Composites: Part A 81 (2016) 145–157

Contents lists available at ScienceDirect

Composites: Part A

journal homepage: www.elsevier.com/locate/compositesa

Modelling the forming mechanics of engineering fabrics using a mutually constrained pantographic beam and membrane mesh

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ARTICLE INFO

Article history:
Received 13 October 2015
Received in revised form 31 October 2015
Accepted 2 November 2015
Available online 11 November 2015

Keywords:
A. Fabrics/textiles
B. Mechanical properties
C. Finite element analysis (FEA)
D. Mechanical testing

ABSTRACT

A method of combining 1-d and 2-d structural finite elements to capture the fundamental mechanical properties of engineering fabrics subject to finite strains is introduced. A mutually constrained pantographic beam & membrane mesh is presented and simple homogenisation theory is developed to relate the macro-scale properties of the mesh to the properties of the elements within the mesh. The theory shows that each of the macro-scale properties of the mesh can be independently controlled. An investigation into the performance of the technique is conducted using tensile, cantilever bending and uniaxial bias extension shear simulations. The simulations are first used to verify the accuracy of the homogenisation theory and then used to demonstrate the ability of the modelling approach in accurately predicting the shear force, shear kinematics and out-of-plane wrinkling behaviour of engineering fabrics.

1. Introduction

The large deformation mechanics of biaxial engineering fabrics and viscous advanced composite prepregs are of considerable interest due to the importance of sheet forming processes for the manufacture of advanced composite products and structures. The success or failure in forming a given geometry and the properties of the final composite component are in large part determined by a material's large deformation mechanics and consequently, a significant amount of time and effort has been devoted to characterising and modelling these mechanics with the ultimate aim of predicting and optimising forming processes using virtual design technologies. Six fundamental mechanical properties dominate the deformation of engineering fabrics and advanced composites during forming:

- The tensile properties along the two fibre directions.
- The (trellis) shear resistance of the sheet.
- The out-of-plane flexural modulus of the sheet.
- The in-plane flexural modulus of the sheet.
- The transverse compressive modulus of the sheet.
- The integrity/cohesion of the sheet.

These properties, together with friction, and the boundary conditions applied during the forming process, determine how an engineering fabric or advanced composite will deform and will influence the generation of unwanted defects. Consequently, an important challenge is in accurately capturing these properties using a suitable combination of constitutive models and modelling techniques to conduct efficient and robust simulations. Equally important are the methods of measuring these properties for real materials; often a time consuming task that can be shortened using multi-scale predictive modelling approaches [1,2]. Generally speaking, the more realistic the modelling approach, the more accurate but computationally expensive the simulation, with longer simulation times reducing the modeller's ability to optimise the forming process. As a result, a compromise is usually made according to the required accuracy, the complexity of the part to be formed and the resources available for computational analysis.

As a first approximation the tensile modulus can be considered as infinite and all other stiffness's of the fabric can be considered negligible; a simplification used in kinematic mapping algorithms [3], allowing fast predictions of draping during forming operations. Nevertheless, accuracy of predictions can be improved by more comprehensive consideration of the forming mechanics. Numerous approaches to modelling biaxial engineering fabrics and viscous advanced composite prepregs during forming have been investigated. Use of continuum elements in modelling relatively thick 3-d fabrics is nowadays computationally tractable and can provide information such as compaction during forming, though long run-times still remain a limiting issue and the approach is less viable for thinner sheets [4]. Instead, constraints on computation speed usually lead to some degree of simplification in order to achieve practical simulation times. This tends to involve the use of

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http://dx.doi.org/10.1016/j.compositesa.2015.11.005
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structural finite elements including truss, beam, membrane, shell elements or some combination of these; each approach brings its own limitations and advantages.

Several viable approaches that ignore out-of-plane bending stiffness and focus on modelling just the tensile and in-plane shear properties of the material have been proposed. For example, use of truss elements to model both fibre and shear resistance allows short run times, though modelling friction with this approach is difficult and requires the use of pragmatic simplifications [5,6]. An alternative is to use membrane elements, here both tensile and shear contributions to the stress are implemented in the element's constitutive law [7–10]. Use of 2-d elements increases simulation times compared to use of 1-d truss elements but potentially allows the implementation of more accurate friction behaviour [11]. When employing 2-d structural elements, careful consideration of the co-ordinate system used to implement the constitutive law is required; the equations must be transformed to the appropriate reference frame used by the finite element code for update of stress and strain using objective derivatives [12,13]. In addition, alignment of mesh and fibre directions is often required to avoid spurious high stresses due to element locking [14] otherwise alternative solutions must be found [15,16]. Yet another approach has been to use 'mutually constrained' elements, using truss elements to represent the fibres and membrane elements to generate in-plane shear resistance [13,17–20]. Here fibre-mesh alignment issues are automatically avoided, though generation of custom meshes is required; a technique that precludes adaptive meshing during the simulation and which may make the application of symmetry conditions more difficult [21]. In all the modelling approaches discussed so far, the formulation of the elements in the mesh means that the elements are freely jointed at their shared nodes. As a result they possess no resistance to out-of-plane bending and compressive stresses can potentially lead to crumpling across the sheet, with the buckling wavelength usually determined by the length of the elements in the mesh. This crumpling can be used to predict the occurrence of in-plane micro-buckles during forming of real-cross ply thermoplastic laminates [20]. However, in practice, real preforms are able to resist a small amount of compressive stress that stabilises the sheet to some degree. From a pragmatic point of view, early prediction of wrinkles is not necessarily a significant problem and represents a worst-case scenario in predicting real wrinkles in the actual forming processes. However, extensive crumpling of the sheet can lead to excessive element distortion, early failure and lack of robustness of simulations; a more important issue in terms of automated virtual optimisation using the finite element method, e.g. [6,22]. One strategy to avoid this is to delete elements as soon as compressive stresses occur [6], another is to implement negligible compressive stiffness in the truss elements to allow fibre compression rather than buckling [13]. These methods can provide more robust simulations but may obscure some of the detailed predictions of defects, such as micro-buckles and wrinkles.

