MESO-STRUCTURAL BEHAVIOUR OF COMPOSITE FABRIC FOR THE SIMULATION OF MANUFACTURING OF THIN COMPOSITE BY SHAPING PROCESS

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SUMMARY

The present study concerns the modelling of the behaviour of preimpregnated woven fabric during the forming process. A new numerical model in finite strains has been developed. It make into account the various dominating mechanics in the physics of the mechanical transformation of composite material during the shaping process, namely large angular variations of yarns, viscoelasticity of resin and evolution of possible damages in yarns. Shear and tensile tests of composite fabric specimens are presented to validate the mesostructural approach. Some numerical simulation of shaping process by deep-drawing are proposed and compared with the experimental results. These results examined the importance of understanding the influence of prepreg shaping deformation and manufacturing conditions on the final properties and resulting structure, which in turn can strongly affect the utilization of these material for the manufacturing of high performance composites parts.

INTRODUCTION

Continuous fibre reinforced composites are now firmly established engineering materials for manufacturing of components in automotive and aerospace industries. The offer design engineers enormous opportunities for introducing new concept into their design whilst reducing costs. In this respect, preimpregnated composite fabric gives flexibility in the design manufacture 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 allowed

the 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 shaping composite processes must permit to improve the delay of the realisation of complex pieces and to optimize costs in an integrated design approach. Indeed, the preimpregnated composite fabric corresponds to a structure composed of the combination of the yarn network and resin membrane. So, it is difficult to globally characterize, by homogeneous methods, the behaviour of this preimpregnated fabric without lose mechanical informations. The new numerical finite element model Belhous 1998 [2] and Cherouat 1998 [8], developed an a mesostructural level permits to take into account the various dominating mechanics in the 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 preprocessing 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 by an better definition of the flat form. The forming process of impregnated reinforcements usually includes important mechanisms which can have a significant effect on mechanical properties of the finished product

1. large angular variation due to in-plane shear strain,
2. straightening and elongation of fibres due to in-plane tension,
3. buckling of fibres due to large in-plane compression,
4. inter-fibre sliding due to relative local stretching of yarns.

The formability of preimpregnated reinforcements is strongly affected by the fabric architecture, the rheological properties of resin and fibres, the size and the geometry of tools. The heterogeneous behaviour must take into account geometrical undulation of yarns, fibre properties, resin behaviour and contact with friction between composite and tools. The proposed model is described by continuum approach for finite strains and geometrical non linearities. Elastic and viscoelastic properties of material are investigated and homogenized on a mesostructural level. Bi-component finite elements is obtained by association of viscoelastic membrane finite elements representative of resin behaviour and truss finite elements representative of warp and weft fibres behaviour.

MESOSTRUCTURAL MODEL OF PREIMPREGNATED COMPOSITE BEHAVIOUR

The woven fabrics impregnated with resin have complex internal microstructures and present an anisotropic behaviour due to the privileged directions of fibres. Some models are proposed to homogenize elastic properties of a composite material and to simulate the deformation of these materials by forming process. Geometrical approach is proposed in the literature to simulate the transformation of fabrics during the draping process. This approach is based on geometrical aspects of the warping where the deformation is restricted to inter-fibre shear mode and the fabric can be approximated by trellis mechanism, Kawabata 1973

[12], Bergsma 1988 [3], Baser 1989 [1], Van de Ween 1991 [18], Long 1995 [14] and Chen 1998 [6]. Micro-macro structural approach is developed in order to take account all weave architecture and mechanical properties associated to the impregnated material and to the resin behaviour, Realff 1993 [15] and Blanlot 1995 [4]. An updated lagrangian formulation in finite deformations was used to simulate the deformation of dry fabric by sheet forming process. The fabric behaviour is obtained by discrete summation of tensile curve of a single yarn and the current of the yarns during the deformation, Sabhi 1993 [16], Cherouat 1995 [7] and Gelin 1995 [9]. So, it is difficult to globally characterise, by homegeneous methods, the behaviour of this fabric without lose mechanical informations. In order to predict structural behaviour of impregnated woven fabric a new finite element model, developed an a mesostructural level is carried out. This approach makes it possible to model the deformation of composite fabrics by taking account of the various dominating mechanisms in the physics of the mechanical transformation of fabrics and geometrical non linearity, Belhous 1998 [2] and Cherouat 1998 [8].

