SIMULATION OF WRINKLING DURING TEXTILE COMPOSITE REINFORCEMENT FORMING.

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1. Introduction

Textile reinforcements are used in composite materials, in particular in case of double curvature geometries requiring large shear strains in the plane of the reinforcement. Simulation codes of the draping of dry textile reinforcements are necessary at the stage of design of composite structures to determine the feasibility of a forming and to know the directions of fibres in the final composite part. Finite element methods take into account the mechanical behaviour of the textile reinforcement and the loads on the boundaries during forming. Therefore they constitute the main alternative to the more simple geometric methods [1, 2]. Among the defects that occur during textile reinforcement forming process, wrinkles are the most common ones. These wrinkles develop easily because of the internal composition of textile reinforcement made out of fibres. Possible relative fibre motions result in a specific mechanical behaviour that characterizes very low bending stiffness creating favourable conditions for wrinkles.

A three node shell element based on the “semi-discrete” approach is used in this paper. Tensile, in-plane shear and bending virtual works are separated and added on a unit woven cell. The form of these virtual works is simple and close to textile material physics and the constitutive data are directly identified through mechanical tests performed in case of textile reinforcements This is a simple alternative to continuous mechanical approach [3, 4]. The shell finite element for fabric forming simulations used in the present work is based on this form of the internal virtual work [5]. It is used to simulate textile reinforcements draping and forming processes and to analyse the onset and growth of wrinkles in function of the three stiffnesses (tension, in plane shear and bending).

Wrinkling can be due to compression in the yarn direction (this is usually avoided in forming process) or to large in plane shear strains. The in-plane shear stiffness of a fabric strongly increases when the shear angle becomes large, especially when it reaches and exceeds the ‘locking angle’. Nevertheless wrinkling is a global phenomenon that depends on the set of all strains and stiffnesses. Bending stiffness plays an important role in the wrinkle shape. An increase of this rigidity leads to an increase of the wrinkle size. The examples shown below analyse the role of tensions, in-plane shear and bending strain energies in wrinkling.

2. The semi-discrete approach for textile composite reinforcements forming simulation

In the present work the approach is called semi-discrete [5]. The textile composite reinforcement is seen as a set of a discrete number of unit woven cells submitted to membrane (i.e. biaxial tension and in plane shear) and bending (Figure 1).

In any virtual displacement field η such as $\underline{\eta} = 0$ on the boundary with prescribed displacements, the virtual work theorem relates the internal, exterior and acceleration virtual works:

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

In the case of the woven fabric reinforcement, the internal virtual work is assumed to be separated into:

$$W_{int}(\underline{\eta}) = W^t_{int}(\underline{\eta}) + W^s_{int}(\underline{\eta}) + W^b_{int}(\underline{\eta}) \tag{2}$$

$W^t_{int}(\underline{\eta})$, $W^s_{int}(\underline{\eta})$, $W^b_{int}(\underline{\eta})$ are the internal virtual work of biaxial tension, in plane shear and bending respectively with :

$$W^t_{int}(\underline{\eta}) = \sum_{p=1}^{ncell} {}^p\varepsilon_{11}(\underline{\eta})\, {}^pT^{11}\, {}^pL_1 + {}^p\varepsilon_{22}(\underline{\eta})\, {}^pT^{22}\, {}^pL_2 \tag{3}$$

$$W^s_{int}(\underline{\eta}) = \sum_{p=1}^{ncell} {}^p\gamma(\underline{\eta})\ {}^pM^s \tag{4}$$

$$W^b_{int}(\underline{\eta}) = \sum_{p=1}^{ncell} {}^p\chi_{11}(\underline{\eta})\, {}^pM^{11}\, {}^pL_1 + {}^p\chi_{22}(\underline{\eta})\, {}^pM^{22}\, {}^pL_2 \tag{5}$$

where ncell is the number of woven cell. ${}^pA$ means that the quantity A is considered for the woven cell number p. L_1 and L_2 are the length of unit woven cell in warp and weft directions. $\varepsilon_{11}(\underline{\eta})$ and $\varepsilon_{22}(\underline{\eta})$ are the virtual axial strain in the warp and weft directions. $\gamma(\underline{\eta})$ is the virtual angle between warp and weft directions. $\chi_{11}(\underline{\eta})$ and $\chi_{22}(\underline{\eta})$ are the virtual curvatures of warp and weft directions. $\varepsilon_{11}(\underline{\eta})$, $\varepsilon_{22}(\underline{\eta})$, $\gamma(\underline{\eta})$, $\chi_{11}(\underline{\eta})$ and $\chi_{22}(\underline{\eta})$ are function of the gradient of the virtual displacement field. T^{11} and T^{22} are the tensions on the unit woven cell in warp and weft directions. M^{11} and M^{22} are the bending moments on the woven cell respectively in warp and weft directions. M^s is the in-plane shear moment. The loads on an edge of the woven unit cell result in the tensions T^{11} and T^{22} in one hand and shear forces in the other hand.

