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Implementation of a non-orthogonal constitutive model for the finite element simulation of textile composite draping

Robert S Pierce[1,a], Brian G Falzon[2,b], Mark C Thompson[1] and Romain Boman[3]

[1]Department of Mechanical and Aerospace Engineering, Monash University, Melbourne, Australia

[2]School of Mechanical and Aerospace Engineering, Queen's University, Belfast, UK

[3]Aerospace and Mechanical Engineering Department, University of Liege, Belgium

[a]robert.pierce@monash.edu, [b]b.falzon@qub.ac.uk

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Abstract. In the pursuit of producing high quality, low-cost composite aircraft structures, out-of-autoclave manufacturing processes for textile reinforcements are being simulated with increasing accuracy. This paper focuses on the continuum-based, finite element modelling of textile composites as they deform during the draping process. A non-orthogonal constitutive model tracks yarn orientations within a material subroutine developed for Abaqus/Explicit, resulting in the realistic determination of fabric shearing and material draw-in. Supplementary material characterisation was experimentally performed in order to define the tensile and non-linear shear behaviour accurately. The validity of the finite element model has been studied through comparison with similar research in the field and the experimental lay-up of carbon fibre textile reinforcement over a tool with double curvature geometry, showing good agreement.

Introduction

The aerospace industry has been increasingly using composite materials for large primary structures of commercial aircraft. However, the scale and complexity often means that these components are difficult and expensive to manufacture. Out-of-autoclave manufacturing techniques, with woven composite reinforcement, have received considerable attention in recent years as they have the potential of reducing manufacturing costs whilst still delivering high quality parts.

Liquid Composite Moulding (LCM) methods, which define the majority of out-of-autoclave approaches, typically rely on a dry reinforcement material being formed (or 'draped') to the desired geometry and subsequently infused with a liquid resin, which is then consolidated and cured. In the development of new components, operator skill and experience are essential throughout the mostly empirical process, which is costly and inefficient.

Instead, recent efforts have focussed on developing predictive tools to simulate the manufacture of complex composite components. Process modelling aims to reduce waste and improve efficiency. LCM processes are typically split into two separate stages for simulation: draping of the dry reinforcement material and resin infusion through the deformed material. This paper focuses on the simulation of draping woven composite reinforcement materials, as the first component of a complete process model.

As fabric materials are formed over complex geometries, the primary mechanism for deformation is a 'trellising' behaviour, where warp and weft yarns reorient themselves due to shear loading [1]. Since the two principal yarn directions exhibit a very high tensile strength and are able to rotate relative to one another under lower shear loads, it is particularly important to track these yarn orientations realistically.

A variety of drape modelling approaches have been developed in literature, ranging from simple kinematic methods, to highly detailed and sophisticated discrete numerical models. Geometric mapping, or 'fish-net', methods operate with simplicity and efficiency [2, 3] by representing fabric materials as a pin-jointed net that assumes yarns to be inextensible. However, they do not account for more complex material behaviour and may not successfully resolve intricate geometries. Alternatively, more realistic numerical models can be developed using continuum, discrete or semi-discrete approaches that have become popular as a result of increasing computational efficiency.

Homogenising the complex architecture of a fabric reinforcement to a continuous sheet of material is one common approach for successful draping. These continuum methods assume yarn slippage is negligible but incorporate in-plane material properties and track fibre directions realistically. In many cases they have demonstrated good agreement with experimental draping [4-6].

Other work has focussed on the discretisation of individual yarns or even fibres within a fabric reinforcement material. Though highly detailed, such discrete methods can be computationally expensive, and for many large scale applications they are still not feasible. These approaches rely on the definition of fibre or yarn properties, their arrangement and interactions, which can also be difficult to characterise. Several studies have shown promising results, but are still limited to smaller scales [7, 8].

Compromises between these two numerical methods result in what are typically termed ‘semi-discrete’ approaches. These complex methods typically represent a fabric material as a continuous sheet of specialised elements, each comprised of a discrete number of repeated unit cells. In some cases these models have been developed to include bending effects for better wrinkling characterisation [9, 10]. As with the other methods, these still neglect yarn slippage, however they do offer a relatively efficient and realistic model.

