A SHELL APPROACH FOR TEXTILE COMPOSITE FORMING SIMULATIONS

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ABSTRACT

The basic assumptions of classical plate and shell theories are not verified by textile materials because of the slippage between fibers. However, simulations of reinforcement forming generally use shell finite elements. A shell approach is proposed for the forming of continuous fiber reinforcements. The large tensile stiffness leads to the quasi inextensibility in the fiber directions. The fiber bending stiffness determines the curvature of the reinforcement. The calculation of tensile and bending virtual works are based on the precise geometry of the single fiber. A simple way to consider friction between fibers is to take it into account in the flexion bending. Simulations and experiments are compared for different reinforcements. It is shown that the proposed fibrous shell approach not only correctly simulates the deflections but also the rotations of the through thickness material vectors. This is particularly interesting in the case of thick interlock reinforcements.

1 INTRODUCTION

The objective of this work is to propose a shell approach for continuous fibre reinforcements, which is consistent with the mechanical behavior of fibrous materials. This is not the case of classical shell theories. The considered reinforcement is composed of continuous fibers in the warp and weft directions. It can be UD, woven, NCF or interlock. The thickness of this reinforcement can be small or large. In the case of interlock reinforcements, it can reach several centimeters. Recent works have shown that the bending stiffness of fibrous reinforcements, although weak, plays an important role particularly in the wrinkle development simulation [1-3]. Consequently, the reinforcement is modeled by shell finite elements in most forming simulations. Given the fibrous nature of the reinforcement, some local slippage between fibers may occur. This makes the mechanical behavior very specific and different from those of a continuous material (such as metals). In particular the bending behavior is particular and must be decoupled from the tensile behavior. Moreover, the classical shell kinematics are not valid. The bending behavior is greatly modified by the possible slippage between fibers [4, 5]. The kinematics of deformation, in particular the rotations of the normal, are mainly driven by the quasi-inextensibility of fibers. The bending stiffness of fibers also plays an important role. The present work aims to propose a modeling of the deformation of fibrous reinforcements by a specific Ahmad shell element [6, 7]. This approach concerns both thin and thick reinforcements. In the latter case the kinematics of the deformation in the thickness is particularly interesting. Another objective is to provide a more computationally efficient alternative to the 3D finite element modellings that are used to simulate thick 3D reinforcement forming.

2 SHELL ELEMENT WITH CONTINUOUS FIBERS

The shell element is in the plane, but it represents the deformation of the 3D shell in plane strain. The fibrous shell element has two nodes. Fiber segments are crossing in the element. (Actually there can be thousands of fiber segments in the element). These fiber segments are initially straight in the element. \( \mathbf{V}_k \) is the unit material director defined at each node k, which is in the direction that joins the top and bottom edge of the shell element. Two assumptions are made for the specific plane shell element based on the bending experimental results:
• A straight line in material director direction remains straight after deformation but not necessarily perpendicular to the mid-surface.
• The element thickness in the direction of material director can be stretched, but the element thickness along the direction of the normal to the mid-surface \( n \) keeps constant since it is the summation of fiber’s thickness.

The position of point \( M (\zeta^1, \zeta^2) \) is decomposed into the position of associated point along mid-surface and the one along the material director direction \( \mathbf{V}_2 \) (see Fig. 1)

\[
x(M) = \bar{x}(H) + y(M)
\]

(1)

The interpolation within the element is given by Ahmad kinematics [7].

\[
x(\zeta^1, \zeta^2) = \sum_{k=1}^{2} N_k x^k + N_k \left( \frac{h_k \zeta^2}{2} \mathbf{V}_2^k \right)
\]

(2)

Where \( x^k \) is the position vector of node \( k \), \( h_k \) is the element thickness along \( \mathbf{V}_2^k \) (at node \( k \)). \( N_k \) are the interpolation functions.

