_{int}^{o}\left(\underline{\eta}\right)-W_{ext}\left(\underline{\eta}\right)=-W_{acc}\left(\underline{\eta}\right) \qquad (1)$$

$\underline{\eta}$ is a virtual displacement field. W_{ext} and W_{acc} are the virtual works due to exterior loads and acceleration quantities. Because the forming is mainly led by yarns in tension accounting for their rigidities that are much larger than others, the modelling effort will mainly concern the tension part . In this term the complete geometry of each yarn will be taken into account. The second order term may be described in a more simple way. In the present work, a simple

form will be considered for this part in order to render identifications of material data simpler and because complexity of the interlock preform is included in the tension term.
Although most forming process are quasi-static, majority of codes (and especially commercial ones) for material forming simulations are based on explicit dynamic approaches [5,6] that have proved to be numerically more efficient than implicit ones. It will be checked that dynamic effects are small enough not to modify results of simulation.
Within a finite element approximation, the dynamic equation (1) written in the set of degrees of freedom leads to:

$$\mathbf{M}\ddot{\mathbf{u}}_{\mathrm{n}} = \mathbf{F}_{\mathrm{ext}} - \mathbf{F}_{\mathrm{int}} \tag{2}$$

with

$$W_{acc}\left(\underline{\eta}\right) = \boldsymbol{\eta}_{\mathrm{n}}^{\mathrm{T}}\mathbf{M}\ddot{\mathbf{u}}_{\mathrm{n}} \qquad W_{ext}\left(\underline{\eta}\right) = \boldsymbol{\eta}_{\mathrm{n}}^{\mathrm{T}}\mathbf{F}_{\mathrm{ext}} \tag{3}$$

$$W_{int}^{t}\left(\underline{\eta}\right) + W_{int}^{0}\left(\underline{\eta}\right) = \boldsymbol{\eta}_{\mathrm{n}}^{\mathrm{T}}\mathbf{F}_{\mathrm{int}} = \boldsymbol{\eta}_{\mathrm{n}}^{\mathrm{T}}\left(\mathbf{F}_{\mathrm{int}}^{t} + \mathbf{F}_{\mathrm{int}}^{o}\right) \tag{4}$$

$\mathbf{u}_n$ and $\boldsymbol{\eta}_n$ are single column matrix of nodal displacement and virtual displacement components. $\mathbf{M}$ is the mass matrix, $\mathbf{F}_{ext}$ and $\mathbf{F}_{int}$ are single column matrix of components of the exterior and interior nodal loads. $\mathbf{F}_{ext}$ is given by the exterior loads on the structure. On a time step Δt^i, from t^i to t^{i+1}, the central difference scheme gets the solution $\mathbf{u}_n^{i+1}$ from $\mathbf{u}_n^i$ [5,6]. The definition of the specific finite element for interlock fabric forming will consist in giving expression of the interior loads vectors due to tension stiffnesses $\mathbf{F}_{int}^t$ and to other rigidities $\mathbf{F}_{int}^o$ in order to apply the explicit scheme.

The 3D interlock woven preform is meshed in a set of 3D finite elements such as the one shown in Figure 2. Yarn segments are crossing the hexahedral element. The interpolation functions of the element are the classical tri-linear functions of the height node hexahedral finite element. In order to be consistent with this interpolation, the yarn segments are straight. The finite element is Lagrangian (as it is standard in solid mechanics). Material in an element is constant during the deformation and positions of yarn in the reference frame of the element (i.e. in the material frame) are constant. Knowledge of these positions is an important data of the problem and influence stiffness and damage properties. After the weaving, the position of each yarn in the preform is known and consequently determines the position of yarn segments in the element when the preform is meshed in 3D finite elements.

$\underline{h}_1^p$ is the unit vector in the direction of the number p yarn. The tension vector in the yarn p is defined as follows:

$$\underline{T}^p = \int_{S^p} \sigma_{11}^p dS\, \underline{h}_1^p \tag{5}$$

where $\sigma_{11}^p = \underline{h}_1^p.(\underline{\underline{\sigma}}^p.\underline{h}_1^p)$ is the axial component of the Cauchy stress in the direction of the yarn p and S^p is the section of the yarn p. The virtual internal work due to tension of the yarn segment p is:

$$W_{int}^{tp}\left(\underline{\eta}\right) = \int_{L^p} T^p\, \varepsilon^p\left(\underline{\eta}\right) dL \tag{6}$$

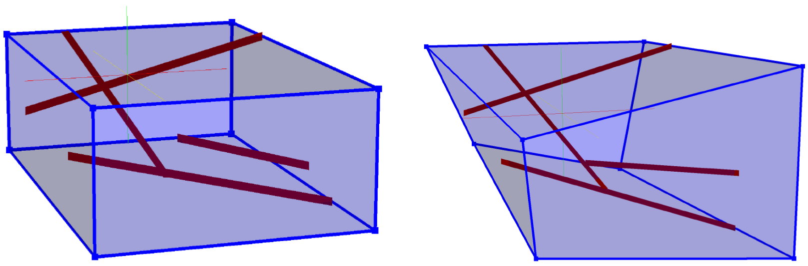

Figure 2: Undeformed and deformed 3D finite element containing fibrous yarns.