Large angular variations of yarns, viscoelasticity of resin and evolution of damage in yarns are the principal mechanics 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 of impregnated composite fabrics 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 actual position is defined in actual configuration by

$$\vec{x}^{\,fibres} = \vec{x}^{\,resin} = F\vec{X}^{\,fibres} = F\vec{X}^{\,resin} \tag{1}$$

F describes the deformation gradient of composite fabric.

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

$$\vec{n}_L^f\left(F,\theta_0\right) = \frac{1}{\lambda_L^f} F\vec{N}_L^f\left(\theta_0\right) \tag{2}$$

A3 : The shear angles deformation of fibres can be associated to the rotation of the rigid body of the fibre. We can note this assumption by the following kinematic relation

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

Using the above assumption, the right stretch tensor for heterogeneous material is defined in reference configuration as

$$\begin{cases} \lambda_i^f = \sqrt{\vec{N}_i^f F^T F \vec{N}_i^f} & fibres \\ U^m = \sqrt{F^T F} & resin \end{cases} \tag{4}$$

The non linearity of the shaping problem imposes the use of incremental formulation. The spatial velocity gradient in the current configuration, expressed in the rigid body rotation frame by

$$\begin{cases} \overline{L}^{fR} = \dfrac{\dot{\lambda}_i^f}{\lambda_i^f} n_i^f \otimes n_i^f + \dot{n}_i^f \otimes n_i^f & fibres \\ \overline{L}^{mR} = \dot{U}^m U^{m^{-1}} = \sum_{i=1}^{3} \dfrac{\dot{\lambda}_i^m}{\lambda_i^m} e_{0i} \otimes e_{0i} & resin \end{cases} \tag{5}$$

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

$$\begin{cases} \overline{D}_L^f = \left(\dfrac{\dot{\lambda}_L^f}{\lambda_L^f} \right) & fibres \\ \overline{D}^{mR} = \sum_{i=1,3} \left(\dfrac{\dot{\lambda}_i^m}{\lambda_i^m} \right) e_i^R \otimes e_j^R & resin \end{cases} \tag{6}$$

For shaping deformation rate constitutive equations must be written in terms of 'objectives rates' in order to maintain correct rotational transformation properties. Using Kirchhoff's and Green-Naghdi's tensor stress, the stress rate in the fibre and the resin can be written at each time as

$$\begin{cases} \left(\overline{\sigma}_L^{fR}\right)_{n+1} = \left(\overline{\sigma}_L^{fR}\right)_n + \int_{t_n}^{t_{n+1}} E_L^f\left(\lambda_L^f\right) \dfrac{\dot{\lambda}_L^f(\tau)}{\lambda_L^f(\tau)} d\tau & fibres \\ \left(\overline{\sigma}^{mR}\right)_{n+1} = \left(\overline{\sigma}^{mR}\right)_n + \int_{t_n}^{t_{n+1}} C^m(\tau) \overline{D}^{mR} d\tau & resin \end{cases} \tag{7}$$

The constitutive law of fibres is non linear and is written in terms of longitudinal modulus of stretching E_L^f function of principal elongation of fibre λ_L^f, elastic modulus of fibre E_f and undulation factor ε_{emb}. The viscoelasticity behaviour law of resin is formulated in the time domain by the hereditary integral and using the relaxation time τ_k and the fourth order relaxation tensor, which are material parameters $C_{ij}^{m^k}$. Approximating the creep functions by a Prony series we have

$$\begin{cases} E_L^f\left(\lambda_L^f\right) = E_f\left(1 - e^{-\dot{\lambda}_L^f / \lambda_L^f \varepsilon_{em}}\right) & fibres \\ C_{ij}^m(t) = C_{ij}^{m^\infty} + \sum_1^k C_{ij}^{m^k} e^{-t/\tau_k} & resin \end{cases} \tag{8}$$

