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Characterisation of the draping behaviour of unidirectional non-crimp fabrics (UD-NCF)

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ABSTRACT

Thin composites shell structures manufactured from stitched unidirectional non-crimp fabrics (UD-NCF) in a liquid composite moulding process provides high lightweight design capabilities. However, draping behaviour of UD-NCF has been investigated only sparsely, in contrast to research on woven fabrics or biaxial non-crimp fabrics. Hence, this contribution focuses on fundamental investigations of the draping behaviour of UD-NCF. Within this investigation picture frame tests and uniaxial bias extension tests are performed to examine the in-plane shear behaviour of UD-NCF. Furthermore, a new method is presented to examine ambivalent tensile behaviour of UD-NCF transverse to the carbon fibre roving orientation. In particular, the influence of thin glass fibres on transverse tensile behaviour of UF-NCFs is investigated using a new clamping mechanism in tensile testing. Finally, hemisphere tests are performed to observe the forming behaviour of UD-NCF in a realistic forming process and to evaluate the proposed material characterisation methods regarding its suitability for UD-NCFs.

1. Introduction

Manufacturing of thin composites shell structures from stitched unidirectional non-crimp fabrics (UD-NCF) in a liquid composite moulding process provides high lightweight design performance. UD-NCFs enable manufacturing of load-tailored structures because the fibre orientation of each layer can be chosen independently from the fibre orientation of other layers. This is contrary to composite shell structures manufactured from biaxial fabrics where two differently oriented layers are linked within one ply by weaving or stitching. For such biaxial engineering textiles like woven fabrics or biaxial NCF, the draping behaviour as well as characterisation methods are well known. The draping behaviour of these textiles is mostly affected by in-plane shear and bending characteristics. In contrast to UD-NCFs, woven and biaxial fabrics are subject of a large number of publications. Therefore, only selected publications are quoted and discussed in the following.

To characterise the shear deformation behaviour of woven or non-crimped fabrics, picture frame tests [1–9] or uniaxial bias extension tests [10,1,5,6,11–14] are commonly used. For balanced woven fabrics, where fibres are approximately "pin-joint", picture frame tests and bias extension tests provide comparable results [10,1,6]. Fibres of biaxial NCF, on the other hand, are not "pin-joint" and, hence, can slide at each other at the junctions of one biaxial NCF ply. This sliding occurs when biaxial NCFs are deformed in a bias extension test [11,14], whereas pure fibre rotation and, thus, pure shear is enforced in a picture frame test [2]. Biaxial tensile tests have shown that tensile behaviour of woven fabrics is nonlinear and depends on the strain ratio at biaxial loading [15,16,7]. For biaxial NCF no nonlinearities in tensile behaviour and no dependencies on biaxial strain ratio can be found due to sewing of fibres [2]. To complete the characterisation of the draping behaviour of textiles, frictional behaviour (ply–ply-friction and tool–ply-friction) and bending behaviour have to be investigated [17–21] and [19,22–24], respectively. However, the investigations presented here do not focus on these two deformation effects.

In addition to material characterisation tests, hemisphere tests are often used to examine the draping behaviour under combined loads and more realistic forming conditions [11,14,25–29]. Daniel et al. [27] and Boisse [28] use hemisphere tests to demonstrate the forming behaviour of a very unbalanced fabric. Furthermore, hemisphere tests have been conducted for biaxial NCF to verify relative sliding between individual layers and to validated new draping simulation models [11,14,29]. Additionally to hemispheres, other generic parts are used to study the draping behaviour of

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woven fabrics or biaxial NCF like a tetrahedral shape [30,31] or a generic helicopter side frame [32].

Although UD-NCF provides high lightweight design performance, in contrast to research on woven and biaxial fabrics, the draping behaviour of UD-NCF is investigated only sparsely [33,12,13,21]. Böhler et al. [33] investigate forming limits of UD-NCF by conducting experimental draping studies at a geometry of a truncated pyramid. They find in-plane wrinkling and formation of gaps between individual carbon fibre tows as significant forming defects of UD-NCF. Furthermore, they classify the deformation modes of UD-NCF in fibre slip, fibre compaction and fibre shear. However, results of fundamental textile characterisation tests are not presented and interaction between forming defects and deformation modes is not discussed. One further open question is the difference between fibre slip and fibre shear. Härtel et al. [12] present a new test rig that enables investigation of textiles forming behaviour under various combinations of in-plane and out-of-plane loads including investigation of in-plane fibre slip of UD-NCF. By comparing results of fibre slip tests and bias extension tests, they found that the force level in fibre slip tests is clearly higher than the force level in bias extension tests. However, interaction between fibre slip and fibre shear is again not discussed in this paper. In [13] normalization methods for uniaxial bias extension tests are evaluated for different classes of engineering textiles including UD-NCF. Due to fibre slip in UD-NCF, the theoretically calculated shear angle deviates from the shear angle measured via optical analysis. However, detailed measurements of strain components within textile's deformation are not presented. In [21] the uniaxial bending behaviour of UD-NCF is investigated in fibre and in transverse fibre direction with the main outcome that bending stiffness of UD-NCF is strongly anisotropic: Whereas bending stiffness in fibre direction is comparable to bending stiffness of biaxial fabrics, bending stiffness in transverse fibre direction hardly exits.