L^p is the length of the yarn segment number p and $\varepsilon^p(\underline{\eta}) = \underline{h}_1^p.(\underline{\underline{\nabla}}^S(\underline{\eta}).\underline{h}_1^p)$ is the component of the symmetrical gradient of the virtual displacement $\underline{\eta}$ in the direction of the yarn. For the number e element:

$$W_{int}^{te}(\underline{\eta}) = \sum_{p=1}^{nye} \int_{L^p} T^P \varepsilon^p(\underline{\eta})\, dL = \boldsymbol{\eta}_n^{e\,T} \mathbf{F}_{int}^{te} \tag{7}$$

where nye is the number of yarn segments in the element e and $\mathbf{F}_{int}^{te}$ is the single column matrix of elementary tensile nodal loads.
The global tensile nodal loads $\mathbf{F}_{int}^{t}$ of equation (4) is the assembly of $\mathbf{F}_{int}^{te}$ on all elements.
The virtual strain $\varepsilon^p(\underline{\eta})$ can be expressed as a function of nodal virtual displacements in order to determine $\mathbf{F}_{int}^{te}$. For the yarn segment number p, the virtual strain in the yarn direction $\underline{h}_1^p$ is:

$$\varepsilon^p(\underline{\eta}) = \underline{h}_1^p.\left(\underline{\underline{\nabla}}^S(\underline{\eta}).\underline{h}_1^p\right) = \bar{\varepsilon}_{ij}(\underline{\eta})\left(\underline{g}^i \cdot \underline{h}_1^p\right)\left(\underline{g}^j \cdot \underline{h}_1^p\right) \tag{8}$$

$$\varepsilon^p(\underline{\eta}) = \alpha_i^p \alpha_j^p \mathbf{B}_{ij} \boldsymbol{\eta}_n^e \tag{9}$$

The elementary tensile nodal load is given by :

$$\mathbf{F}_{int}^{te} = \sum_{p=1}^{nye} \int_{L^p} T^P \alpha_i^p \alpha_j^p \mathbf{B}_{ij}^{\ T}\, dL \tag{10}$$

The detail of the calculations can be found in [7].

The above explicit scheme gives nodal displacement and velocity fields at time t^{i+1}. The value of the tension in the yarn $T^{p\ i+1}$ at time t^{i+1} must be computed, in particular in order to preform the next time step. In each yarn segment of the element e:

$$T^{p\ i+1} = T^{p\ i} + \Delta T^p \tag{11}$$

with

$$\Delta T^p = C^{p\ i} \frac{L^{p\ i+1} - L^{p\ i}}{L^{p\ i}} \tag{12}$$

C^p is the tensile stiffness of the yarn. If C^p is constant during the preforming, then:

$$T^{p\ i+1} = C^p \int_0^{t^{i+1}} \frac{dL}{L} = C^p \mathrm{Log} \frac{L^{p\ i+1}}{L_0^p} \tag{13}$$

In this case, the tensile law relates tension to the logarithmic strain in the yarn direction.
Main part of mechanical behavior of the interlock preform during the forming process is due to tensile stiffness of yarns. Nevertheless other aspects such as transverse compression rigidity of yarns, friction between yarns and fibres add some stiffness to the preform. These rigidities are second-order in comparison with tensile rigidities of yarns; still, they can be important, especially in the directions in which tensile stiffness of yarns does not generate a

rigidity of the preform. In particular, that is the case for global transverse compression of the preform and some shear strains. Geometrical and physical descriptions of yarns, fibres, interfaces concerned in these rigidities are very complex. Since it is about second-order rigidities, their modelling has to be simple. Complexity of the preform has been taken into account in the principal part of rigidity due to tensile stiffness of yarns. Consequently it is assumed that second rate rigidities can be modelled by those of an isotropic hypoelastic material. These constitutive models (also called rate constitutive equations) are widely used in F.E. codes to model isotropic mechanical behaviour of continuous material at large strain [8,9].