Introduction of out-of-plane bending stiffness can improve both the realism of wrinkle prediction and the robustness of finite element forming simulations. A simple approach to introducing bending stiffness is to use beam rather than truss elements. Ascough et al. [23] used a square mesh of beam elements to model the draping of clothing fabrics. The formulation of beam elements means that axial and out-of-plane bending stiffness were naturally modelled. Since the beam elements were not freely jointed at shared nodes this inevitably produced in-plane shearing resistance of the sheet due to bending moments between the two fibre directions; resistance unrelated to the fabric's actual shear compliance. Ben Boubaker et al. [24] overcame this issue by connecting the two sets of initially orthogonal beam elements using frictionless hinges. A similar approach was recently adopted in d'Agostino et al. [25], who modelled a pantographic lattice using beam elements. An alternative modelling strategy to introduce out-of-plane bending stiffness is to use shell elements rather than membrane elements [21,26–30]. This approach can produce realistic wrinkling predictions [30] though the shell element formulation requires significantly greater computation power; Yu et al. [31] reported a 3-fold increase in run time when comparing membrane and shell element-based forming simulations. In an approach designed to permit both trellis shearing and a limited amount of inter-tow sliding, Sidhu et al. [32] combined truss and shell elements; the two sets of tows (initially orientated in orthogonal directions) were indirectly connected via shared shell elements rather than directly with each other. Li et al. [33] also used mutually constrained truss and shell elements to conduct forming simulations; here the elements were directly connected using shared nodes. Later, truss elements were exchanged for beam elements and again the beam and shell elements shared the same nodes; realistic looking wrinkling and forming predictions were reported [34,35]. Combination of continuum and beam elements has also been reported in modelling thick 3-d interlock fabric sheets; beam elements were shown to enhance kinematic predictions in finite element simulations of out-of-plane bending tests [4].

In addition to axial, in-plane shear and out-of-plane bending stiffness, biaxial engineering fabrics and viscous advanced composites also possess an in-plane bending stiffness, with the tows providing resistance to abrupt spatial changes in fibre direction within the plane of the sheet. Relatively little work has been conducted in modelling this property, though awareness of its importance on accurate prediction of fibre direction during forming is growing e.g. [36]. Ferretti et al. [37] used second order continuum theory to predict the gradual rather than abrupt changes in fibre direction observed during actual bias extension tests; augmenting a hyperelastic energy potential to depend not just on strain but also on the strain gradient. d'Agostino et al. [25] demonstrated the effectiveness of a pantographic beam lattice in reproducing equivalent second-order gradient effects and simultaneously highlighted the limitations of first order continuum approach to modelling fabric mechanics.

The modelling approach used in the current investigation can perhaps best be described as a mutually constrained pantographic beam & membrane mesh. The novelty in the method lies in the manner in which elements are connected and the simple derivation of the homogenised properties of the mesh. The approach is relatively simple and intuitive, and allows independent control of: the axial stiffness along fibre directions, the in-plane shear compliance and both the out-of-plane and in-plane flexural moduli of the sheet. Evaluating the accuracy of a model prior to conducting complex forming simulations is very important for accurate predictions. To do this, methods of identifying the various parameters of the material model and to subsequently evaluate the associated predictions of the model should exist; this can be achieved through the use of simple characterisation tests to isolate the predictions of the model under different deformation modes. This point of view provides the motivation for the current paper and is especially important if additional mechanical properties such as in-plane bending stiffness are introduced in the model.

The structure of the remainder of this paper is as follows: in Section 2 the modelling approach is explained, describing the mutually constrained pantographic beam & membrane mesh in detail. In Section 2.1, simple homogenisation theory is presented, showing how the axial, out-of-plane and in-plane bending stiffness of the sheet are determined from the mesh density, modulus and cross-section of the beam elements (or vice versa). The relationship between average sheet density and the density of the elements in the mesh is also provided. Section 3 is an evaluation of the accuracy of the combined homogenisation/mutually constrained