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Deformability of a non-crimp 3D orthogonal weave E-glass composite reinforcement

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ABSTRACT

Deformability of a single-ply E-glass non-crimp 3D orthogonal woven reinforcement (commercialized under trademark 3WEAVE® by 3Tex Inc.) is experimentally investigated. The study is focused on the understanding and measurement of the main deformation modes, tension and in plane shear, which are involved during draping of composite reinforcements by: (i) uniaxial and biaxial tension; (ii) in-plane shear investigation using uniaxial bias extension and picture frame tests; and (iii) measurements of the fabric thickness variation during shear. The test methods common for 2D fabrics are validated for the thick 3D reinforcement. The obtained results represent a data set for the simulation of a forming process with the 3D reinforcement.

1. Introduction

In any composite manufacturing process a crucial step is the forming of the initial planar reinforcement into a desired (three-dimensional) shape. After shaping, the formed reinforcement is injected with resin and consolidated. In this process, the deformability of the reinforcement plays a key role in definition of the fiber orientations, which influences permeability of the preform and finally defines the mechanical quality of a composite component. Therefore, the knowledge of deformation behavior of a dry composite reinforcement is important to predict and avoid defects (e.g. wrinkling) in complex preform shapes.

Focusing on continuous fiber materials, many investigations available in the literature [1,2] are mainly dedicated to the deformability of textile reinforcements with 2D interlacements, these being adapt for producing three-dimensional shapes.

In spite of the fast growing interest for 3D orthogonal interlock woven reinforcements in the composites industry for a broad range of applications [3], the deformation properties of these reinforcements are not deeply known and investigated. Recently, Boisse et al. [4–6] have reported experimental data and modeling of deformability of a specific type of angle interlock carbon fabrics for fan blades applications. The authors are not aware of similar studies for orthogonal 3D woven reinforcements. Their behavior, due to a specific geometry of Z-binding and extreme straightness of the stuffing warp and weft yarns [7,8], is quite different from the tight heavily interlaced angle interlock weaves [9].

In this work, the deformation resistance of a dry single-ply E-glass non-crimp 3D orthogonal woven reinforcement is experimentally investigated. The deformation during extension is investigated under uniaxial and biaxial loading in the in-plane tows directions (i.e. warp and weft). The biaxial tensile tests provide information on the initial nonlinear stiffening due to the low crimp in the tows. The effect of different velocity rate ratios is also investigated.

Particular attention is dedicated to the behavior during shear loading because this is considered the primary deformation mechanism in the reinforcement shaping [10]. The mechanisms occurring when the material is subjected to in-plane shear is studied by two different tests, namely uniaxial bias extension and picture frame. The non-linear responses of the material to both tests are compared in terms of macroscopic shear force vs. shear angle. The shear deformation is observed and measured at the macroscale, by means of digital image correlation technique.

Furthermore, picture frame tests with laser thickness registration were performed in order to estimate the fabric thickness variation (directly connected to fiber volume fraction) due to in-plane shear loading and therefore during draping processes.

The obtained results constitute a data set for the simulation of forming processes with such 3D reinforcement.

2. Material

The fabric is a single-ply E-glass non-crimp 3D orthogonal woven reinforcement (commercialized under trademark 3WEAVE® by 3Tex Inc.). The fiber architecture of the preform has three warp and four weft layers, interlaced by through thickness (Z-directional)

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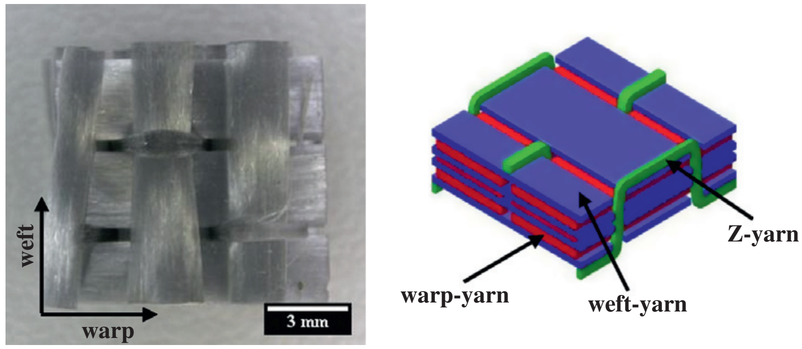

Fig. 1. Architecture of the tows inside the non-crimp 3D orthogonal weave preform [11]: photo (left) and schematics (right) of the unit cell.

yarns (Fig. 1 [11]). The fabric construction results in ~49%/~49%/~2% ratio of the fiber amounts (by volume) in the warp, weft and Z fiber directions, respectively. The same 3D glass reinforcement was adopted in the composite experimentally investigated in [11–13]. A detailed description of the 3-D orthogonal weaving production process is presented in [14,15]. The fiber material is PPG Hybon 2022 E-glass. Some features of the non-crimp 3D orthogonal weave reinforcement are listed in Table 1. The reader is referred to [8] for detailed description of the preform architecture, studied with optical microscopy and micro-CT.

