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Defect formation during preforming of a bi-axial non-crimp fabric with a pillar stitch pattern

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ABSTRACT

To capture the asymmetrical shear behaviour of a bi-axial NCF with a pillar stitch, a non-orthogonal constitutive model was developed and implemented in finite element forming simulations. Preforming experiments indicate that the local distribution of defects is significantly different on both sides of each bi-axial ply, with two different defect mechanisms observed. Correlation with simulation results indicates that one defect type is caused by excessive shear, inducing out-of-plane wrinkling in regions of positive shear (macro-scale wrinkling). The other defect type is caused by fibre compression, inducing in-plane wrinkling in regions of negative shear (meso-scale wrinkling). Local distributions of shear angle and wrinkling strain were used to determine the wrinkling mode and to confirm the corresponding defect mechanism. Results indicate that simulations based on the advanced constitutive model can predict local shear angles within ±5° of experimental values and that predicted wrinkling positions and defect types correlate well with the experiments.

1. Introduction

Non-Crimp Fabrics (NCF) offer increased stiffness and strength over frequently used woven fibre architectures [1] as reinforcement in composite structures, but have been shown to be more difficult to form into 3D shapes [2]. Bi-axial NCFs are composed of two layers of aligned yarns, typically at 0°/90° or ±45°, which are bonded together by through-thickness stitches. The stitch pattern can be adapted to either prevent unwanted shear deformation during handling through improved stability, or improve drapeability through relaxation of in-plane constraints. In addition, multiple plies can be bonded together using local supplementary stitches to aid automated forming of complex lay-ups [3,4].

The dominant forming mechanism of bi-axial NCFs is in-plane shear deformation, similar to other bi-directional materials such as woven fabrics. However, the mechanisms of shear are different, as the mesoscopic architecture of an NCF is established by introducing intra-ply stitches rather than by interlacing the primary yarns. In addition to rotation of the primary yarns, tension in the in-plane segments of the intra-ply stitches contributes to the shear resistance of the NCF. Inter-yarn friction also provides some resistance to shear deformation during yarn rotation. The orientation of the in-plane segments of the stitches relative to the primary yarn direction can lead to asymmetric shear behaviour, which may make it difficult to avoid defects during forming [5]. Here, the terms positive and negative shear refer to in-plane segments of the stitch thread being in tension or compression, respectively [6], as shown in Fig. 1. The influence of the intra-ply stitches on the shear resistance can be significant (for ±45° fabrics with pillar stitches, which are aligned at 0°) under positive shear, as the shear resistance is dominated by the tensile properties of the stitch thread. The in-plane segments of the stitch are likely to fail at high tensile strains (induced by large shear angles), causing irreversible damage to the fabric and a reduction in the shear resistance [7]. In negative shear, NCFs tend to exhibit similar phenomena as woven fabrics when the in-plane segments of the stitch are loaded in compression [1] (Fig. 2). The shear stiffness is low, while the main source of shear resistance is friction between the primary yarns. This is followed by a rapid increase in shear stiffness with the onset of lateral yarn compression once the fabric locking angle is reached.

However, the fundamental difference in fabric architecture, caused by the inclusion of the stitch thread, means that the mechanisms for defect formation in NCFs are somewhat different to those in woven materials. In-plane fibre buckling [5] and out-of-plane fibre wrinkling [8] are the most common mechanisms, but fibre pull-out, stitch thread failure and inter-layer sliding have also been reported [9]. The change in fabric surface area during shear means that spaces between adjacent yarns decrease in size. Com-

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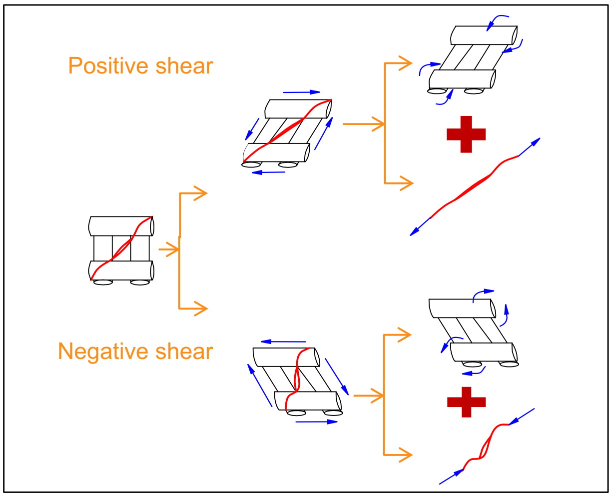

Fig. 1. Schematic showing the difference between positive and negative shear. In this example, the primary yarns are at 0°/90° and the in-plane segment of the stitching thread is at 45°. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

pressive stresses result in out-of-plane wrinkling [8] when lateral compaction is restricted once the shear exceeds the fabric locking angle. Most macro-scale ply wrinkles occur where large shear deformation occurs, but meso-scale bundle-level wrinkles (i.e. increase in yarn curvature between points of fixation through the stitch thread) have been reported in regions where the local shear angle was small [5].

