Composites: Part A 67 (2014) 131–139

Contents lists available at ScienceDirect

Composites: Part A

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

Review

Characterisation of the shear–tension coupling of carbon-fibre fabric under controlled membrane tensions for precise simulative predictions of industrial preforming processes

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ARTICLE INFO

Article history:
Received 3 March 2014
Received in revised form 27 August 2014
Accepted 29 August 2014
Available online 6 September 2014

Keywords:
A. Preform
A. Fabrics/textiles
D. Mechanical testing
E. Forming

ABSTRACT

A novel picture frame tester concept is introduced, allowing shear characterisation of reinforcement fabrics with both untensioned and defined membrane tension states. Reproducible preparation and handling routines are presented which kept fibre misalignments low and increased reproducibility significantly. Shear characterisations of woven fabrics are carried out with variance in magnitude, region and time of membrane tension initiation. The sensitivity of different woven fabrics to membrane tensioning is also investigated. It is found that the shear response of woven fabrics under membrane tensions is defined by the respective tension state on each axis due to the resulting normal friction forces at the crossing points. As initiated tensions on one axis are partially deflected to crossing yarns, complex tension states can be expected in the fabric. A nonlinear correlation of the global response and the initiated tension state can be observed, depending on the tension state and the woven fabric's architecture.

Contents

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http://dx.doi.org/10.1016/j.compositesa.2014.08.030
1359-835X/

1. Introduction

Present material models used for predicting the forming of textile reinforcements lack the reliability necessary for overcoming expensive experimental trials. Macroscale continuum models are widely used for the simulation of woven fabric forming [1–3]. However, effects occurring on the yarn level like gaps, fibre slippage, and fibre pull-out cannot be accurately predicted. Material tests – actual or virtual – are required as input. Mesoscale models allow the virtual testing of woven fabrics on the yarn level but their application is still challenging [4,5]. While these models are suitable for describing the forming of generic geometries like hemispheres, industrial part complexity (like small radii [6]) and process boundaries still lead to deviations from simulative calculations. Automotive composite parts particularly complicate the applicability of simulation tools because of the higher part complexity compared to aerospace structures. The underlying high volume manufacturing processes also differ from current aerospace processes and lead to process-induced effects on the textile material forming behaviour, which have to be included in simulative material models.

When punch and die processes are used for industrial preforming of reinforcement fabrics, blank holders [7–10], rollers [11] or tensioned clamps [12,13] can be deployed as defined boundaries, to suppress wrinkles and as a measure to control the material draw-in of the fabric. Additionally, when complex parts are formed, the fabric will be in gradual contact with the mould at different points. Due to the interaction of the fabric with both the blank holders and the contact points of the moulds, membrane stresses will be introduced to the plies throughout forming. The couplings of these membrane stresses to the forming mechanisms of fabrics are currently barely considered in material models.

On one side process and geometric boundaries induce membrane stresses in the fabric. On the other side woven fabrics undergo changes in their configuration especially by shearing. Due to the

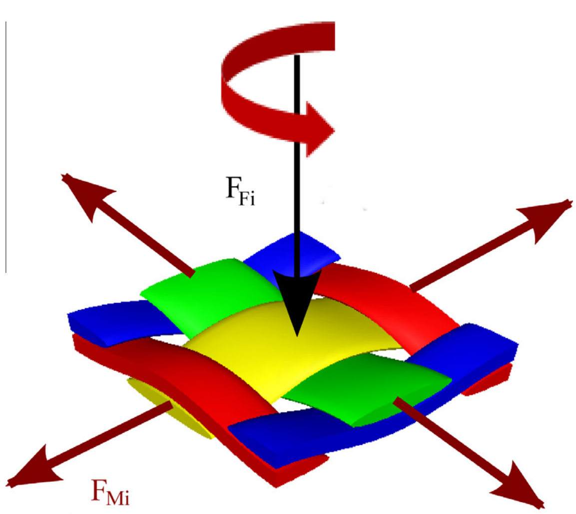

Fig. 1. Resulting friction forces F_{Fi} due to initiated membrane forces (F_{Mi}) in woven fabrics. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

interlacing of warp and weft yarns in woven fabrics, the initiation of membrane tensions will result in higher frictional forces at the crossing points (Fig. 1). The rotatory movement of the rovings determines the shear behaviour and is characterised by the friction interaction, which increases with higher normal forces.

Therefore, to model the material configuration properly and to gain a deeper material understanding, characterisations should not only be performed in the material's initial configuration but for all settings occurring during preforming. This paper aims at extending the existing experimental basis for further developments of material models and broadening experimental methods of shear characterisation, taking into account the changes in the fabrics configuration by shearing under the influence of process-induced membrane stresses.

2. Literature review

2.1. Forming mechanisms of woven reinforcements

Reinforcement fabrics differ in their forming modes [14] but have in common the high stiffness in the length direction of their rovings. Therefore, after an initial straightening and decrimping limited forming potential is given by *strain*. For fabrics, the out-of plane *bending* stiffness is significantly lower and decoupled from the in-plane stiffness. It is the only forming mode necessary for forming of single curvature geometries. Biaxial reinforcements like woven fabrics can undergo in-plane *shear deformation* in double curved areas and are accordingly appropriate for the forming of complex geometries as they allow a local change in the fabric's unit cell configuration. *Fibre slippage* will occur when axial tensile forces on the roving exceed frictional forces to the neighbouring rovings locally. In the final stage of press forming the fabric is compressed. For multilayer preforming *compaction* influences the fibre volume fraction and the laminate's mechanical properties after impregnation.

2.2. Shear characterisation: picture frame and bias extension tests

As shearing is the major forming mechanism for forming of double curved geometries with woven fabrics it has been the most intensively studied forming behaviour. Nevertheless, no standard for characterisation of shearing for textile reinforcements could be derived yet. Two methods to describe the intra-ply shearing behaviour are widely used: picture frame (e.g., [15–18]) and bias extension (e.g., [17–20]) tests, both showing benefits and disadvantages [21,22]. For picture frame tests a cross shaped test sample is mounted on a square frame hinged in the corners. The picture frame is extended subsequently on a tensile testing machine. Shear force vs. shear angle curves can be calculated from the force–displacement curves. Rectangular specimens are used for the bias extension test, which are directly extended by a tensile testing machine with an angle of 45° between the load and tow directions (Fig. 2).

As no standard for shear characterisation of woven reinforcements exists yet, a benchmark study [18] was carried out by seven research institutions to compare both evaluation methods and the results obtained from different picture frame testers. Normalisation