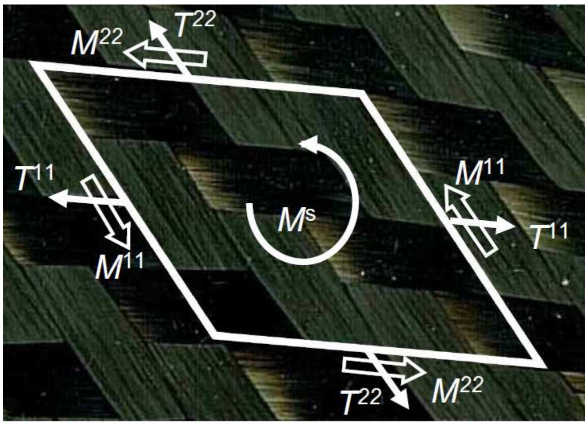

Fig 1. . Unit woven cell submitted to tension, in plane shear and bending

This shear forces on a warp and weft sections have a moment at the centre of the woven unit cell in the direction normal to the unit cell. The component of this moment is called in-plane shear moment M^s. This quantity is conjugated to the in-plane shear angle γ. The internal virtual work of in plane shear is directly given from M^s and the virtual shear angle (Eq. 4). In the case of a textile material, the shear angle γ is a significant and clearly defined quantity and it is interesting to express the internal virtual work of in plane shear in function of this quantity.

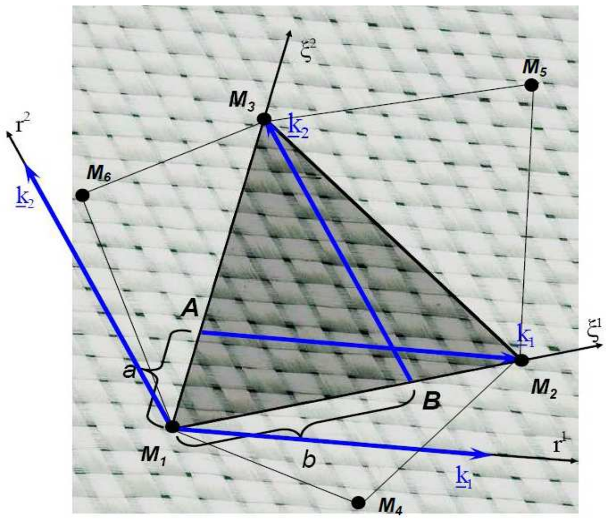

Fig 2. Three node finite element made of woven cells

The mechanical behaviour of the textile reinforcement defines a relation between the loads $T^{\alpha\alpha}$, M^s, $M^{\alpha\alpha}$ and the strain field. The experimental tests specific to textile composite reinforcements are used to obtain these mechanical properties. The biaxial tensile test gives the tensions T^{11} and T^{22} in function of the axial strain ε_{11} and ε_{22} [6], the picture frame or the bias extension test gives the shear moment M^s in function of the angle change γ between warp and weft yarns [7, 8] and the bending test give the bending moments $M^{11}$and M^{22} in function respectively of χ_{11} and χ_{22} [9].

The three node triangle shown in Fig. 2 is composed of woven cells. This finite element is detailed in [5].