3 Bias extension test

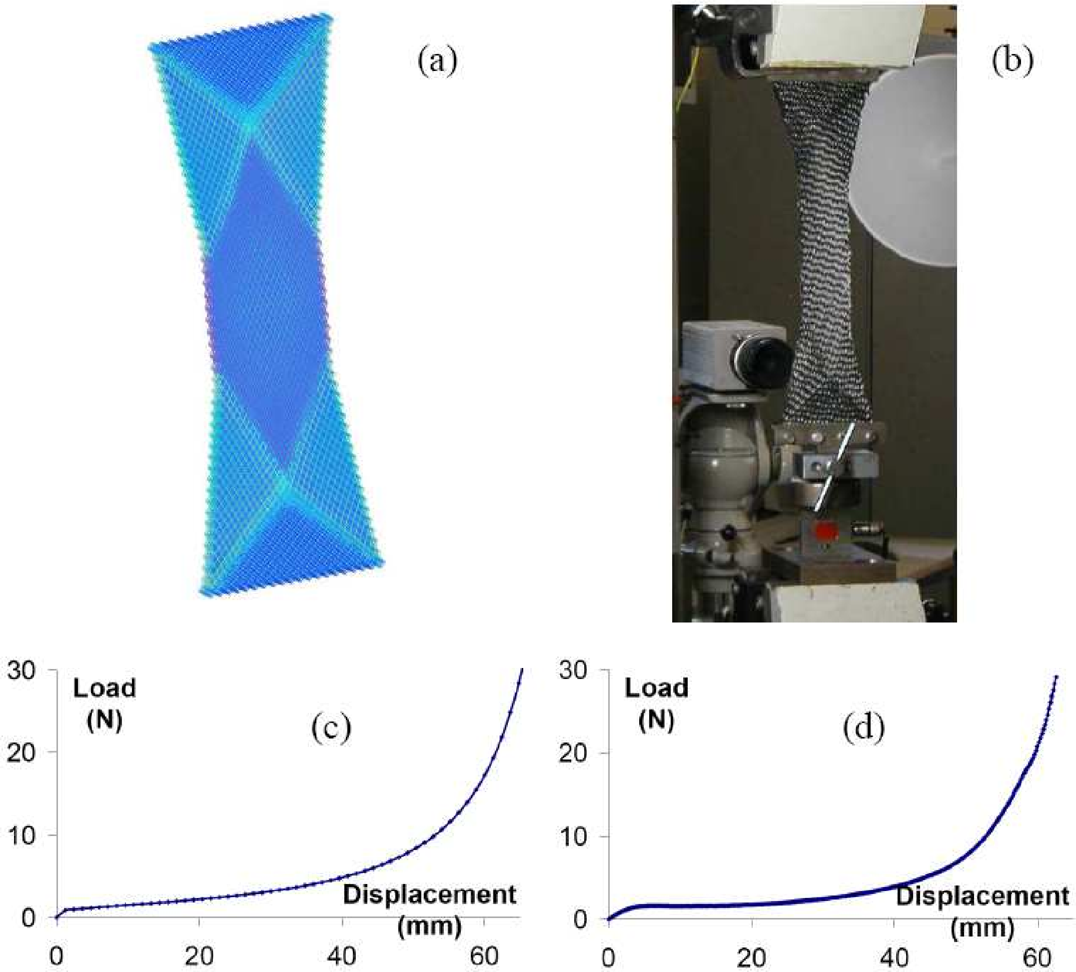

Figure 3: Bias test – 3(a).Computed deformed shape – 3(b).Bias test experiments – 3(c).Computed load versus displacement – 3(d).Measured load versus displacement

The bias extension test is a traction test on a sample oriented at 45°. It is much used and analyzed for the determination of composite reinforcement mechanical behavior [10,11]. Numerical simulation of a 3D woven specimen gives a deformation very close from the real test, and simulated behavior compared with the measured one shows a good accuracy of the hypoelastic model especially knowing that it represents second-order terms (figure 3). This test allows validating the shearing contribution of our model.

4 Forming simulations

Deep drawing simulations for 3D interlock fabrics have been performed. Fibre orientations clearly drive deformation as shown in Figure 4, for two different orientations of yarns. This test have been intensively studied in the case of thin fabric reinforcements [12,13]. The simulation gives after forming the position of each yarn in the preform (Figure 4b). This is important for further resin flow simulation and finite element analysis of the final composite part.

