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Development of a new 3D beam element with section changes: The first step for large scale textile modelling

Sasa Gao, Biao Liang, Emmanuelle Vidal-Salle*

Université de Lyon, INSA-Lyon, LaMCoS UMR5259, F-69621, France

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ABSTRACT

The need of efficient modelling of textile materials at meso-scale increased considerably in the last decade. Several approaches have been proposed which present different kinds of drawbacks, the most important being their high computation time. The present paper aims to present a new tool for modelling textile materials using the yarn as constitutive element. Because fibre tows length is much higher than their transverse dimensions, beam elements seem to be the most convenient structural finite element tool. Unfortunately, classical beam theories assume that the cross section acts as a rigid which cannot describe the transverse compression and shape change of the yarn. In this paper, we present a new 3D beam element with the aim to achieve the results with section changes while breaking from classical beam hypothesis. Firstly, we start from 2D beam element with thickness change by adding a transverse strain component, which is inspired by previous works on the shell elements. Secondly, the formulation is extended to 3D beam elements, two transverse normal strain components are added with coupling so that full 3D constitutive law can be used. Finally, some numerical examples are presented using the new 3D beam elements which show that the results are exactly the same as those given by 3D elements in ABAQUS/Standard.

1. Introduction

Textile reinforcements are widely used in the composite industry. In order to save time (and money), it is of primary importance to reduce the time between the product idea and its delivery. To achieve this goal, it is necessary to have a good comprehension of the fabric behaviour. Composite materials are certainly the materials for which the interaction between design and process is the most important because each composite structural component is made of a unique material if one considers the reinforcement distribution (in terms of fibre orientation, fibre density…). Consequently, designing a composite structural part requires the knowledge of the mechanical behaviour of the dry reinforcement (which can be woven, knitted, braided). A large amount of studies have been developed to understand and model the fabric behaviour at micro- (fibre) or meso- (yarn) scale [1–9].

Those works have shown that if at the microscopic scale, some mechanical analyses have been performed in which each fibre is considered as a 3D beam interacting with its numerous neighbours [3], the very large number of fibres within a yarn results in large computation. For computational reasons, those modellings are generally limited to a small piece of fabric so that the whole composite part is generally modelled at higher scale considering the textile preform as a continuum [10–16]. These macroscopic simulations consider the deformation of a whole preform (in particular to simulate draping processes), but the internal woven structure of the fabric is not described. An intermediate way consists in developing models for yarns or tows, considered as continuous media, it is possible to build intermediate approaches to the behaviour of fabrics at a mesoscopic scale, considering the fabric as an assembly of interlacing tows (or yarns). Some approaches are available in the references concerning the modelling of fabrics at mesoscopic scale, considering the yarns as beams that bend according to the beam theory [17] or shell elements [20,21].

Using structural elements seems a good idea because of the geometry of the yarn, unfortunately, classical beam theories assume that the cross section acts as a rigid which cannot describe the transverse deformation of the yarn (i.e. transverse compression and shape change), which is essential to the yarn behaviour.

The objective of the present paper is to propose a new 3D beam element with section changes which can be used to model yarn at the mesoscopic scale and describe its transverse behaviour.

* Corresponding author. Tel: 33 472438146.
E-mail addresses: sasa.gao@insa-lyon.fr (S. Gao), biao.liang@insa-lyon.fr (B. Liang), emmanuelle.vidal-salle@insa-lyon.fr (E. Vidal-Salle).

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Inspired by previous works on enriched shell elements [22,23] where an additional node is introduced in the centre of three-node and four-node shell elements with two through-thickness translational degrees of freedom which makes it possible to extend plane stress state into full 3D elasticity. Using the same idea, a 2D beam element with thickness change is built by adding a central node with two degrees of freedom to an initially 2 nodes element.

After the validation of that first development step, the formulation is extended into three-dimensional, which takes the deformation of cross section into account. The main features of newly proposed 3D beam element are: each element has two end nodes which are treated by combining Saint-Venant and Timoshenko hypothesis [24–26]; the transverse strains of both thickness and width direction are introduced based on the additional central node. The transverse strain distributions are linear, and the formulations of displacement are completely quadratic by adding the terms coupling the deformation in both transverse directions; fully 3D constitutive stress/strain relations can be used directly.

Then, it is shown how the extra degrees of freedom act on beam elements and makes it a full 3D elasticity before a generalization either based on Euler-Bernoulli or Timoshenko assumptions. Finally a series of numerical examples are carried out using a FEM code for the new-proposed 3D beam element developed in Matlab, and the results are systematically compared with corresponding values of ABAQUS/Standard 3D simulations, which do not show any significant discrepancies. If this new 3D beam element is used to model the yarns, not only it can describe the transverse deformation of the yarn, but also can save lot of computation time, which can be of great importance for the process simulation during the preforming of dry reinforcement.

