A NON-CRIMP 3D ORTHOGONAL WEAVE E-GLASS COMPOSITE REINFORCEMENT: DEFORMABILITY PROPERTIES

V. Carvelli[1]*, J. Pazmino[1], S.V. Lomov[2], I. Verpoest[2]

[1] *Department of Structural Engineering, Politecnico di Milano, Italy*
[2] *Department of Metallurgy and Materials Engineering, K. U. Leuven, Belgium*
* *Corresponding author (valter.carvelli@polimi.it)*

Keywords: 3D composite reinforcement, Deformability, Mechanical properties

Abstract
The deformability of a single layer E-glass non-crimp 3D orthogonal woven reinforcement (commercialized under trademark 3WEAVE® by 3Tex Inc.) are 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) biaxial tension and (ii) in-plane shear.

1. Introduction

In any composite manufacturing process a crucial step is the forming of the initial planar reinforcement into a desired three-dimensional shape. In this and in the injection phase, the deformability of the reinforcement plays a key role in the fiber orientations and has relevant influence on the permeability and finally on the mechanical quality of a composite component. Therefore, the knowledge of deformation mechanisms of a composite reinforcement is very important to avoid defects in complex preform shapes.
Many investigations available in the literature [1] are mainly dedicated to the deformability of textile reinforcements with 2D interlacements. In spite of the fast growing interest for 3D interlock woven reinforcements in the composites industry, for a broad range of applications [2], the deformability properties of these reinforcements are not deeply known and investigated.
In this paper, the deformability of a single layer 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. Biaxial tension and in-plane shear, using uniaxial bias extension and picture frame tests, have been performed.
The obtained results represent a data set for the simulation of a forming process with such 3D reinforcement.

2. Material

The fabric is a single layer 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) yarns (Figure 1 [3]). 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 [3]. The textile preform is produced by means 3-D orthogonal weaving technology in 3Tex Inc. [4]. The fibre material is PPG Hybon 2022 E-glass. Some features of the non-crimp 3D orthogonal weave reinforcement are listed in Table 1.

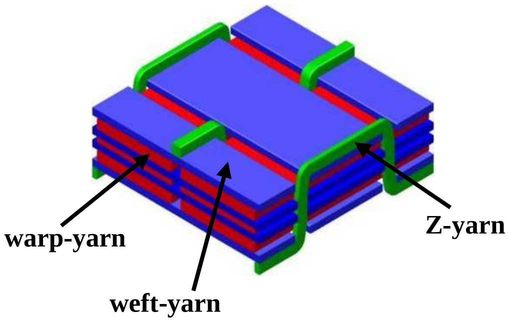


Figure 1. Architecture of the tows inside the non-crimp 3D orthogonal weave preform [3].

	Fabric plies	1
	Areal density [g/m^2]	3255
Warp	**Insertion density [ends/cm]**	2.76
	Top and bottom layer yarns [tex]	2275
	Middle layer yarns [tex]	1100
Weft	**Insertion density [ends/cm]**	2.64
	Yarns [tex]	1470
Z-yarns	**Insertion density [ends/cm]**	2.76
	Yarns [tex]	1800

Table 1. Properties of the non-crimp 3D orthogonal weave preform [3].

3. Experimental details

Biaxial tensile tests at different velocity ratios 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 behaviour of the non-crimp 3D orthogonal weave preform. During testing, digital image correlation technique (Vic-2D software - LIMESS system, Correlated Solutions Inc.) has been used to measure strain components.

3.1. Biaxial tension tests

Cruciform specimens of 145 mm and 60 mm length and width of the arms, respectively, have been adopted. The biaxial testing machine is equipped with two independent orthogonal axes. Along each direction the load is applied by a pair of beams that can translate parallel to the edges of the specimen that is placed in the centre of the device. During the movement, the two cross-bars of each loading axis are always equidistant from the centre of the device (Figure 2). The clamping system consists of a hinge on each specimen sides to have the alignment of the loads to the axes of the cruciform specimen.

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). Four load cells of 2.5 kN were used to measure the force applied to each side of the specimen.