3. Experimental methodologies and devices

Biaxial tensile tests at different velocity ratios at two axis were performed to gather information on the initial non-linear stiffening due to the low crimp in the tows; while uniaxial bias extension and picture frame tests were carried out to experimentally determine the in-plane shear behavior of the non-crimp 3D orthogonal weave preform. During testing, images were recorded by a digital camera for image correlation analysis by Vic-2D software (LIMESS system, Correlated Solutions Inc.). For this purpose the specimen surface was speckled with black and white acrylic paint for strain components measurements with digital image correlation systems [16]. The procedure followed for image analysis is detailed in [17].

3.1. Biaxial tension tests

Biaxial tension tests were performed on cruciform specimens of the fabric (according to the geometry depicted in Fig. 2a), using a biaxial testing machine equipped with two independent orthogonal axes Fig. 2b (see details in [18,19]). Velocity of the two loading axes was set in the range 1–3 mm/min to have different warp to weft velocities ratios (k = warp velocity/weft velocity). It should be underlined that the velocity ratio (imposed by the device) does not coincide to the strain ratio in the center of a specimen under biaxial loading. Four load cells of 2.5 kN were used to measure the force applied to each side of the specimen. Glass fiber-epoxy tabs 2 mm thick, 60 mm wide and 30 mm long, were glued at the ends of the cross arms. During testing, a digital camera acquired frames at a frequency of 1 Hz for image post-processing. The biaxial tension test set up is illustrated in Fig. 2b. The same device has been adopted for uniaxial tensile tests. Rectangular specimens have been used whose geometry is that of an arm of the cruciform specimen (350 × 60 mm) (Fig. 2a).

3.2. In-plane shear behavior

Two tests are generally performed for in-plane shear characterization of engineering fabrics, named uniaxial bias extension and picture frame test (see e.g. [1,2,20]). Bias test provides an excellent method of estimating a material's locking angle, i.e. the angle at which intra-ply and/or out-of-plane bending (wrinkling) become significant deformation mechanisms [21,22]. Unlike bias test, picture frame requires particular attention to avoid errors resulting from its boundary conditions: sample misalignment may produce large forces due to tensile strain along the fiber directions [23], while yarn pretensions increase significantly the shear stiffness of the fabric [22]. Most of the studies concerning shear testing of fabrics [20–22,24–29] include normalization procedures for the bias force, based on the energy approach proposed by Harrison et al. in [27]. The aim of normalization procedures is to obtain the intrinsic shear behavior of fabrics, in order to allow a comparison between bias extension and picture frame results.

In the present work, uniaxial bias extension and picture frame tests are compared using the normalization procedures detailed in [22,25] and [20,29], respectively.

During both shear tests a digital camera acquired frames at a frequency of 1 Hz, for image post-processing and measurement of the local shear angle. The local shear angle measurement follows the procedure detailed [29], i.e. it is based on the coordinates of the corners of the facets (initially square), virtually imposed on the textile surface, extracted on each image by the software Vic-2D.

3.2.1. Uniaxial bias extension test

Uniaxial bias extension tests involve rectangular specimen of material such that the warp and weft directions of the tows are orientated initially at ±45° to the direction of the applied tension load. The specimen is characterized by the free length/width ratio ($\lambda = L_o/w_o$), where the total free length (L_o) must be at least twice the width (w_o), in order to guarantee a pure shear zone in the center of the specimen (see theoretical and observed specimen deformation in Fig. 3). It has been shown in [28] that the in-plane shear angle in region A (see Fig. 3) can be assumed to be twice that in region B, while region C remains undeformed assuming yarns being inextensible and no slip occurs in the sample [25]. Therefore, the deformation in region A can be considered equivalent to the deformation produced by the pure shear of a picture frame test. When the length/width ratio (λ) of the bias extension specimen is at least 2, the shear angle in region A (see Fig. 3b) should obey Eq. (1), as long as deformation mechanisms, such as intra-ply slip, are insignificant compared with trellis shearing [30]. Eq. (1) can be derived by a kinematic analysis of bias extension sample (see Fig. 3a). It correlates the shear angle (γ) to the fabric geometry and the end displacement (d).

$$\gamma = \frac{\pi}{2} - 2\cos^{-1}\left(\frac{D+d}{D\sqrt{2}}\right) \tag{1}$$

The normalization technique for a bias extension test can be obtained following the four basic assumptions: (a) shear angles in each zone are considered uniform; (b) the shear angle in zone