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Numerical modelling of 3D woven preform deformations

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ABSTRACT

In order to accurately predict the performance of 3D woven composites, it is necessary that realistic textile geometry is considered, since failure typically initiates at regions of high deformation or resin pockets. This paper presents the development of a finite element model based on the multi-chain digital element technique, as applied to simulate weaving and compaction of an orthogonal 3D woven composite. The model was reduced to the scale of the unit cell facilitating high fidelity results combined with relatively fast analysis times. The results of these simulations are compared with micro computed tomography (CT) scans of a dry specimen of fabric subjected to in situ compaction. The model accurately depicted all of the key features of the fabric including yarn waviness and cross-sectional shapes as well as their development with compaction. A parametric study is presented to characterise the effect of the model inputs on the analysis speed and accuracy.

1. Introduction

Composite materials have many desirable properties, most notably excellent stiffness and strength combined with low mass. However, the key disadvantages of traditional 2D composites are that they require expensive, labour intensive manufacturing and are prone to delamination due to the lack of through thickness reinforcement. 3D woven composites can address both of these issues due to the addition of yarns, known as binders, which interlace through the fabric thickness. This means that near net shape preforms can be produced directly from the loom to form composites with greatly improved interlaminar properties. However, despite these advantages, 3D woven composites have been largely limited to niche applications. One of the key reasons for this is the lack of predictive numerical tools, which limits their ability to be used at the early stages of design.

The literature lists several models to predict the mechanical performance of these materials, with many using idealisation assumptions with respect to the fabric geometry, e.g. [1–4]. Such assumptions may include; warp and weft yarns are straight and yarns have a constant cross-sectional shape along length. In reality however, the textile architecture of a 3D woven fabric is very complex, often characterised by significant levels of both in-plane and out-of-plane waviness or crimp, as well as significant changes in cross-sectional shape due to yarn pinching. These characteristics play a significant role in determining the resulting composite performance, especially during damage and failure, where they can lead to strain hardening in tension [5] and kink-band formation in compression [6]. Also, cracks frequently initiate at low strain levels in resin rich regions which form around the binder yarns [7], sometimes even in as-manufactured specimens due to thermal stresses induced from curing [8]. Furthermore, compaction of an as-woven preform to an as-moulded composite causes additional deformations to the textile geometry. Mahadik et al. demonstrated the importance of this effect in an angle interlock 3D woven fabric where the amount of yarn waviness and size and shape of resin pockets varied significantly with the level of compaction [9].

Experimental imaging techniques such as optical microscopy and micro computed tomography (CT) can be used to characterise the internal mesoscopic architecture of textile composite materials. Zhou et al. [10] demonstrated a methodology involving segmentation and reconstruction for using this data to generate geometric models. The key difficulty in such a process is identification of yarn boundaries and Djukic et al. resorted to coating yarns prior to weaving in order to enhance contrast [11]. Any experimental-based method is non-predictive with significant cost and time requirements for each new textile and numerical models to predict fabric deformations have been the subject of considerable interest in recent years. Potluri et al. proposed a finite element (FE) model for fabric compaction consisting of solid continuum elements between rigid plates [12,13] considering geometric non-linearity and contact with friction. The yarns were assigned transversely isotropic material properties with a relatively low transverse modulus compared to fibre direction modulus and a linear material constitutive law. Lin et al. extended the method by applying a non-linear power law to link pressure and fibre volume fraction (VF) [14]. These models have the ability to consider the important

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effects of yarn compaction and bending, as well as friction. As such, they could be used to gain better understanding of the effect of these mechanisms in textile compaction. However, a key limitation is the use solid continuum elements since they do not truly represent the behaviour of a bundle of fibres in a real yarn. Moreover, the initial as-woven geometry used in these models was highly idealised, therefore placing a significant limitation on the accuracy of the final geometry.

The concept of a 'digital element' was introduced by Wang and Sun [15] whereby a yarn is discretised into a chain of 1D rod elements connected by frictionless pins. As the rod length falls towards zero, so does the flexural rigidity of the digital chain so that it possesses only tensile stiffness. In the original approach, the yarn cross-section was considered to be circular and rigid, however, the multi-chain digital element method presented by Zhou et al. [16] extended this method by considering each yarn to be an assembly of several digital chains. Whilst a woven fabric typically comprises of several thousand individual fibres per yarn, 19–69 chains per yarn were used in the study to achieve reasonable analysis times. Inter-yarn contact determined yarn trajectory and intra-yarn contact determined the geometry of the yarn cross-sections, allowing them to take any shape and vary along the yarn length.

