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## **► To cite this version:**

Renzi Bai, Philippe Boisse, Biao Liang, N Naouar, Julien Colmars. A Shell Formulation for Textile Composite Forming Simulations. 23rd International Conference on Material Forming (ESAFORM 2020), May 2020, Cottbus (virtual ), Germany. <10.1016/j.promfg.2020.04.125>. <hal-03020216>

**HAL Id: hal-03020216**

**<https://hal.science/hal-03020216v1>**

Submitted on 23 Nov 2020

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23rd International Conference on Material Forming (ESAFORM 2020)

# A Shell Formulation for Textile Composite Forming Simulations

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## Abstract

The bending stiffness of fibrous reinforcements although weak plays an important role in the wrinkle development simulation, and the fibrous nature of continuous fiber textile reinforcement modifies their behavior especially the bending. The slippage between fibers and the quasi-inextensibility of fibers make the theory of Mindlin and Kirchhoff not verified during the bending process of multi-layer reinforcement. Therefore, a specific shell formulation is proposed in this article. This shell approach can not only determine the transverse slippage between layers but also the rotations of material director.

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Peer-review under responsibility of the scientific committee of the 23rd International Conference on Material Forming.

*Keywords:* Fabric; Finite Element; Forming

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## 1. Introduction

The fibrous reinforcements have been extensively applied in many industrial programs. However, the defaults and mechanical properties of fibrous composites after the forming process are mainly found and determined during the fabrication of product, this is costly. In order to avoid this procedure and optimize the forming process, the simulation of fiber reinforcement forming is necessary.

Numerical simulation can be developed in 3 different scales: Macroscopic[1,2], mesoscopic[3] and microscopic[4]. We mostly use model at macroscopic because some defaults like wrinkles and delamination could be observed in this scale. In these simulations, continuous materials often model the woven fibrous reinforcement; hence, most models are based on continuum mechanism. Meanwhile the bending properties are proved very important for the production of wrinkle. [5] Consequently, the reinforcement is modeled by shell finite element.

The classical shell elements are mainly developed by using Kirchhoff and Mindlin shell theory; these are not valid because the bending behavior is modified by the relative

slippages between fibers (Shown in section 2). This is different from continuous materials like metal. The 2D fibrous shell element will be introduced at section 3, and the result of simulation and experiments will be compared at section 4. In section 5, the shell approach will be extended to 3D.

## 2. Specific behavior of multilayer fabrics

In order to represent the bending behaviour of thick multilayer materials, some initially straight lines are drawn on the side of specimens. As shown below, we can easily find:

- At zone A, there is no rotation for the material director but the curvature at the same place is not zero. (According to Mindlin shell theory, the curvature is directly related to the first derivative of rotation angle of material director [6,7])
- At zone B, the thickness is stretched which is supposed to be constant in the classic assumption.
- The material director is clearly not perpendicular to the mid-line.

These differences between classical behaviour and our

experiment are produced by the slippage between layers, especially when the thickness is relatively large.

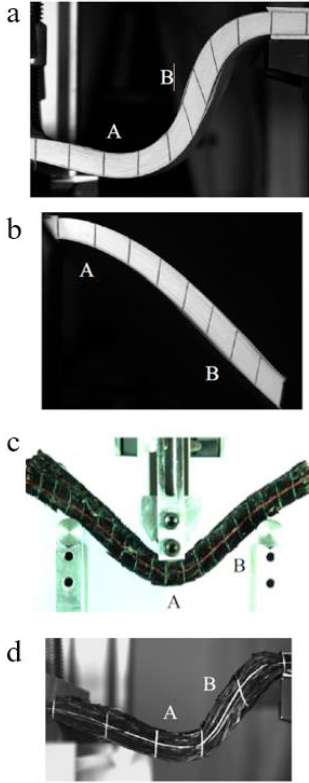


Fig. 1. Bending deformation experiments (a) Complex bending experiment for multilayer papers; (b) Cantilever test for multilayer papers; (c) 3 Points bending test for interlock; (d) Complex bending experiment for multilayer reinforcements).

As we can see in Fig.2. the existent element S4R used in Abaqus will lead to spurious numerical tension for fibers.