Draping model

For this research, a continuum-based draping model has been implemented, offering efficient and realistic results in addition to relative simplicity when compared with discrete and semi-discrete methods. A hypoelastic constitutive model was developed as a customised material subroutine within Abaqus/Explicit [11], similar to those in use by other researchers [4-6, 12]. Layers of fabric material are treated as continuous sheets of membrane elements, where the intricate effects of the underlying fabric architecture are incorporated as complex material behaviour in the VUMAT subroutine. This approach assumes the independence of yarn tensile properties from the fabric shear response, and is designed to include non-linear material properties defined through experimental characterisation. Yarn slippage is also neglected, as is common for draping simulations, though the output from modelling may help identify regions where slippage would occur. The strength of this continuum-based method is attributed to the realistic tracking of yarn directions within the VUMAT subroutine.

The model was developed within Abaqus/Explicit due to the high degree of geometric and material non-linearity expected in draping analyses, where implicit solvers often run into numerical difficulties. Specifically, the model operates with three-dimensional, four-node, M3D4R membrane elements. Though elements with reduced integration, such as these, can sometimes cause spurious modes of deformation in finite element analysis packages, Abaqus includes sophisticated ‘hourglass’ controls to monitor and restrict the effect of such problems.

Bending is neglected, though since the bending stiffness of fabrics is very weak (typically demonstrated in literature to influence only the nature of free wrinkling in fabrics [10]), it is sufficient for the model to simply predict the location and potential onset of wrinkling as a result of modelled shear deformation.

Material subroutine

The customised VUMAT subroutine has been written to describe the hypoelastic constitutive behaviour of dry textile reinforcement materials. It defines the constitutive model and implements a custom algorithm to track the non-orthogonal yarn orientations throughout deformation, based on the inbuilt orthogonal, planar strains and the deformation gradient tensor.

The hypoeastic theory is based on the work by Khan et al. [4] and earlier described by Peng et al. [12], though within Abaqus/Explicit, the physical behaviour of the material is tracked using the deformation gradient tensor, $\underline{\underline{\boldsymbol{F}}}$, and right stretch tensor, $\underline{\underline{\boldsymbol{U}}}$. Through the polar decomposition of the deformation gradient, the rotation tensor, $\underline{\underline{\boldsymbol{R}}}$, can be found, as seen in Eq. 1. This rotation is the average orthogonal rotation of the material axes and is based on the Green-Naghdi (GN) approach. Subsequently a set of, ever orthogonal, GN axes can be determined for the current configuration, $\underline{\boldsymbol{g}_{\alpha}}$, which can be simply related to the initial GN axes configuration, $\underline{\boldsymbol{g}_{\alpha}^{0}}$, with the rotation tensor (Eq. 2, where the index 'α' can take the values 1 or 2, signifying two independent directions).

$$\underline{\underline{\boldsymbol{R}}} = \underline{\underline{\boldsymbol{F}}}\,\underline{\underline{\boldsymbol{U}}}^{-1} \tag{1}$$

$$\underline{\boldsymbol{g}_{\alpha}} = \underline{\underline{\boldsymbol{R}}} \cdot \underline{\boldsymbol{g}_{\alpha}^{0}} \tag{2}$$

Next the current warp and weft fibre directions, $\underline{\boldsymbol{f}_{\alpha}}$, can be calculated from the initial fibre axes, $\underline{\boldsymbol{f}_{\alpha}^{0}}$, and deformation gradient (assuming that the fibre axes are initially aligned with the GN axes in the undeformed state):

$$\underline{\boldsymbol{f}_{\alpha}} = \frac{\underline{\underline{\boldsymbol{F}}} \cdot \underline{\boldsymbol{f}_{\alpha}^{0}}}{\left\| \underline{\underline{\boldsymbol{F}}} \cdot \underline{\boldsymbol{f}_{\alpha}^{0}} \right\|} = \frac{\underline{\underline{\boldsymbol{F}}} \cdot \underline{\boldsymbol{g}_{\alpha}^{0}}}{\left\| \underline{\underline{\boldsymbol{F}}} \cdot \underline{\boldsymbol{g}_{\alpha}^{0}} \right\|} \tag{3}$$