2. 2D beam element with thickness change

2.1. Inspired by shell enrichment

Classical shell elements based on the degenerated shell concept or classical shell theories generally include the assumption of a plane stress state and can handle analyses of shells satisfactorily. However, problems may arise when they are used to simulate sheet metal forming because the normal stress in the thickness direction is omitted. In order to solve this problem, several authors [22] have proposed a new approach with an additional node which is introduced with two through-thickness translational degrees of freedom. The method mainly consists of adding a central node at the centre of three-node and four-node shell elements with two degrees of freedom: two translations normal to the mid-surface for which one corresponds to the top surface ("upper skin" of the shell) and the other to the bottom surface ("lower skin" of the shell). Then full 3D constitutive stress/strain relations can be used. It shows how the extra degrees of freedom act on shell elements in bending cases while breaking from plane stress state hypothesis. Those extra degrees of freedom allow them to actualize the shell thickness during deep drawing applications, the main consequence being an improvement of the friction prediction. Such enrichment can be applied to other structural elements like beams.

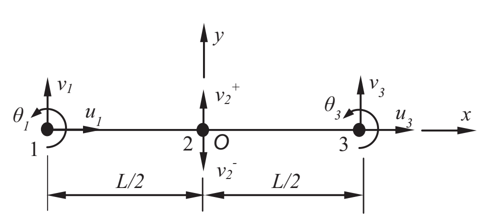

Fig. 1. Additional two degrees of freedom on Timoshenko beam element.

2.2. A new 2D beam element formulation

Classical beam elements are based on Euler–Bernoulli or Timoshenko assumptions, the problem is that the beam elements cannot describe the transverse deformation because the transverse stresses in both the thickness and width directions are omitted. So when it is used to model fabrics at mesoscopic scale, the transverse deformation of the yarn (i.e. its transverse compression and shape change) cannot be obtained. The objective of the present work is to propose a new approach to solve this problem. Based on the methodology of shell elements described previously, a 2D beam element is built with thickness change by introducing a central node with two degrees of freedom to an initially 2 nodes element. The two degrees of freedom correspond to the relative displacements of the top and bottom surfaces of a beam respectively which are dedicated to the transverse strain and make it into plane stress state so that calculating the thickness change is possible.

2.2.1. Geometry and kinematics

The geometrical description of the proposed 2D beam element is shown in Fig. 1. A single extra node (numbered 2) is added in the centre of a standard two nodes Timoshenko beam element for which nodes are numbered 1 and 3. This extra node has only two degrees of freedom: two relative translations normal to the centroidal axis through thickness respectively called v_2^+, v_2^- since they correspond to the normal relative displacements of the top surface ("upper skin" of the beam) and bottom surface ("lower skin" of the beam) facing the node 2. These values are defined latter.

Let u, v be the axial and transverse displacements of a beam respectively, and θ the rotation angle. Working in the global system with the original coordinates O $(0, 0)$, the displacements field for a point P of coordinates (x, y) can be obtained. As a result, the displacement field of the 2D beam element can be written as

$$\overrightarrow{u_P} = \begin{bmatrix} u(x) - \theta(x) \cdot y \\ v(x,y) \end{bmatrix}, \; x \in [-L/2, L/2] \tag{1}$$

For that beam element, length is noted as L ($x_1 = -L/2$, $x_2 = 0$, $x_3 = L/2$), thickness is h. In order to obtain a transverse strain $\varepsilon_{yy} = (\partial v / \partial y)$ linear in thickness direction, the function $v(x,y)$ should be quadratic with respect to y, so a quadratic polynomial is assumed for $v(x,y)$

$$v(x,y) = v(x,0) + b_0 y + c_0 y^2 \tag{2}$$

where, b_0 and c_0 are coefficients, which can be solved in terms of nodal variables corresponding to node 2; $v(x,0)$ is transverse displacement of the centroidal axis, the interpolating function will be introduced latter.

Denoting v_2^t and v_2^b the normal displacement of top and bottom surfaces facing node 2 respectively, and imposing $v(0,0) = (v_1 + v_3)/2$, $v_2^t = v(0, h/2)$, $v_2^b = v(0, -h/2)$, the quadratic form for $v(x,y)$ is

$$v(x,y) = v(x,0) + \frac{y}{h}\left(v_2^t - v_2^b\right) + \frac{2y^2}{h^2}\left(v_2^t + v_2^b - 2v(0,0)\right) \tag{3}$$

For node 2 ($x_2 = 0$), function $v(x,y)$ becomes

$$v(0,y) = \frac{1}{2}\left(1 - \frac{4y^2}{h^2}\right)(v_1 + v_3) + \frac{2y^2}{h^2}(v_2^t + v_2^b) + \frac{y}{h}(v_2^t - v_2^b) \tag{4}$$

Eq. (4) satisfies the characters of interpolating function and has the same form as the enrichment shell element in reference [22]. Knowing relative translations normal to the centroidal axis