![Fig. 1. Shell element made of fiber segments.](image)

To ensure that element thickness along the normal to the mid-surface keeps constant, the following constraint is imposed:

\[
h_k \mathbf{V}_2^k \cdot \mathbf{n} = h
\]

(3)

Where \( h \) is a constant that equals to the initial thickness, \( \mathbf{n} \) is the unit normal vector to the element mid-surface. Each fiber segment in the element is considered as an Euler-Bernoulli beam. It’s subjected to tensile and bending deformations. The internal virtual work in the element is separated into two parts: the tension and bending virtual works:
\[ \delta W_{int}^e = \sum_{j=1}^{n} \int_{L^j} T^{11j} \delta \varepsilon_{11j} \, dL + \sum_{j=1}^{n} \int_{L^j} M^{33j} \delta \chi_{33j} \, dL \]  

(4)

Where \( n \) is the total number of fiber segments in the element, \( T^{11} \) is the tension force, \( \delta \varepsilon_{11} \) is the virtual tensile strain in the fiber segment direction, \( f \) means the value of quantity in the fiber segment. \( M^{33} \) is the bending moment on the fiber segment, \( \delta \chi_{33} \) is the virtual curvature, and \( L^j \) is the length of fiber segment \( f \). Friction exists between fibers and would have an influence on the fibrous reinforcement mechanical behavior. Its consideration will be discussed in section 4 on different examples. It can be neglected in some cases. In other cases it can be taken into account in the bending term. The tension force \( T^{11} \) is related to tensile strain by a linear elastic law. The bending experiments such as presented in [8-10] give the bending moment as a function of the curvature.

\[ M^{33} = \Gamma (X_{33}) \]  

(5)

The incremental displacement \( \Delta u(M) = \dot{x}(M) - \ddot{x}(M) \) follows the Ahmad kinematics (Eq. 3),

\[ \Delta u(z^1, z^2) = \sum_{k=1}^{3} N_k \Delta u_k + N_k \frac{z^2}{2} (i^1 h^1 i^1 V^k_2 - i^2 h^2 V^k_2) \]  

(6)

Assuming that the rotations during the loading step are small enough [7],

\[ \Delta u(z^1, z^2) = \sum_{k=1}^{3} N_k \Delta u_k - \sum_{k=1}^{3} N_k \frac{z^2}{2} i^2 h^2 \Delta \alpha_k \hat{V}^k_1 \]  

(7)

Where \( \Delta \alpha_k \) is the incremental rotation of material director at node \( k \) around \( \hat{V}^k_1 \) and \( \hat{V}^k_2 \). \( \hat{V}^k_1 \) is an in-plane vector perpendicular to material direction \( V^k_2 \) (Fig. 1).

The fibrous shell element uses linear interpolation functions (\( C^0 \) continuous). Following the finite element kinematics, the fiber segment initially straight would remain straight after deformation. To enhance the approach, the fibers will be described by a curve. This is of great interest for both tension and bending modes of the fibrous material. This curve is determined using the method developed for rotation free shell elements [11-14]. This approach is based on the displacements of neighbor element nodes. This approach enhances the calculation of the curvature but also of the length of the fiber without increasing the number of degree of freedoms. A local curve \( w^j \) representing each fiber segment \( f \) after deformation is determined. The method considers one element and its two neighbor elements, i.e. a four points set \((1', 2', 3', 4')\) shown on Fig. 2.

![Diagram](image)

Fig. 2. Local curve \( w \) fitted on neighbor elements 2 and 3. (a) Global view. (b) Focus on one fiber with local rotation \( \theta \) of fibers.
Construction of the local curves \( w \) is made by fitting a third order polynomial curve on the four nodes set. The tensile internal nodal loads for a single element are:

\[
F_{\text{int}}^{\text{Ten}} = \sum_{f=1}^{n} \int \left( \mathbf{B}^{\text{Ten}} f \right)^T T^{11f} dL \tag{8}
\]

where \( \mathbf{B}^{\text{Ten}} \) is the tensile strain interpolation matrix:

\[
\delta \varepsilon_{11} = \mathbf{B}^{\text{Ten}} \delta \mathbf{u} \tag{9}
\]

\[
\delta \varepsilon_{11} = \frac{\delta l}{l_1} + \frac{1}{1 + \frac{1}{16} (\theta_1 + \theta_2)^2} \left[ \frac{1}{16} \theta_1 + \frac{1}{16} \theta_2 \right] \delta \theta_1 + \left[ \frac{1}{16} \theta_1 + \frac{1}{16} \theta_2 \right] \delta \theta_2 = \delta \varepsilon_{11}^{\text{1}} + \delta \varepsilon_{11}^{\text{2}} \tag{10}
\]