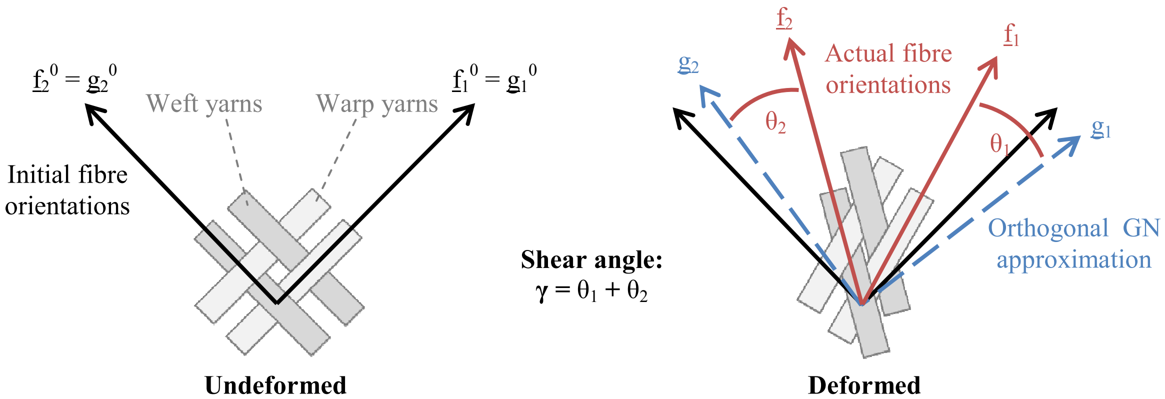

Fig. 1: Changes in the Green-Naghdi (GN) and fibre axes as a result of deformation.

Fig. 1 shows the physical representation of the GN and fibre reference frames before and after deformation, where the fibre directions are initially enforced to be aligned with the GN frame. During deformation these fibre directions need to be monitored so that the constitutive material properties can be defined in their true directions. The angles between the two independent fibre frames and the orthogonal GN axes can be determined from the sine and cosine definitions, and subsequently used to define the transformation matrices in Eq. 4. These matrices are used to convert stresses and strains between the native GN frame and the non-orthogonal fibre frames, as in Eq. 5 for the incremental strain tensor.

$$[\boldsymbol{T}_{\alpha}] = \begin{bmatrix} \cos\theta_{\alpha} & -\sin\theta_{\alpha} \\ \sin\theta_{\alpha} & \cos\theta_{\alpha} \end{bmatrix} \tag{4}$$

$$\left[\boldsymbol{d\varepsilon}^{f_{\alpha}}\right] = [\boldsymbol{T}_{\alpha}]^{T}[\boldsymbol{d\varepsilon}][\boldsymbol{T}_{\alpha}] \tag{5}$$

The constitutive law can be applied for each warp and weft fibre direction, $\left[\boldsymbol{C}^{f_{\alpha}}\right]$, and solved for incremental stress in the fibre frames, $\left[\boldsymbol{d\sigma}^{f_{\alpha}}\right]$:

$$[\boldsymbol{d\sigma^{f_\alpha}}] = [\boldsymbol{C^{f_\alpha}}][\boldsymbol{d\varepsilon^{f_\alpha}}] = [\boldsymbol{C^{f_\alpha}}]\begin{bmatrix} d\varepsilon_{11}^{f_\alpha} \\ d\varepsilon_{22}^{f_\alpha} \\ d\varepsilon_{12}^{f_\alpha} \end{bmatrix} = \begin{bmatrix} d\sigma_{11}^{f_\alpha} \\ d\sigma_{22}^{f_\alpha} \\ d\sigma_{12}^{f_\alpha} \end{bmatrix} \tag{6}$$

$$[\boldsymbol{C^{f_1}}] = \begin{bmatrix} E_1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & G_{12} \end{bmatrix}, \qquad [\boldsymbol{C^{f_2}}] = \begin{bmatrix} 0 & 0 & 0 \\ 0 & E_2 & 0 \\ 0 & 0 & G_{12} \end{bmatrix} \tag{7}$$

Here the tensile modulii in each of the fibre directions, E_1 and E_2, and the in-plane shear modulus, G_{12}, are the only values required in the definition of the constitutive tensor. The accuracy of this behaviour law therefore relies on the suitable characterisation of these values as non-linear relationships.