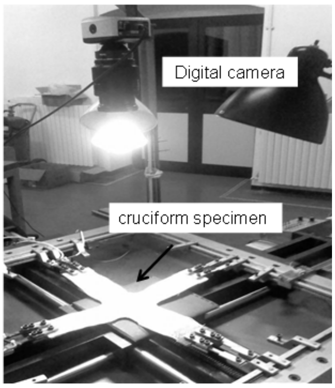
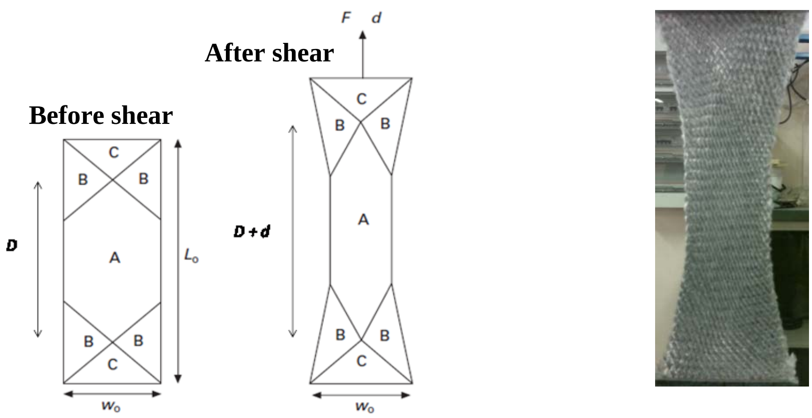


Figure 2. Biaxial tension test set-up.

3.2. In plane shear behaviour

Two tests have been performed for in-plane shear characterization, i.e. uniaxial bias extension and picture frame test. Most of the studies concerning shear testing of fabrics use normalization procedures of the bias force, based on the energy approach proposed by Harrison et al. in [5]. The aim of normalization procedures is to obtain the intrinsic shear behaviour of fabrics, 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 [6] and [7], respectively.
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 has free length/width ratio ($\lambda = L_o/w_o$), such that the total free length (L_o) is at least twice the width (w_o), in order to guarantee a pure shear zone in the centre of the specimen (see theoretical and observed deformation in Figure 3). It has been shown in [8] that the in-plane shear angle in region A (see Figure 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. Therefore, the deformation in region A can be considered equivalent to the deformation produced by the pure shear of a picture frame test.



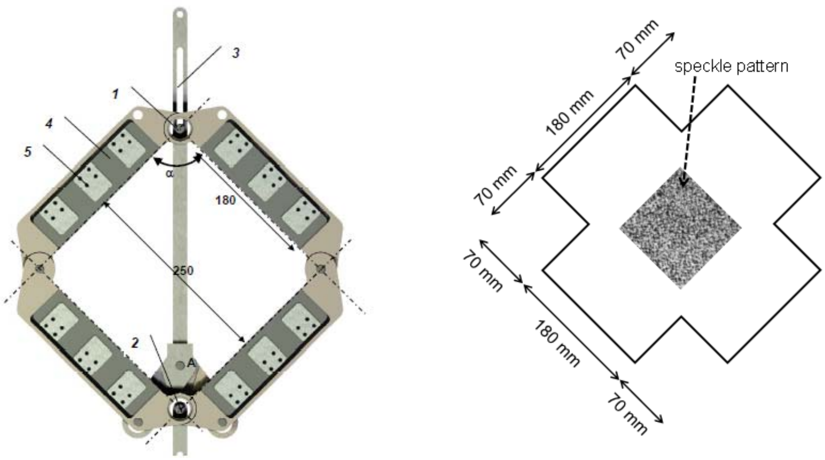
(a) (b)

Figure 3. In-plane shear angle distribution under uniaxial bias extension: (a) theoretical; (b) observed on the non-crimp 3D orthogonal weave reinforcement (λ = 2).

Assuming intra-ply slip insignificant compared with trellis shearing and the ratio λ at least 2, the shear angle in region A (Figure 3) is obtained by

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

In eqn. 1, d is the applied displacement.
Tensile machine MTS 858 Bionix was used with a load cell of 2.5 kN. Test speed of 3 mm/min was imposed up to the maximum capacity of the load cell. Glass fibre-epoxy tabs 2 mm thick were glued at the ends of the fabric specimens, leaving 200 mm free length between the grips, which gives a length/width ratio (λ) of 2.
The picture frame shear test consists in clamping a fabric on a hinged frame whose directions are those of the fabric yarns. In the present study the setup of the K.U. Leuven (see Figure 4a) has been used.
The test procedure used in this work follows "best practice" recommendations described in [9].



(a) (b)

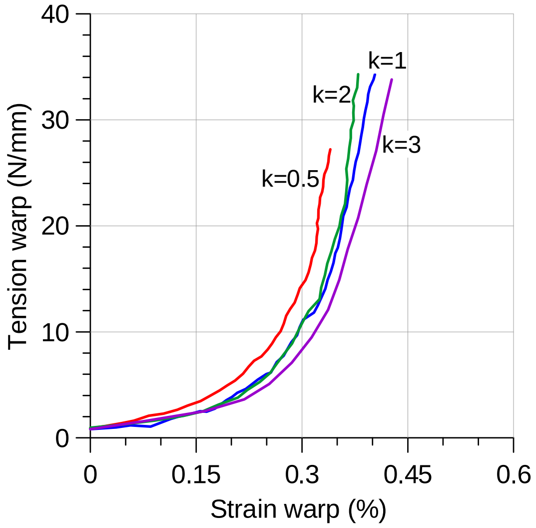
Figure 4. Picture frame: (a) device; (b) sample geometry.