FINITE ELEMENT MODELLING

The continuum movement of each material point, ensured by the non-sliding inter fibre due to fabric weaving and resin behaviour, means that a nodal approximation for the displacement can be used. A finite element method is used to modelling the equilibrium of fabric during the shaping deformation. The deformation of prepreg woven fabric is described with membrane assumptions. The global equilibrium of the fabric is obtained by minimization of deformation energy

$$\Pi(u) = \int_{V^{resin}} \overline{\sigma}^{mR} \delta \overline{D}^{mR} dV + \int_{L^{fibre}} \overline{\sigma}_L^{fR} \delta \overline{D}_L^{fR} ds - \int_{S_\sigma} f_v \dot{u} dV - \int_{S_u} f_s \dot{u} dS \tag{9}$$

The equilibrium equation on the actual configuration (9) is non-linear (viscoelasticity behaviour of resin, elastic non linear of fibres, finite transformation and contact with friction between fabric and tools) it is linearized by an iterative Newton method. According to the different modes of deformation occurring in the material, bi-component finite elements are developed to characterize mechanical behaviour of thin woven composite structures. The bi-component element is based on an association of 2D membrane finite elements combined with a complementary truss finite elements. The resin is modelling by isotropic viscoelastic three or four nodes membrane finite elements and the warp and weft fibres are modelling with linear truss finite elements.

APPLICATIONS TO SOME PROCESS

The present section relates experiments and models developed for the validation of the numerical model of impregnated composite fabric. First experimental investigation is carried out a shear test on a dry woven fabric specimens. Then tensile tests carried out on a impregnated woven fabrics specimens in non polymerized phase consisting. To illustrated how the developed model can be used to predict the deformation of the composite fabric during the forming process, some examples are treated and discussed.

1. Shear test of dry woven fabric

The validation of the mesostructural behaviour of impregnated reinforcements is carried out on shear tests. As the experimental tests are carried out with Serge 3x4 dry fabrics Sabhi 1993 [16] and Gelin 1996 [9]. A glass fibres fabric specimen is clamped on rigid shear rig. The shear rig was used to measure shear stiffness and the locking angle of the fabric reinforcement. Applying a vertical load (120 N), the specimen is subjected to a shear strain state. The equilibrium of the parallelogram rigid bars gives a relationship between the loads of the yarns in tension to the vertical load at crosshead mounting point. The experimental load

measured for a given displacement and for different orientation of fibres is compared to the numerical value obtained by using the numerical model.

The numerical simulation is carried out with Abaqus software, where the fabric is modelled by 300 linear truss finite elements representative of warp and weft fibres behaviour. For this test, the computation is first made neglecting the influence of the resin effect and the undulation on the fabric behaviour. Numerical results, obtained by bi-component finite elements, are compared with the experimental elongation effort imposed by the machine. These results are illustrated in Figures 1 for different orientations of fibres 0° and 10°. The agreement between numerical and experiment values is good and prove the validity of the mesostructural approach to modelling the behaviour of preimpregnated woven fabric.