In order to calculate the new fibre stresses at the end of the current time increment, $\left[\boldsymbol{\sigma_{New}^{f_\alpha}}\right]$, a midpoint integration scheme is applied (Eq. 8), where the incremental fibre stresses are added to the fibre stresses from the previous increment, $\left[\boldsymbol{\sigma_{Old}^{f_\alpha}}\right]$. Then finally, the updated new fibre stresses must be converted back to the original GN frame, $[\boldsymbol{\sigma_{New}}]$, for Abaqus to continue the analysis successfully (Eq. 9).

$$\left[\boldsymbol{\sigma_{New}^{f_\alpha}}\right] = \left[\boldsymbol{\sigma_{Old}^{f_\alpha}}\right] + [\boldsymbol{d\sigma^{f_\alpha}}] \tag{8}$$

$$[\boldsymbol{\sigma_{New}}] = [\boldsymbol{T_1}]\left[\boldsymbol{\sigma_{New}^{f_1}}\right][\boldsymbol{T_1}]^T + [\boldsymbol{T_2}]\left[\boldsymbol{\sigma_{New}^{f_2}}\right][\boldsymbol{T_2}]^T \tag{9}$$

Material characterisation

In order to characterise the tensile and shear properties required for the draping model, experimental testing has been performed on an aerospace grade, carbon fibre plain weave material. The tensile strip method was employed according to the ASTM standard for fabric materials [13] in both warp and weft yarn directions. The material behaves non-linearly at first (during transverse yarn de-crimping), but quickly tends towards linearity, with an elastic modulus of around 15 GPa for both warp and weft orientations.

Shear testing of the same material was performed, in the absence of any standardised approaches, using the bias extension method in accordance with previous studies [14, 15]. The test operates similarly to typical tensile coupon testing, however samples are oriented in the fabric bias direction (45° from the two yarn directions). This generates three distinct regions of near-uniform shearing, as can be seen in Fig. 2, with the central diamond shaped region exhibiting a 'pure' shear state. In order to accurately determine the shear angles in this zone, and subsequently characterise the shear modulus, Digital Image Correlation (DIC) was used to track and measure the yarn orientations. A customised Matlab code was developed for this purpose and is freely available on the MathsWorks File Exchange website [16].

The resulting shear modulus reflects the non-linear material response, gaining exponential stiffness as the shear strain (shear angle) increases (Eq. 10). The validity of these material properties has been confirmed by running a bias extension simulation, as shown in Fig. 2, which shows good agreement with experimental results.

$$G_{12}(\gamma) = 0.008196e^{4.24\gamma} + 2.502 \times 10^{-10}e^{23.69\gamma} \tag{10}$$

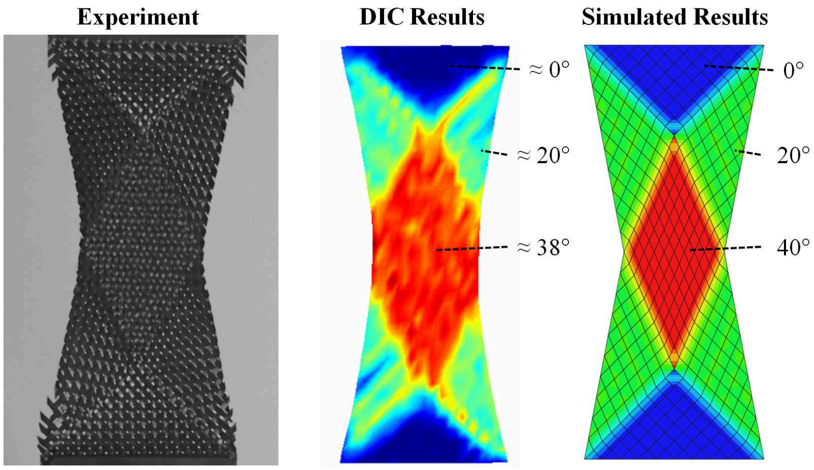

Fig. 2: Bias extension testing, DIC and simulated results at 15 mm extension.