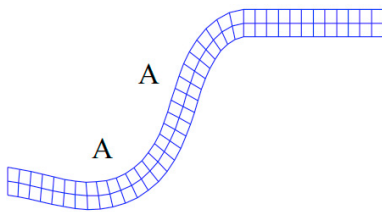


Fig. 2. Simulation with S4R shell element in Abaqus

Therefore, we have developed a new shell approach based on one important property of fibers: quasi-inextensibility of fiber. The local curvature will not be related to rotation of material director.

### 3. Shell element formulation in 2D

The framework of this element is the A-I-Z element. This framework can express the interpolation of geometry and

displacement field in an efficient way; five DOFs are proposed (three translations and two rotations) [8].

For the first step, the shell element is in the plane, but it can represents the 3D deformation when the deformation obey the in plane strain condition. Consequently, the DOFs will be modified to three with two translations and one rotation. This approach has been introduced at Ref. [1].

#### 3.1. Assumption

- 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  $\mathbf{n}$  keeps constant since the compression in this direction is neglected which is not significant during the bending deformation.

#### 3.2. Kinematic equation of 2D fibrous element

A natural coordinates  $\zeta^1, \zeta^2$  is defined in this element. The position vector for any points in this element is represented by the equation below:

$$\mathbf{x}(\zeta^1, \zeta^2) = \sum_{k=1}^2 N_k \mathbf{x}_k + N_k \sum_{k=1}^2 \left( \frac{\zeta^2 h_m^k}{2} \mathbf{v}_1^k \right) \quad (1)$$

$$N_1 = \frac{1}{2}(1 - \zeta^1), N_2 = \frac{1}{2}(1 + \zeta^1) \quad (2)$$

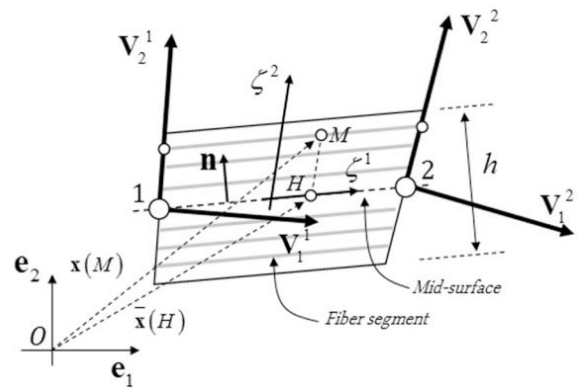


Fig. 3. Geometry of shell element

Because in 2D, we assume that the fibre directions are always correspond with our element's boundary that will be different at the 3D element. Therefore, the covariant vectors with respect to the natural coordinates  $\zeta^1$  will correspond with the fibre direction's director.

$$\mathbf{g}_1 = \frac{\partial \mathbf{x}}{\partial \zeta^1}, \mathbf{g}_2 = \frac{\partial \mathbf{x}}{\partial \zeta^2} \quad (3)$$

The kinematic equation is shown below:

$$\Delta \mathbf{u}(\zeta^1, \zeta^2) = \sum_{k=1}^2 N_k \Delta \mathbf{u}_k - \sum_{k=1}^2 N_k \frac{\zeta^2}{2} h_m^k \Delta \alpha_k^i \mathbf{V}_1^k \quad (4)$$

### 3.3. Bending Calculation

The fiber will be described as a curve. This method will optimize the description of bending and tension behavior; In order to find the curve function, the displacements of neighbor element nodes will be used which is introduced in many articles about rotation free element [9].