Mahadik and Hallett [17] implemented a similar technique in the commercial FE code LS-DYNA, with the key difference being the use of beam elements without a pin connection at the nodes. The yarns therefore possess considerable flexural rigidity and so an elastic–plastic material property was used to assist flexural deformation. Work by Durville [18] described another multi-filament based technique, using an enriched beam element formulation which can account for planar deformations of the cross-sections and allow application of reduced second moment of area properties to prevent inducing a high bending stiffness.

A novel technique was developed by Pickett et al. [19] whereby an initial reference geometry with solid, non-interpenetrating, circular cross-section beams was generated alongside a 'pre-stressed' reference geometry with more realistic elliptical cross-sections attributed to the yarns. The 'initial metric method' in FE code PAM-CRASH was then used to deform the initial mesh towards the reference mesh whilst being bounded by moulding plates and preventing any yarn interpenetration. Stig and Hallström proposed a fundamentally similar technique involving the expansion of yarns, while utilising a slightly different modelling approach [20,21]. Here, the initial geometry was similar to that used by Pickett et al. but with yarn surfaces instead meshed with shell elements to form hollow tubes. These yarns were then inflated through the use of hydrostatic fluid elements under general contact conditions until the target yarn volume was achieved.

The work presented in this paper builds on the technique initially developed by Mahadik and Hallett for implementation in a commercial FE code. The model has been reduced to the unit cell scale which has allowed a significant increase in the level of model refinement alongside much reduced analysis times. A technique for applying periodic constraints has been developed since the boundaries of a dry fabric without a resin matrix need special treatment if the output is to give a periodic unit cell for further use in mechanical performance predictions. The modelling process considers not only the effect of weaving but also additional deformations due to compaction during moulding. The results are validated against detailed CT scans at increasing levels of fabric compaction where such additional deformations considerably affected the final fabric configuration. The technique has also been integrated with textile pre-processor TexGen [22] though the use of python scripting for automated model generation. Moreover, a thorough investigation of model input parameters is conducted and used to determine parameter values as well as characterise the effect of each parameter on model results. It is additionally demonstrated that the same parameters identified for the first orthogonal 3D woven fabric investigated can be applied to a different layer-to-layer 3D woven fabric with good results. The model could also be used in the design of 3D woven fabrics to predict the textile features of many different weave styles prior to committing to the time consuming process of setting up the loom for manufacture. This would give designers greater scope to exploit the wide range of textile architectures made possible with 3D weaving technology.

2. Modelling workflow

The workflow of the proposed modelling methodology is illustrated in Fig. 1. Details of steps 1–3 are outlined in the subsequent sections of this paper, while steps 4 and 5 list additional necessary steps required to generate FE models for mechanical performance analysis and are the subject of further publications [23,24]. The procedure is as follows:

1. An idealised unit cell model of the 3D woven fabric is generated in the textile geometry pre-processor TexGen (Fig. 1a).
2. A python script is used to read the TexGen file and generate and mesh a loosely woven LS-DYNA beam element model with each yarn represented by bundles of chains of beam elements (Fig. 1b). A further script is used to apply boundary conditions in the form of constraint equations.
3. The simulation is conducted, beginning with the loading of yarns to generate an as-woven fabric. Compaction to the target VF is then achieved using rigid plates to produce an as-moulded composite (Fig. 1c).
4. In order to complete the geometrical modelling process the model, consisting of chains of beams, must then be converted to a solid geometry (Fig. 1d). This is done with another user written python script to generate a realistic TexGen model [23].
5. From this model, a FE mesh can be produced (Fig. 1e) for mechanical performance analysis [24], or any other desired analysis for example, resin permeability.

3. Unit cells and boundary conditions

Efficient modelling is based on consideration of the smallest region possible which is representative of a larger structure. Fortunately, the nature of textile composites is that they exhibit a regular, periodic structure. Therefore, an infinite textile can be represented as assembled copies of a unit cell without rotation or reflection [25,26]. Analysis of a unit cell with the application of appropriate periodic boundary conditions has often been used in the mechanical analysis of 3D woven composites, e.g. [1,3,4]. One of the key drivers for the deformation modelling presented in this paper is to produce realistic geometry of a 3D textile to be used as an input for such models. However, previous deformation models have used fabric sizes much larger than the unit cell [17,18]. Compared to a unit cell model, this approach leads to increased analysis time and will place a limit on the level of fidelity that is achievable. Furthermore, without explicitly enforcing the periodicity of the boundary conditions, any edge effects and likely variation though the fabric will make selection of a unit cell, which must be unique and periodic, problematic.

The fabric considered in this study was an orthogonal 3D weave with two sets of binder yarns, each arranged in a 5 harness satin style. One set of these binder yarns float on the upper surface of the fabric while the other float on the bottom surface. This fabric