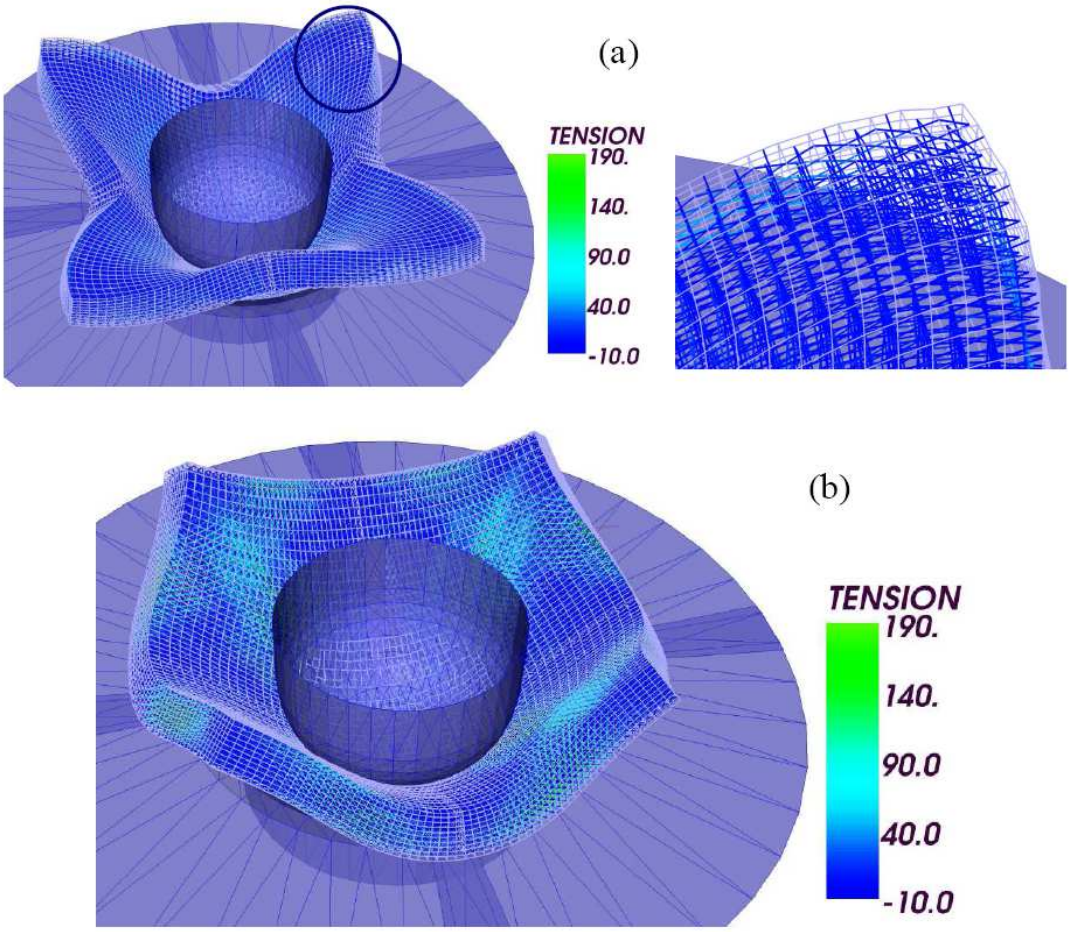

Figure 4: Hemispherical deep drawing of a thick interlock preform
(a).Fibers orientation : +0° +90° (b).Fibers orientation : +45° -45° –

A twisted plate forming simulation is performed as shown in Figure 5. The simulation gives the conditions for the feasibility of the forming process and above all, the position of fibers in the final part. These positions are essential for further structural computation.

5 Conclusions

A hexahedral finite element made of yarn segments has been proposed for the simulation of 3D interlock fabric forming. The position of each yarn within the finite element is taken into account. The rigidities due to transverse properties of the yarns are secondary. They are taken into account within a rate constitutive equation.

Acknowledgement

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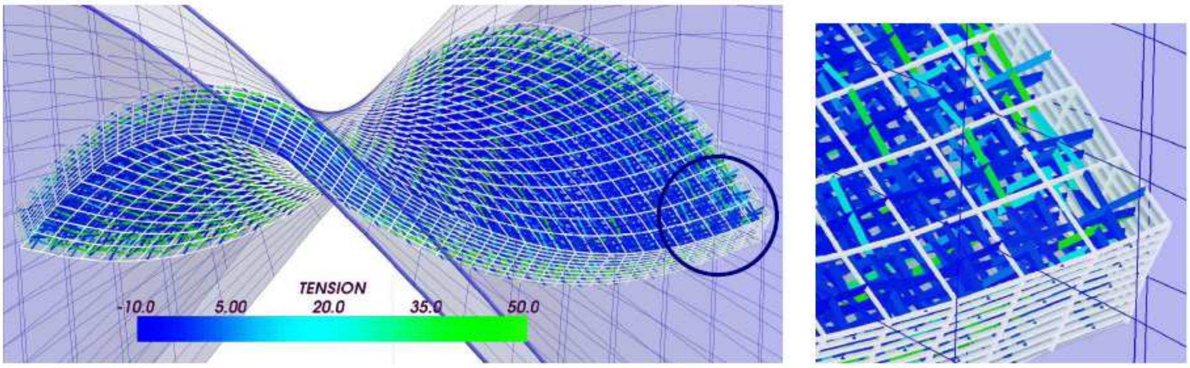

Figure 5: Forming of a twisted plate

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