The fiber curve is developed separately for each layer:

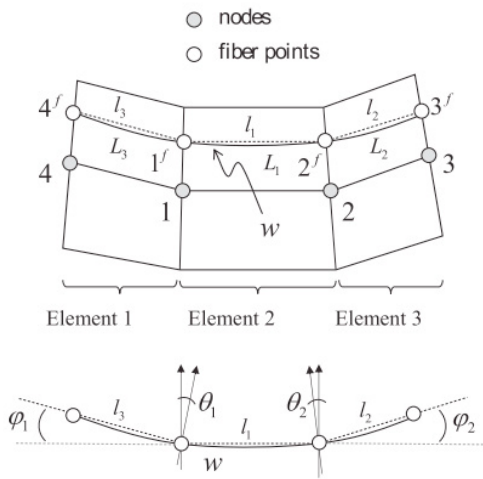


Fig. 4. Local curve created by neighbor elements

The curve function is in function of rotations of fiber points  $\theta_1, \theta_2$ . Rotations can be expressed as function of nodal displacement.

$$\Delta \theta = \mathbf{AGH} \Delta \mathbf{u} \quad (5)$$

$$w = x(1 - \frac{x}{l_1})^2 \theta_1 + \frac{x^2}{l_1} (\frac{x}{l_1} - 1) \theta_2 \quad (6)$$

Matrix **A**, **G**, **H** will be explained as the geometry matrixes. Matrix **A** can transform the angle  $\varphi_1, \varphi_2$  into  $\theta_1, \theta_2$ , matrix **G** can find the relation between  $\varphi_1, \varphi_2$  and displacements of fibre end points; matrix **H** can be obtained from the kinematic equation, which is used to transform the nodal points displacements into fibre end points displacement. The internal nodal force could be calculated:

$$F_{int}^{Ten} = \sum_{f=1}^n \int_{L^f} (\mathbf{B}^{Tensf})^T T^{11f} dL \quad (7)$$

$$F_{int}^{Ben} = \sum_{f=1}^n \int_{L^f} (\mathbf{B}^{Bensf})^T M^{11f} dL \quad (8)$$

## 4. Comparison between experiments and simulations

The bending experiment for 20 layer G986 is shown below; The simulation based on the proposed shell element correspond well with the experiment. The form of after the deformation correspond well, and Fig 5 presents the comparison of experiment and simulation for orientation of the material directors and thickness along the material director. They are in good agreement.

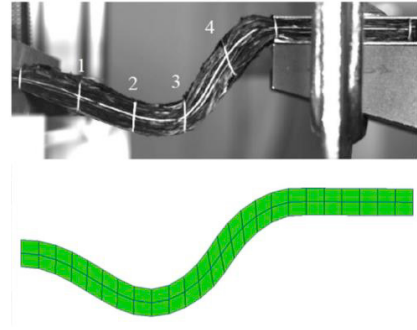


Fig. 5. Bending test for a multilayer reinforcement

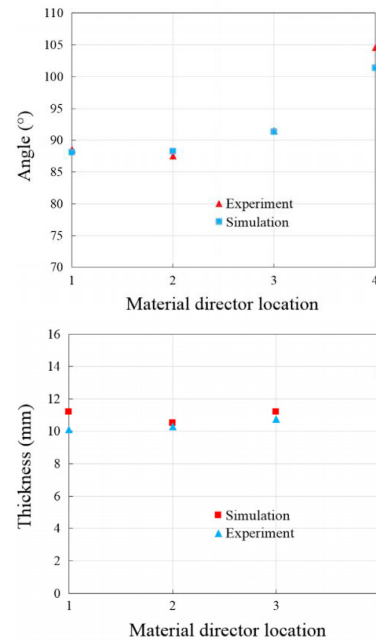
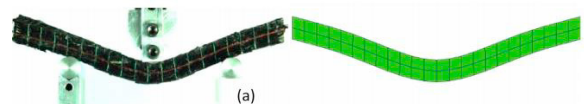


Fig. 6. Orientation of material directors and thickness in the material director direction

Figure.7 shows a 3 points bending test, which prove that this approach can simulate bending behavior for thick interlocks[10]; specially, this shell element can show correctly the deformation form of external parts of specimen.



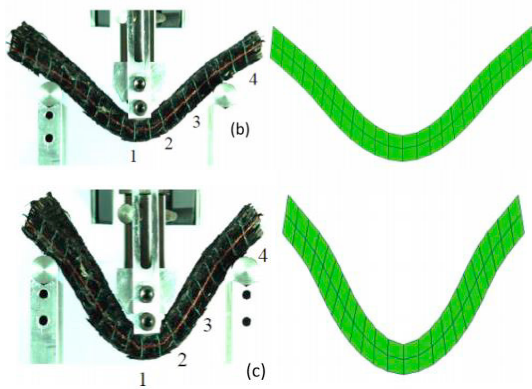


Fig. 7. 3 Points bending test on a thick interlock reinforcement

However, all these test are supposed to be a 2D condition, in the forming process, the slippage between layers will be an important factor that have influence on the quality of product [11].