The tensile strain can be separated into two parts: a first term which represents the strain of linear segment obtained by interpolation, and a second part which can be interpreted as a correction term considering the curvature of fibers.

The virtual curvature gives the bending strain interpolation matrix \( \mathbf{B}^{\text{Ben}} \):

\[
\delta \chi_{33} = \left[ \frac{4}{l_1^2} - \frac{6 x}{l_1} \right] \left[ \frac{2}{l_1^2} - \frac{6 x}{l_1} \right] \delta \theta_1 + \left[ \frac{4}{l_1^2} - \frac{6 x}{l_1} \right] \left[ \frac{2}{l_1^2} - \frac{6 x}{l_1} \right] \delta \theta_2 = \delta \xi_{33}^{\text{1}} + \delta \xi_{33}^{\text{2}} \tag{11}
\]

Finally, elementary internal bending loads are written:

\[
F_{\text{int}}^{\text{Ben}} = \sum_{f=1}^{n} \int \left( \mathbf{B}^{\text{Ben}} f \right)^T M^{33f} dL \tag{12}
\]

The bending moment \( M^{33} \) is determined as a function of the curvature \( \chi_{33} \) from bending tests. Details on these calculations can be found in [15].

3 SIMULATION AND COMPARISONS WITH EXPERIMENTS

3.1 Bending test of a parallel fibers shell

One end of the specimen is clamped, and both horizontal and vertical displacements are imposed on the other (Fig. 3a). The deformation shapes from experiment and simulation are shown in Fig.3b and 3c. Midline shape comparison is shown in Figure 4a. They are almost coincident. Comparison for the material director orientations in experiment and simulation is presented in Fig 4b. They are close to each other. The thickness in the director vector direction also has been checked (Fig. 4c). They are in good agreement.

3.2 Bending test of a multilayer reinforcement

One end of the specimen is clamped, and both horizontal and vertical displacements are imposed on the other (Fig. 5). The deflection obtained in experiment and simulation are shown in Fig. 5b and 5c. Figure 6a gives the comparison of midlines. They are close. Fig. 6b presents the comparison of experiment and simulation for orientation of the material directors. They are in good agreement. The thickness in the material director direction also has been checked. Fig. 6c shows the comparison. An extension of thickness in the material director direction is observed and they are in good agreement with experiment results.
Fig. 3. Bending test on a parallel fiber shell: (a) Boundary conditions. (b) Experiment. (c) Simulation.

Fig. 4. Deformation shape of parallel fiber shell in bending test: Comparison of (a) the experiment and deflections simulation. (b) the angle between the material director and the horizontal direction, (c) the thickness in the material director direction.

Fig. 5 Complex bending test on a multilayer reinforcement, (b) Experiment (c) Simulation.
Fig. 6. Experimental-simulation comparison for a multilayer reinforcement in complex bending:
(a) deflection. (b) Orientation of the material directors. (c) Thickness in the material director direction.

4 CONCLUSIONS
A set of simulations have shown that the results obtained using the proposed shell approach are in good agreement with experiments. This is particularly interesting for thick interlock reinforcements. Their preform forming simulations can be performed with a limited number of degree of freedom.

Among the assumption of classical plate theory, only the assumption that the normals remain straight has been retained. The deformation of the reinforcement is obtained from the quasi-inextensibility of fiber and fiber bending stiffness. Friction between fibers can be taken into account in the bending stiffness. This is simple since it only needs to measure the bending stiffness of the reinforcement. This is physically justified because it is the friction that makes the reinforcement more rigid in bending than the sum of its constituent fibers.

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