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Inter-ply stitching optimisation of highly drapeable multi-ply preforms

S. Chen, A. Endruweit, L.T. Harper *, N.A. Warrior

Polymer Composites Group, Division of Materials, Mechanics and Structures, Faculty of Engineering, The University of Nottingham, NG7 2RD, UK

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ABSTRACT

An efficient finite element model has been developed in Abaqus/Explicit to solve highly non-linear fabric forming problems, using a non-orthogonal constitutive relation and membrane elements to model bi-axial fabrics. 1D cable-spring elements have been defined to model localised inter-ply stitch-bonds, introduced to facilitate automated handling of multi-ply preforms. Forming simulation results indicate that stitch placement cannot be optimised intuitively to avoid forming defects. A genetic algorithm has been developed to optimise the stitch pattern, minimising shear deformation in multi-ply stitched preforms. The quality of the shear angle distribution has been assessed using a maximum value criterion (MAXVC) and a Weibull distribution quantile criterion (WBLQC). Both criteria are suitable for local stitch optimisation, producing acceptable solutions towards the global optimum. The convergence rate is higher for MAXVC, while WBLQC is more effective for finding a solution closer to the global optimum. The derived solutions show that optimised patterns of through-thickness stitches can improve the formability of multi-ply preforms compared with an unstitched reference case, as strain re-distribution homogenises the shear angles in each ply.

1. Introduction

For medium volume applications, composite components are frequently manufactured based on preforming of fibrous reinforcement structures, followed by impregnation with a thermoset resin. The challenge in introducing advanced preforming technologies is characterising and optimising the forming behaviour of 2D reinforcements in order to produce repeatable 3D components with acceptable quality, which is related to the level of shear deformation. In particular, wrinkling and fibre buckling are undesirable in a preformed reinforcement because of the influence on mechanical properties. Fixation of the fibrous structure through application of through-thickness stitch-bonds reduces in-mould assembly time and can aid robotic placement by enabling multi-layer stacks to be processed as one single preform. Previous research on reinforcement forming has generally addressed the simulation of components consisting of a single fabric ply [1,2], or preforms of multiple plies with identical orientation [3,4], where the difference in draw-in between plies and inter-ply friction is not as significant as in heterogeneous multi-ply preforms [5,6]. However, little work has been reported on forming of complex stacking patterns or multi-ply preforms containing localised stitch-bonds. The present work seeks to understand the opportunities offered by locally stitching multiple plies together to create a single preform blank which can be formed into a complex 3D shape.

One approach for simulation of multi-ply forming is to use multi-layered finite elements (FE), where one layer of elements represents multiple fabric layers, for more efficient simulation [6]. However, this method ignores relative sliding between plies, which is one of the main forming modes for multi-ply systems. In order to account for sliding, each ply needs to be modelled independently as a separate element layer. Cheruet et al. [7] modelled forming of a Z-shaped component consisting of 10 pre-impregnated plies and found that predicted relative inter-ply sliding agreed well with experimental data. Harrison et al. [8] conducted forming simulations for two cross plies (0°/90° UD) of thermoplastic prepreg, assuming a biaxial constitutive relationship. The viscous nature of the matrix material ensured that the main in-plane deformation mode was trellising (shear), similar to a woven material. However, when the fibres are dry, the deformation mechanism changes, and intra-ply sliding of loosely fixated yarns becomes more important, particularly for multi-ply forming of non-crimp fabrics (NCF) [9]. Experimental results show that NCFs experience high levels of slip within each layer of the bi-directional material, as the stitches provide less restraint than interweaving of warp- and weft-yarns. This phenomenon was captured in simulations by using bar elements to represent the stitch between UD plies modelled as shell elements. Good agreement was shown between numerical simulations and experimental results for forming of a hemisphere, but sliding was limited to the fibre direction, which may be an oversimplification for more complex geometries.

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* Corresponding author.

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Investigations into the influence of stitches have been generally limited to studying intra-ply stitches in NCFs [9] or single woven plies [3], to understand how they can be used to control local yarn angles. Molnar et al. [4] investigated the influence of inter-ply stitching experimentally. Local stitch-bonds were found to affect shear deformation in the formed fabric. It was concluded that it is possible to transfer shear forces into un-sheared regions of the ply during forming. Through-thickness stitching in multi-ply preforms has been simulated in explicit finite element analyses using spot weld constraints [3,10]. Whilst only multi-ply stacks with identical ply orientations were studied, for certain cases, redistribution of strains within the fabric through use of stitches was proven feasible to avoid wrinkling. Duhovic et al. [3] studied the force–displacement relationship for stitches in detail. It was found that stitches did not restrict the fabric shear behaviour when a strain offset was defined to account for slack in the thread during tensile loading, and was set to a value obtained from experiments. Bel et al. [11] investigated the influence of local stitch-bonds on preforming of commercial components, using beam spring elements to model the stitches in explicit FE studies.

Margossian et al. [12] found that the contribution of stitches to the in-plane mechanical properties of a ply is almost negligible compared to that of the yarns in the fabric. Assembly stitches behave as additional local inter-ply constraints, providing connecting forces to decrease the relative local inter-ply displacement. This effect becomes much more significant for adjacent plies with different initial fibre orientations, since the relative inter-ply displacement is greater under these circumstances. Since their in-plane influence can be ignored, each through-thickness stitch can be considered in isolation (in-plane stitch path can be overlooked).