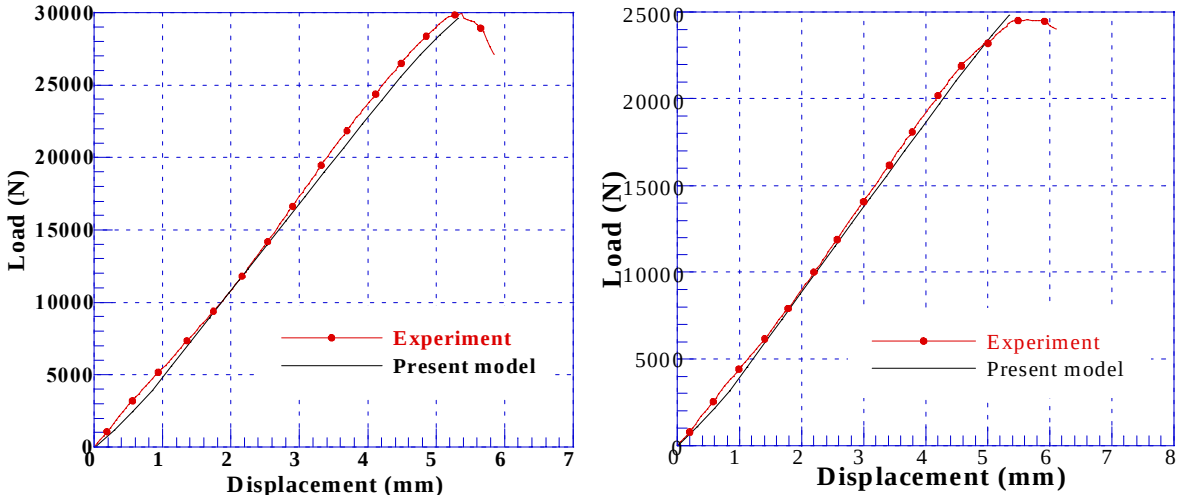

Fig. 1 : Variation of load force for 0° and 10° fibre orientations

2. Tensile test of preimpregnated woven fabric

The impregnated fabric developed in this study was a satin 5 woven fabric in non polymerized phase consisting of carbon fibres Blanlot [4,5]. The behaviour of composite fabrics subjected to shearing can be measure experimentally to determine the effective shear compliance on the shaping process. The locking angle is considered to be the shear angle at the commencement of out-of plane movement leading to wrinkling of the fabric. At processing, the impregnated fabric is idealised as a viscous material subject to the kinematic constraints of incompressibility and inextensibility in the fibre direction. Application of tensile strain caused a membrane stress within the fabric. The effect of the membrane stress upon the locking angle has also been investigated.

A vertical displacement is imposed at the moving extremity of the rectangular impregnated woven fabric specimen. Four phases of transformation are identified in the global behaviour : visco-elastic phase results from resin shearing behaviour (relaxation modulus), a pseudo-kinematic phase results from geometrical rotation of fibre and geometrical undulation of yarns, a hardening phase results from locking fibre, frictional resistance and from increasing density of fibres and linear phase results from fibre tensile behaviour. The experimental effort imposed by the tensile machine is compared to the numerical values for different orientation of fibres 30° and 45°. Figures 2 describe, at the beginning of the curves, the viscoelastic phase followed by a kinematic stage which increases with the angle of loading. The end part of this curves represents the hardening phase with a very high stiffness du to fibre elongation. The

agreement between numerical and experiment values prove the validity of the proposed model and show clearly the strong non linearity of impregnated composite behaviour Lepage 1998 [13].

All the calculated are worked out using the following values of material constants : mechanical characteristics of fibres are :

E_f (MPa)	ε_{emb}	ρ (g/cm^3)
230000	0.005	1,76

and mechanical characteristics of non polymerized resin are :

time (s)	0.01	0.1	1	10	100	100
Shear C_{12}^{mk}	0.02332	0.023332	0.83509	0.11723	0.14423	0.178

