

EXPERIMENTAL AND NUMERICAL ANALYSES OF 3D INTERLOCK COMPOSITE PREFORMING

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ABSTRACT: The preforming of interlock reinforcement is analysed in the present paper. Interlocks are 3D textile reinforcements that prevent the delamination that can occur in the case of laminate composites. A 3D semi-discrete finite element that allows to model the deformation of an interlock perform is described. Each three-dimensional element contains some fibres that contribute to the element stiffness. The material parameters are identified from mechanical tests and the simulation is validated by comparison with experiment.

KEYWORDS: Fabrics, 3D textiles, Interlocks, Mechanical properties, Finite element analysis (FEA) , Forming

1 INTRODUCTION

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].

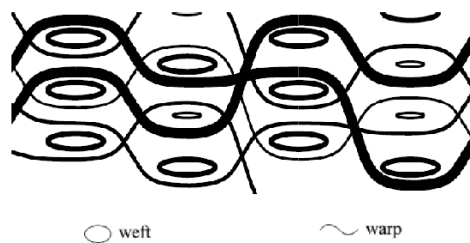


Figure 1. Interlock weaving

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 (up to 100 mm). 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.

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

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is a critical structure. Thus simulation of the preforming stage has two main goals:

- 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.
- 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.

The objective of this present paper is to propose a simulation method for 3D interlock fabric forming. The different methods proposed for draping simulations of thin fabrics (2D) cannot be used in this 3D problem. The proposed simulation method is based on a specific hexahedral finite element that is composed of yarns segments. Position of each yarn is taken into account in accordance with the geometry obtained after the weaving process. Tensile rigidities of yarns lead to the main part of the element stiffness. Beside this stiffness, the other rigidities of the interlock preform due to transverse properties of the yarns and frictions are second-order. Nevertheless they can be important especially in the direction where a deformation can occur without yarn stretching. These rigidities are supposed to be those of an isotropic hypoelastic material.

2 3D FABRICS PREFORMING SIMULATIONS

Within the virtual work principle, the virtual internal work due to tensions and the other internal virtual works are distinguished:

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

$\forall \underline{\eta}$ a virtual displacement field such as $\underline{\eta} = 0$ on the boundary with prescribed displacements. $W_{ext}(\underline{\eta})$ and

$W_{acc}(\underline{\eta})$ 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 $W_{int}^t(\underline{\eta})$. 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. This explicit approach will be used in the present work. 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:

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

$$\text{with } W_{acc}(\underline{\eta}) = \underline{\boldsymbol{\eta}}_n^T M \ddot{\mathbf{u}}_n \quad W_{ext}(\underline{\eta}) = \underline{\boldsymbol{\eta}}_n^T \mathbf{F}_{ext} \tag{3}$$

$$W_{int}^t(\underline{\eta}) + W_{int}^o(\underline{\eta}) = \underline{\boldsymbol{\eta}}_n^T \mathbf{F}_{int} = \underline{\boldsymbol{\eta}}_n^T (\mathbf{F}_{int}^t + \mathbf{F}_{int}^o) \tag{4}$$

\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].

Definition of the specific finite element for interlock fabric forming will consist in giving expression of the interior loads vectors due to yarn tension stiffness and to other rigidities in order to apply the explicit scheme

3 HEXAHEDRAL FINITE ELEMENT

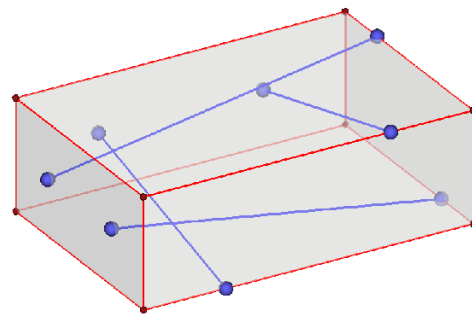


Figure 2: Eight node hexahedral finite element containing yarns

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. In order to be consistent with the tri-linear 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.

Denoting \underline{h}_1^p the unit vector in the direction of the number p yarn, L^p the length of the yarn segment number p and $\varepsilon^p(\underline{\eta}) = \underline{h}_1^p \cdot (\underline{\nabla}^S(\underline{\eta}) \cdot \underline{h}_1^p)$ the virtual extension in the direction of the yarn, the virtual internal tensile work in element e is:

$$W_{int}^{te}(\underline{\eta}) = \sum_{p=1}^{nye} \int_{L^p} T^p \varepsilon^p(\underline{\eta}) dL = \underline{\eta}_n^{eT} \mathbf{F}_{int}^{te} \quad (5)$$

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

Main part of mechanical behaviour 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].

4 FORMING EXAMPLES

4.1 HEMISPHERICAL DEEP DRAWING

Deep drawing simulations for 3D interlock fabrics have been performed. Fibre orientations clearly drive deformation as shown in Figure 3, for two different orientations of yarns. This test have been intensively studied in the case of thin fabric reinforcements [10,11]. The simulation gives after forming the position of each yarn in the preform (Figure 3). This is important for further resin flow simulation and finite element analysis of the final composite part.