Shear deformation in the fabric plies caused by the introduction of stitch bonds may negatively affect the properties of the finished component. A mathematical algorithm is required to determine optimised stitching patterns, to minimise local fabric shear. While there is no published work on the optimisation of inter-ply stitching, several suitable approaches have been identified from other optimisation problems. For optimisation based on large numbers of non-linear FE analyses, the enumeration approach is unsuitable, as the total computation time is unfeasibly long. Also, gradient/sensitivity-based search methods are inapplicable due to the lack of explicit relationships between the stitching patterns and the shear angle distribution. On the other hand, heuristic algorithms are an effective way to solve problems with large numbers of variables, and consequently genetic algorithms (GAs) have been chosen for this work.

This paper presents a finite element model developed to study the effect of local stitch-bonds in multi-ply preforms, particularly those with multiple ply orientations. Results from a numerical study of a simple hemisphere geometry demonstrate the capability of simulating the forming behaviour of a multi-ply stack in a single operation. A genetic algorithm has been developed to determine the optimum position of local stitches, in order to improve preform quality and ultimately facilitate automated component manufacture. Two different criteria have been implemented to assess the forming outcome; the maximum value criterion (MAXVC) and the Weibull distribution quantile criterion (WBLQC). The convergence rates and optimum solutions for both criteria have been compared to understand the compromise between accuracy and computational efficiency.

2. Modelling approach

2.1. Material model for non-orthogonal bi-axial materials

The proposed material model captures the dominant factors in fabric forming, including in-plane shear, fibre elongation and inter-tow/intra-ply slipping. A macro-scale homogenisation scheme has been adopted to avoid modelling discrete tows. The effects of parameters associated with the fibre architecture (yarn spacing, cross-sectional shape, crimp, etc.) are captured in the in-plane shear behaviour, which is defined by a non-linear stress–strain curve with a progressive hardening step. A hypo-elastic model [5,13] has been adopted to capture both material and geometric non-linearity due to large displacements and large rotations of the yarns [5,13,14]. Elastic models are typically used for forming simulations for simplicity, even though the fabric response during deformation is not necessarily elastic. However, deformation is arrested when the forming process is complete in order to conform to permanent deformation [15].

2.1.1. Implementation of material model

The material model is implemented in a user-defined subroutine in Abaqus/Explicit. A non-orthogonal fibre coordinate system, where the axes coincide with the current orientations of yarns at any material point, has been used. The non-orthogonal constitutive relation captures anisotropic behaviour of biaxial composite materials under large shear deformation more accurately than an orthogonal model [16,17]. A VFABRIC subroutine has been developed to define the mechanical constitutive relations of woven fabrics. The VFABRIC routine is valid for materials that exhibit two structural directions, which may not remain orthogonal following deformation.

The non-orthogonal material model is summarised in Fig. 1. The in-plane engineering strains at the beginning of each time increment in the explicit time integration scheme ($\varepsilon^{old}_{f_1}$, $\varepsilon^{old}_{f_2}$, γ^{old}_{12} i.e. $[\varepsilon]^{old}_{f_1 f_2}$) and the corresponding strain increments ($d\varepsilon_{f_1}$, $d\varepsilon_{f_2}$, $d\gamma_{12}$ i.e. $[d\varepsilon]_{f_1 f_2}$) are calculated internally. The raw material data are transformed to the current non-orthogonal fibre coordinate system. For each fibre direction in the non-orthogonal system, material properties ($[C]^{ort}_{f_1}$, $[C]^{ort}_{f_2}$) are defined in an orthogonal system, where one base vector is parallel to the fibre direction. For the fabric forming process, the shear deformation can be large, and the two yarn orientations may no longer be perpendicular to each other during forming. Material properties are transformed into the non-orthogonal fibre coordinate system ($[C]^{non\text{-}ort}_{f_1 f_2}$) using the current coordinate transformation matrix, [Q]. Finally, the initial stress tensor ($[\sigma]^{old}_{f_1 f_2}$) can be updated to be $[\sigma]^{new}_{f_1 f_2}$ by superimposing it with the stress increment tensor ($[d\sigma]_{f_1 f_2}$), which is calculated from the current constitutive matrix in the non-orthogonal fibre coordinate system. This is subsequently returned to Abaqus/Explicit for further processing.

Although material properties along the fibre directions (such as E_{11}) can be applied directly in VFABRIC, other properties (such as E_{12}) need to be transformed into the non-orthogonal fibre coordinate system (i.e. the system defined by the warp-fibre vector $\underline{f}_1$, the weft-fibre vector $\underline{f}_2$ and the out-of-plane vector $\underline{f}_3$) using the current coordinate transformation matrix. Only very minor modifications are required in VFABRIC to establish a non-orthogonal constitutive matrix compared with the more generalised VUMAT approach in Abaqus/Explicit. Implementing a VFABRIC routine

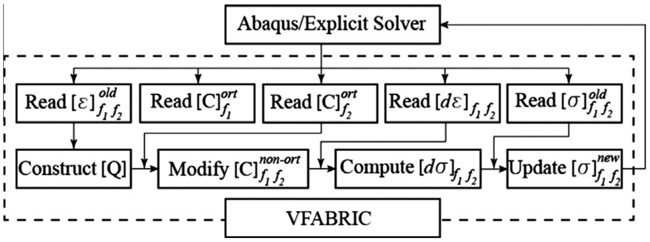

Fig. 1. Flow chart of user-defined VFABRIC material model.