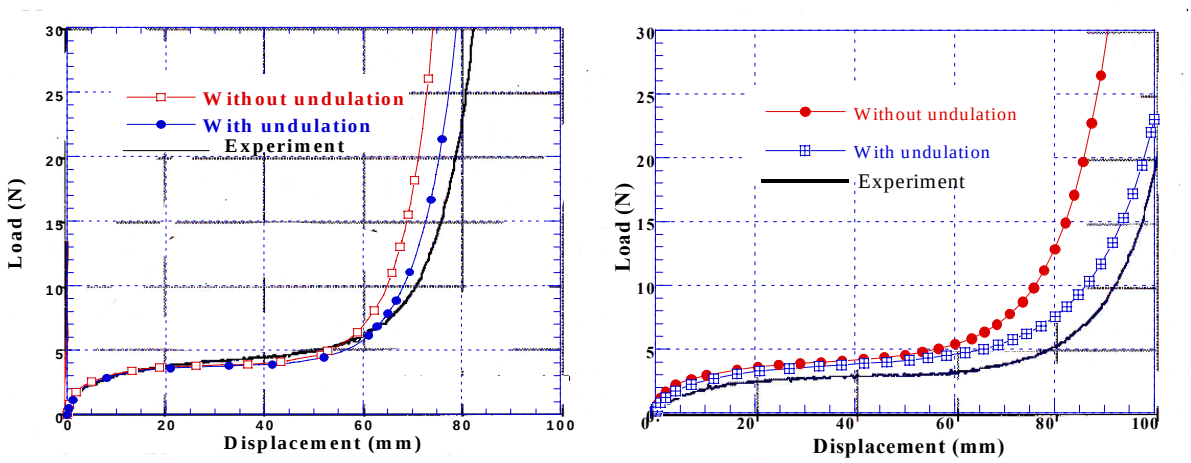

Fig. 2 : Variation of load force for 30° and 45° fibre orientations

3. Deep-drawing process by hemispherical tools

Deep-drawing is a common process used to manufacture composite structure by stamping impregnated fabric into complex final geometric form. Configuring a new deep-drawing process is highly empirical with many parameters determined by trial and error. The flange of the fabric is held against the die with a blank holder, preventing the flange from folding upward and to avoid the formation of the folds in fabric. As the punch is lowered, the material is drawn into the die, forming the hemispherical shape.

The ability to perform a successful deep draw operation depends on many parameters. These include the mechanical behaviour of fabric material, initial direction of fibre, the hold down force on the blank holder, the velocity of the punch, the friction between the fabric and tools, the corner radius of tools. The effects of some of these parameters on a simple cup are explored using numerical analysis. In this study of shaping process, we are interested in the shear angular variation between the fibre weft and warp along symmetrical and diagonal directions of final parts, contour of the final shape, the strain and the distribution of fibre surface density in certain zones.

An experimental shaping test of dry glass fibre fabric by deep drawing process with a hemispherical tools have been simulate in the laboratory for different orientation of fibres Cherouat 1995 [7]. The initial shape of the glass fibre fabric is a square (360 x 360mm). Its edges are free but a pressure equal 2 MPa is applied on the blank-holder and friction coefficient between the glass fabric and the tools is 0.1.
The numerical analysis of woven fabric shaping is developed in the ABAQUS explicit software. The impregnated composite is modelling with 400 membrane finite elements representative of resin behaviour and 1600 truss finite elements representative of warp and weft fibres behaviour. The hemispherical die and punch rigid are modelling with 1600 Bezier patches.

The parameter study was performed on the effect of the fibre direction factor on the shear angles of fabric. Figures 3 and 4 give the final results in terms of angular distorsion within the fabric along the diagonal and median lines. The experimental and the numerical values indicate a good agreement for (0°,90°) and (-45°,+45°) along the diagonal and median directions of the final shaped part. We notice that these angular distorsion values are very large along the diagonal line for (0°,90°) fabrics and along the median line for (-45°,+45°) fabrics.