To manufacture complex structures with UD-NCF and to simulate the draping process reliably, the draping behaviour of UD-NCF has to be investigated fundamentally and appropriate methods to characterise the draping behaviour are required. Consequently, this work evaluates existing standard material testing methods in terms of their capability to characterise the draping behaviour and discusses the draping behaviour of UD-NCFs regarding the well-known draping behaviour of woven fabrics. The correlations between the applied material characterisation methods, the observed basic deformation modes and the resulting deformation defects are investigated. Initially, in-plane shear and in-plane tensile behaviour is investigated. Based on the observed results, a new test method to characterise the tensile behaviour in transverse fibre direction is presented. Finally, hemisphere tests are performed to correlate the measured material properties with real forming behaviour of UD-NCF on double curved geometries.

2. Materials

To investigate the draping behaviour of stitched UD-NCF, a unidirectional NCF from SGL Group with the labelling SGL "HPT-320-C0" is used (see Fig. 1a). Within UD-NCF, thin glass fibres that are oriented perpendicularly to the carbon fibres are stitched with carbon fibres via polyethylene (PE) fibre stitching. The stitching in this fabric is done by knitting. The function of the glass fibres is only to ensure the structural cohesion of the UD-NCF in manufacturing. The total area weight of "HPT-320-C0" UD-NCF is 320 g/m^2 whereas the area weight of carbon fibres is 300 g/m^2. The carbon fibres tow width is 5 mm and its yarn count is 3300 tex. The area weight of the stitching thread is 7 g/m^2 and the area weight of the glass fibres is 13 g/m^2. The yarn count of the glass fibre tows is 68 tex. To compare picture frame test results of UD-NCF with results of a woven fabric, Hexcel's "HexForce® PrimeTex™ 48331 C 1500" balanced plain weave is used (see Fig. 1b). The area weight of "HexForce® PrimeTex™ 48331 C 1500" is 330 g/m^2 and the tow width is 4 mm.

3. Experimental setups and test procedures

For all material characterisation tests described in the following, a Zwick universal testing machine with a Xforce 2.5 kN load cell, provided by Institute for Applied Materials at KIT, is used. Crosshead displacement velocity for all material characterisation tests is 100 mm/min.

3.1. Picture frame test

A picture frame or trellis frame is an apparatus to measure shear characteristics of textiles [1–9] (see Fig. 2). Textiles are clamped in the frame with fibres being aligned parallel to the arms of the frame. To minimize friction forces induced by the picture frame itself, needle bearings are used in this frame's joints. A thin rubber-layer on the clamps allows for alignment of initially

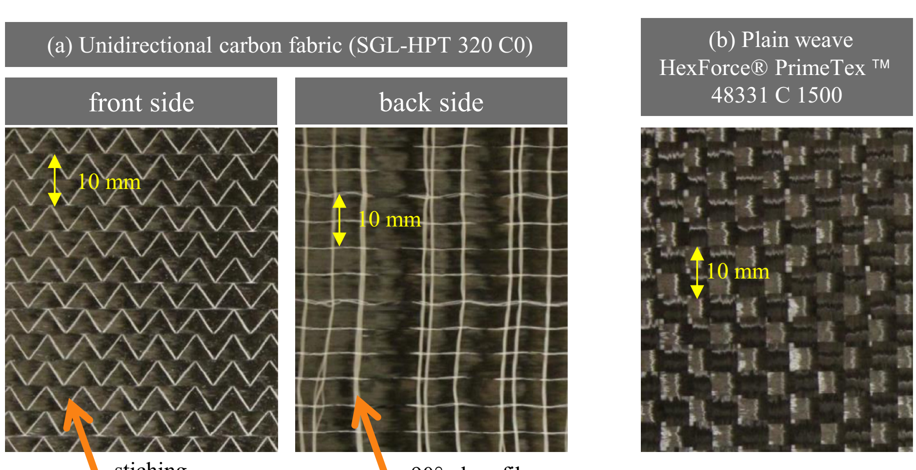

Fig. 1. (a) SGL HPT-320-C0 unidirectional non-crimp carbon fabric; (b) Hexcel "HexForce® PrimeTex™ 48331 C 1500" balanced plain weave. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)