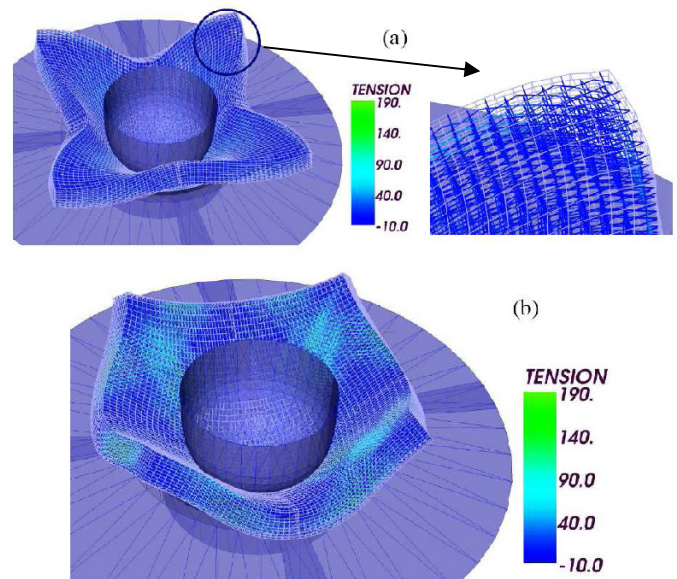


Figure 3: Hemispherical deep drawing of a thick interlock preform
(a).Fibers orientation : +0° +90°
(b).Fibers orientation : +45° -45°

4.2 TWISTED PLATE

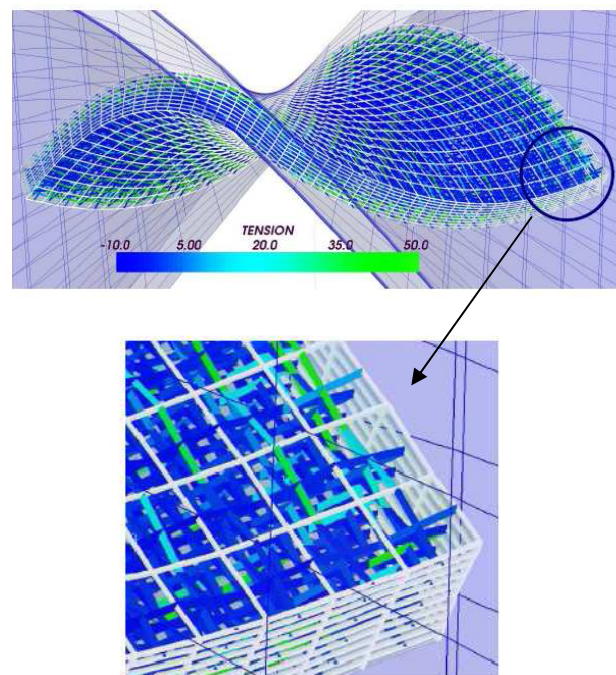


Figure 4: Forming of a twisted plate

A twisted plate forming simulation is performed as shown in Figure 4. 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.

4.3 EXPERIMENTAL VALIDATION

In the case of a hemispherical forming (the punch and die are shown Figure 5) a comparison is performed between the simulation and the experimental forming. The shear angles are measured by Digital image correlation (DIC) measurements [11] on both faces of the preform. They are in good agreement with the simulation.

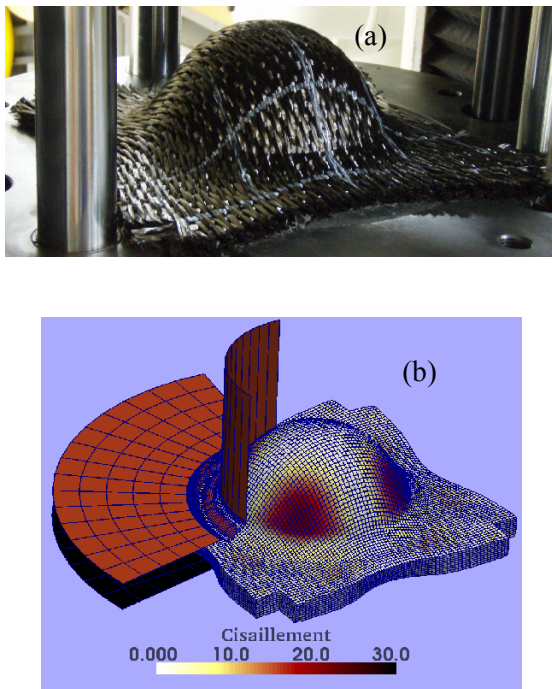


Figure 5 – Experimental validation
(a) Experimentation (b) Simulation

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.

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