Modelling example

The current draping model has been verified by comparison with several similar studies in literature [4-6], and it has been additionally applied to our own experimental hemi-ellipsoid case. As can be seen in Fig. 3, the model was able to realistically predict the deformed shape of the initially square fabric sample, particularly when compared to more basic orthogonal models. The draw-in profile of the modelled fabric closely resembles that of the experimental results due to the realistic, non-orthogonal, fibre tracking algorithm that is implemented in the material subroutine.

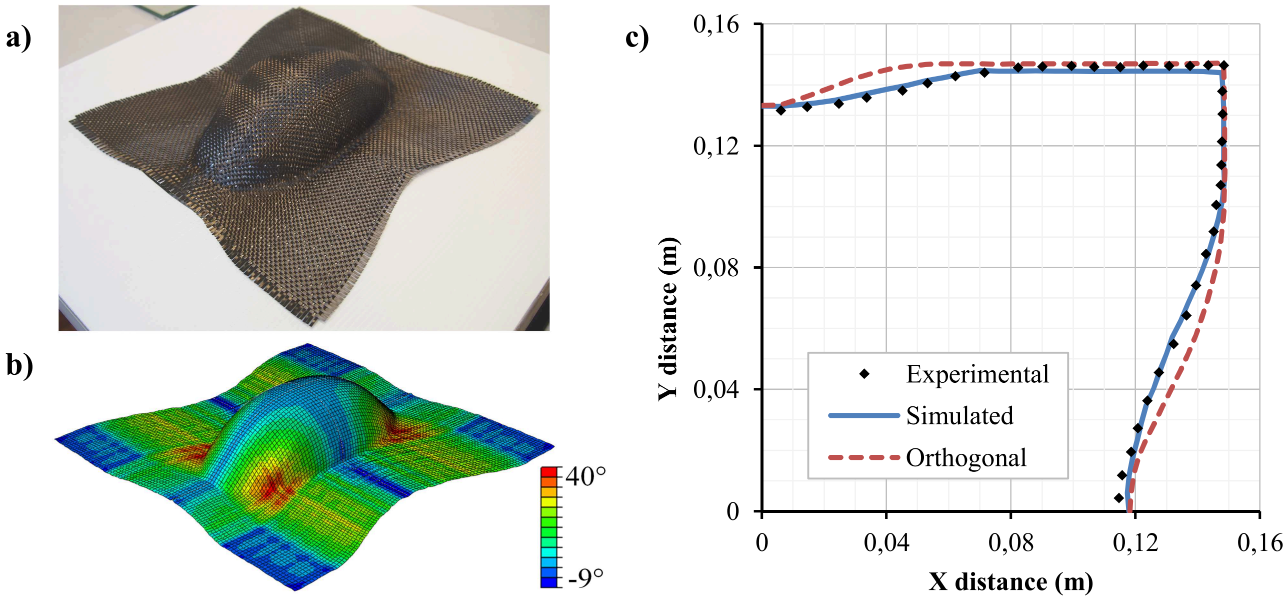

Fig. 3: Hemi-ellipsoid draping case: a) experimental lay up, b) the modeled shear angle results, and c) the material draw-in profile.

Conclusion

This study demonstrates the successful development and implementation of a realistic draping model that is able to predict textile reinforcement deformation. The continuum-based, finite element approach offers relative simplicity and efficiency, while the customised non-orthogonal material subroutine is able to track yarn orientations and only requires the definition of tensile and shear modulii. Characterisation of these properties was performed for an aerospace grade carbon fibre plain weave fabric, using a standardised uni-axial tensile test and the bias extension shear test. The latter was supplemented by an accurate DIC code developed in-house. The model was subsequently validated by comparison with existing test data and a new hemi-ellipsoid forming case.

This draping model represents the initial component of a complete process model that is under development. Further work is being undertaken to implement a coupled infusion model based on the relationship between shear deformation and permeability in textile reinforcements.

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Implementation of a Non-Orthogonal Constitutive Model for the Finite Element Simulation of Textile Composite Draping
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