3. Wrinking simulations

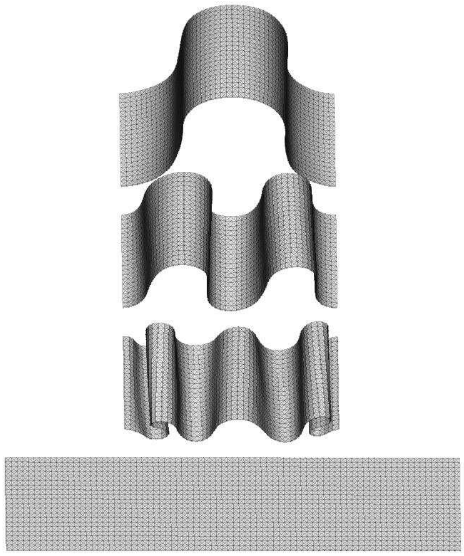

Fig 3. Wrinkles in compression

Textile reinforcements are very sensitive to in plane compression loadings. Their very weak bending stiffness leads to buckling for small compression loads. When a woven fabric is submitted to compression in the yarn direction it tends to an out-of-plane deformation if this one is possible. The bending strain energy induced by this out-of-plane deformation is much smaller than the decrease of compression strain energy. A fabric strip is considered in Fig. 3a. A compressive displacement field is prescribed. Figures 3b, 3c and 3d show the deformed shape obtained for bending rigidities increasing with a factor 10. The size of the wrinkles increases with the bending stiffness [10]. If the textile reinforcements are very sensitive to compression state for which buckling is quasi immediate, this situation is generally avoided in forming processes. Some tools and especially blank holders are used in order to apply tensions and avoid compressive states in the fabric.

The draping of a woven reinforcement on a circular cylinder is considered (Fig. 4). The first deformed shape (Fig. 4a) is obtained only accounting for the tensile part in the virtual internal work. The draping is perfectly obtained without any wrinkle but the shear angles near the corners of the fabric are close to 90°. The obtained solution is similar to the one given by a fishnet algorithm. Only the axial strains due to tensions in the yarns can lead to a difference. But these strains are very small in the present case because there are very weak tensions during the draping. The second deformed shape (Fig. 4b) is obtained when the tension and in-plane shear parts are taken into account in the virtual internal work. The draping is performed with wrinkles. Those wrinkles are numerous and small. The third deformed shape (Fig. 4c) is obtained when all the terms (tension, in-plane shear and bending) are taken into account. In this case too, the draping leads to wrinkles but they are less numerous and the deformed shape is realistic.

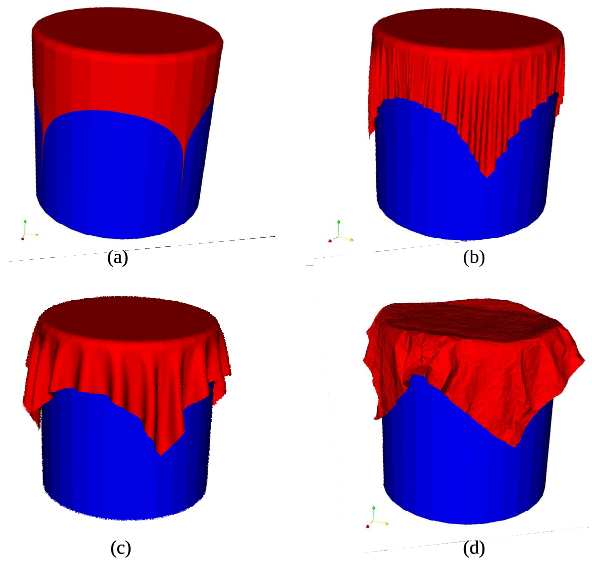

Fig 4. Draping on a cylinder
(a) Tensile rigidity only
(b) Tensile and in-plane shear rigidities
(c) Tensile + in-plane shear + bending rigidities
(d) Isotropic membrane

In Figure 4d, an isotropic behaviour is used for the sheet. For instance it could be a paper sheet. The draping is not possible. The required large shear angles in the corners are not allowed by this behaviour for which the in-plane shear behaviour is related to the tensile one. That shows the very important role of the in plane shear behaviour in draping/forming of membrane. A textile can be shaped on a double curved surface because there are possible large rotations between warp and weft fibres and in plane shear stiffness is weak. In the case of an isotropic membrane that is not possible. On the other hand the shear stiffness that increases when the shear angle becomes large leads to wrinkles. If this shear stiffness is neglected there will be no wrinkle in any case.

4. Conclusions

Forming double curved parts requires large shear angles that lead to an increase of the in-plane shear stiffness and consequently frequent wrinkling. Nevertheless the onset and growth of wrinkles is a global phenomenon that depends on the set of all strains and stiffnesses. Especially blank holders can create tensions that avoid wrinkling even for large shear angles. Bending stiffness plays a main role in the shape of wrinkles. This rigidity must be taken into account in the simulations in order to verify that wrinkles do not extend to the useful part of the preform. This is not possible when the simulation is based on a membrane approach.
The quality of the wrinkle simulation depends on the mechanical properties that are taken into account. Some assumptions are made in the present work such as the independence of the in-plane shear and bending rigidities on the tension state. Similarly the twist term is neglected in bending stiffness. Some further experimental data on these points will be taken into account in the internal virtual work in order to improve the wrinkle simulations.

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