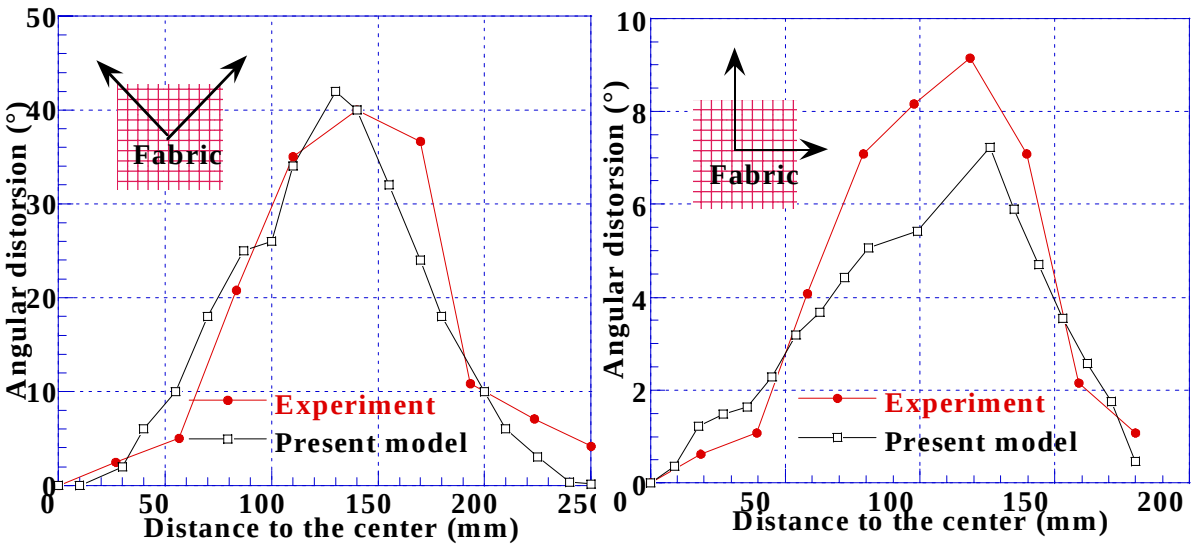

Fig. 3 : Shear strain for (0°,90°) fabric along diagonal and median lines

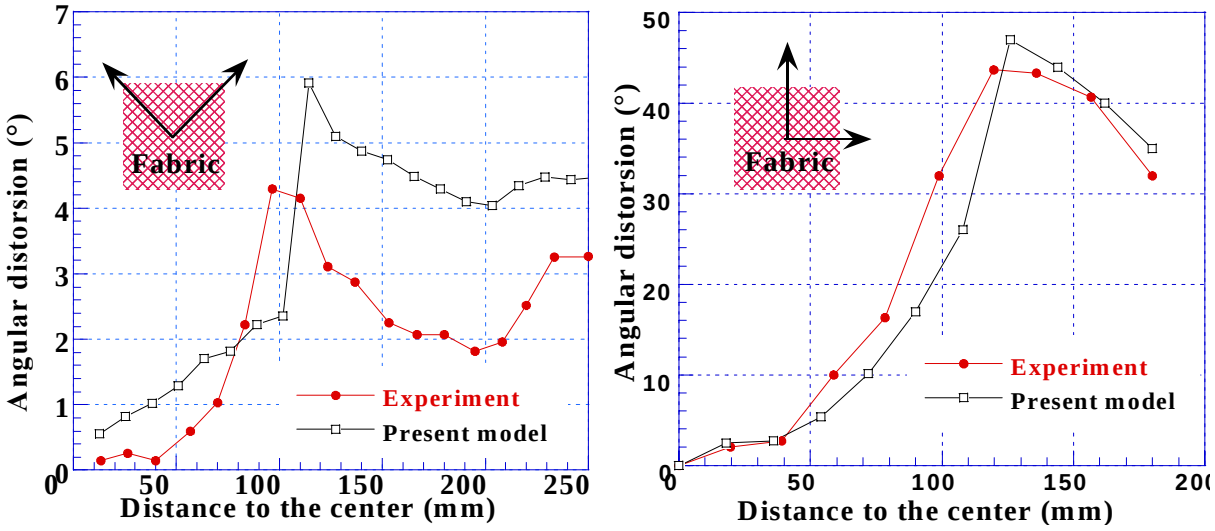

Fig. 4 : Shear strain for (-45°,+45°) fabric along diagonal and median lines

CONCLUSIONS

Numerical analysis are an efficient mean of evaluating factors related to manufacturing process, such as deep-drawing and laying-up. It is possible to obtain good, quantitative information on the forming process. A proposed manufacturing process, or a modification to an existing process, can be easily investigated prior to investment in tooling. There are usually several problems that are identified in an initial highly non linear numerical analysis, such as the behaviour of the material, the geometrical non linearities of the process and the contact with friction. A numerical mesostructural approach is proposed to modelling the behaviour of the impregnated composite and implemented in Abaqus software. The mechanical formulation take account the specific deformations of fibre, the effects structural of the fabric weaving and the viscosity effects behaviour of the resin. The bi-component finite elements of the heterogeneous material is obtained by 2D membrane isotropic viscoelastic finite elements representative of resin behaviour added to the isotropic elastic rod finite elements representative of warp and weft fibres behaviour. Experimental test has been carried out in order to validate the proposed computational method of the forming processes. Numerical forming results are in good agreement and prove the validity and the pertinence of the numerical formulation.

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