In this 3D condition, there is not an efficient approach for thick multilayer material by taking into account the slippage. Specially, when the number of layers is large ( $>100$ ), the simulation by using semi-discrete element will be costly, and the contact between layers will be complex

## 5. 3D approach

### 5.1. The slippage during the forming experiment

The previous part has shown the 2D shell element who has a good performance for the simulation of bending behavior of multilayer materials. The next step aims to develop a 3D element who can not only achieve the modeling of 2D bending but also take into account the in-plan shear and finally realize the simulation of forming process for multilayer materials.

This research is do necessary, the slippage is observed during the 10 layers reinforcement forming process. Initially, the edge of these fabrics are at the same plan that is perpendicular to the blank holder plan, but after the deformation, the displacement for Top and bottom layer are obviously different. Shown in the image below. (The slippage have been also observed in [12])



Fig. 8. Forming process for multi-layer reinforcement

### 5.2. The strategy of development of 3D element

The element semi-discrete has been developed [2]. The method used in this element could be applied to our new approach, in which tension, bending and in-plan shear will be decoupled, similarly, the classical shell theory will not be used and the quasi-inextensibility of fiber will always be our fundamental assumption.

The rotation free method will be applied for the calculation of bending behavior that we called 'S3' [13], the difference is that in the thickness direction of element, it will be divided into several layers, therefore the 'rotation free' method is applied to fiber's points but not node.

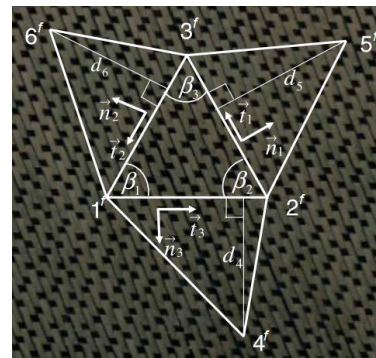


Fig. 9. Triangular fiber segment and its three neighbors

The orientation of fiber will not be obligatory to maintain the same direction of elements boundary, but in order to avoid the shear locking, aligning the mesh with the fiber directions is a better way [14]. The in-plan shear is a behavior not exist in the 2D, it has the influence on the prediction of the shape of the woven reinforcement during the forming [5, 15].

### 5.3. Difficulties

Some difficulties will be encountered, the choose of section points will modify the efficiency and the accuracy of this element; the study of the deformation behavior in the direction of thickness also has a certain discussion value. For example, in order to guarantee the quasi-inextensibility of fiber, the lobatto points is necessary because the dangerous position for this model is the top and bottom layer.

Besides, in 3D, new constitutive laws by taking into account the friction between layers need to be developed, like Liang's work [1], the equivalent bending stiffness will be larger than the one layer bending stiffness multiply the number of layer. In addition, the contact need to be taken into account, and for further research, the different orientation of fiber at different layer could be necessary.

## 6. Conclusion

A shell approach in 2D was introduced for fibrous reinforcement bending simulation. The classical shell theory are not verified by the bending experiment, because the deformation is mainly driven by the quasi-inextensibility of

fiber and fiber bending stiffness in which the friction between layers are taken into account.

Some comparisons between simulations and experiments are shown, they are in good agreement. A fewer number of elements in the thickness direction can realize the thick reinforcement simulation.

However, the 2D element cannot do the simulation of fabric forming process and meanwhile the in plane shear behavior cannot be represented. Therefore, the new 3D shell approach should be studied.

A 3D shell element is developing by our team; it aims to achieve the 3D forming simulation of thick multi-layer fabrics, finally the multilayer reinforcement with different orientation of fiber in each layer will be an interesting point for further research. The 3D A-I-Z shell element has been introduced in many articles, the framework could be applied, but whether the formulation need to be modified or not will be verified in our further research.

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