Bias extension testing of NCF has shown that additional deformation mechanisms can also occur during fabric shear, such as fibre sliding [9,10]. Hemisphere forming tests indicate that fibre sliding leads to ply deterioration, where only one primary yarn direction may remain in some regions around the ply perimeter. The slip distance is dependent on the modulus and pre-tension of the stitching thread. If the modulus is high, the slip distance is negligible, and the NCF deformation resembles that of a woven fabric.

Few studies have been presented on the constitutive modelling of NCFs and their numerical forming simulation, despite their potential advantages in terms of manufacturing and performance over woven materials. Mesoscopic constitutive models are the most common [6,11], which are related to discretisation of the fabric at the unit cell level (fibre/yarn scale). However, sufficiently fine discretisation requires significant CPU resources, which is not practical for analysing industrial-scale components. Mesoscale models are therefore limited to simulating laboratory-scale processes such as forming hemispheres. Macroscopic NCF models consider the material as a continuum based on homogenisation of several unit cells. Yu et al. [12] adapted a non-orthogonal model originally developed for woven materials at the macroscale, which successfully captured the asymmetric shear behaviour of an NCF. However, no attempt was made to correlate the macroscale behaviour to mescoscale mechanisms, in order to identify the cause of defects.

Semi-discrete approaches have also been developed [9], where the two fibre layers are modelled separately with shell elements, and 1D beam elements are used to connect them to account for the influence of the stitch. Simulation of fibre slippage can be controlled by a Coulomb friction law with a sliding threshold. However, this approach is computationally expensive as it involves additional degrees of freedom and complex contact constraints. There is currently no universal approach for modelling the deformation of bi-axial NCFs. Differences in the meso-scale architecture can significantly influence the forming behaviour and therefore the choice of modelling route. For example, the shear behaviour of a bi-axial NCF using a pillar stitch with high stitch stiffness may be very similar to that of a woven material, and therefore a macro-scale continuum approach may be appropriate. On the other hand, a meso-scale approach may be required for an NCF using a tricot stitch in order to capture the high levels of fibre sliding which may occur for this type of fabric.

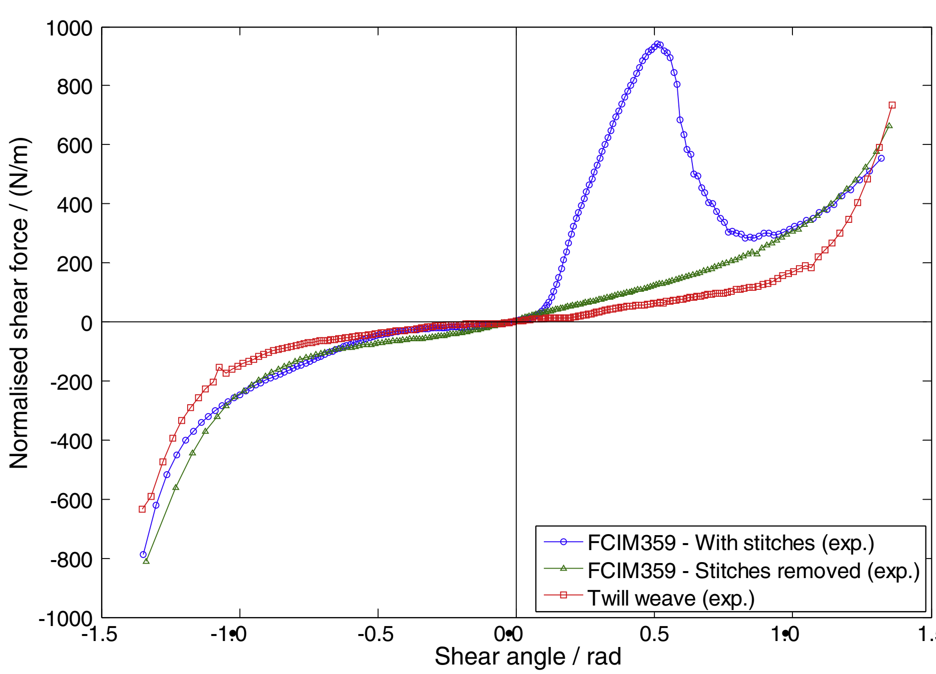

Fig. 2. Experimental picture frame shear results (average values) for FCIM359 bi-axial NCF. Testing was performed in two directions, placing the stitch yarn in tension (positive shear) and compression (negative shear). Stitches were fully removed in some samples. Results for a 400 gsm twill weave fabric are shown for comparison. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)