The frame was mounted on an Instron 5567 tensile machine with 30 kN load cell. Test speed of 10 mm/min and a maximum displacement of 20 mm, corresponding to a frame shear angle of 45°, were set. The tested samples had the cross-like shape depicted in Figure 4b. The basics of the picture frame kinematics, as well as the calculation procedures for the shear force and the shear angle (by means DIC), are detailed in [7].

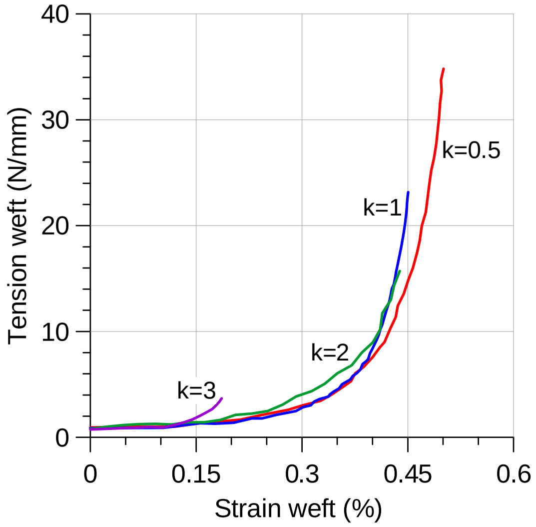
4. Results

4.1. Biaxial behavior

The biaxial tests were performed with four different ratio k (warp velocity/weft velocity) 0.5, 1, 2 and 3. A pre-load of 40 N was applied in both directions for all the specimens, to compensate the initial slack of the horizontal fabric specimen. Figure 5 summarizes the results of the biaxial tension in principal directions. Each curve in Figure 5 is an average of two specimens.
The reinforcement shows similar response in the direction of the yarns. The biaxial curves show initial nonlinear strain range up to ≈0.3 (Figure 5a) and ≈0.4% (Figure 5b), respectively.



(a)



(b)

Figure 5. Biaxial tests: Tension vs. strain: (a) warp; (b) weft.

The diagram tension-strain in warp direction in Figure 5a shows that when the deformation in the direction perpendicular to load (weft) increases, i.e. decreasing k, the stiffness of the fabric increases. This is consequence of the transverse contraction of the weft yarns on warp deformation. After the nonlinear range, the behaviour becomes approximately linear with slope decreasing increasing the ratio k. The opposite behaviour is observed when the tension-stain in weft direction is considered (Figure 5b), i.e. the stiffness of the fabric increases increasing k.

4.2. In-plane shear behavior

The assumptions of the normalization procedure adopted for bias tension, have been assessed for several 2D reinforcements (see e.g. [9]). These hypotheses are here verified for the 3D woven fabric under consideration.

The comparison of the shear angle measured by DIC in the specimen centre, during bias tests, and the theoretical based on kinematic analysis eqn. (1) is detailed in Figure 6a. The measured and the theoretical shear angles are in agreement up to ≈30°, than they start to diverge. This

shear angle level indicates the influence of other deformation mechanisms (e.g. compression of the yarns) not considered in the kinematic model of eqn. (1).
The DIC measured shear angle distribution on the complete surface (200x100 mm) of a bias specimen for an applied theoretical shear angle of ≈20° is presented in Figure 6b. The assumption of the kinematic model (see Figure 3), is clearly observed in the experiments.
The average normalized shear force vs. shear angle curves, for bias extension and picture frame tests, are depicted in Figure 7. The curves have been obtained as average of five specimens for each test. The diagram is limited to ≈30°, as discussed above.
In each picture frame test three load-unload cycles have been performed. The first cycle is distinctly different from the second and the third. Those are quite close to one another. This behaviour may be explained as a relaxation of some irregularities of the yarn pretension during production in the first cycle. The shear curves show two different regions: an initial region (up to ≈3°) of high initial stiffness, and a second region of low shear stiffness (up to 15°), followed by a fast increase of the curves slope. These regions correspond to different shear resistance mechanisms. These are well explained in the literature for two-dimensional fabrics (see e.g. [10]), while investigations are not available for three-dimensional composite reinforcements.

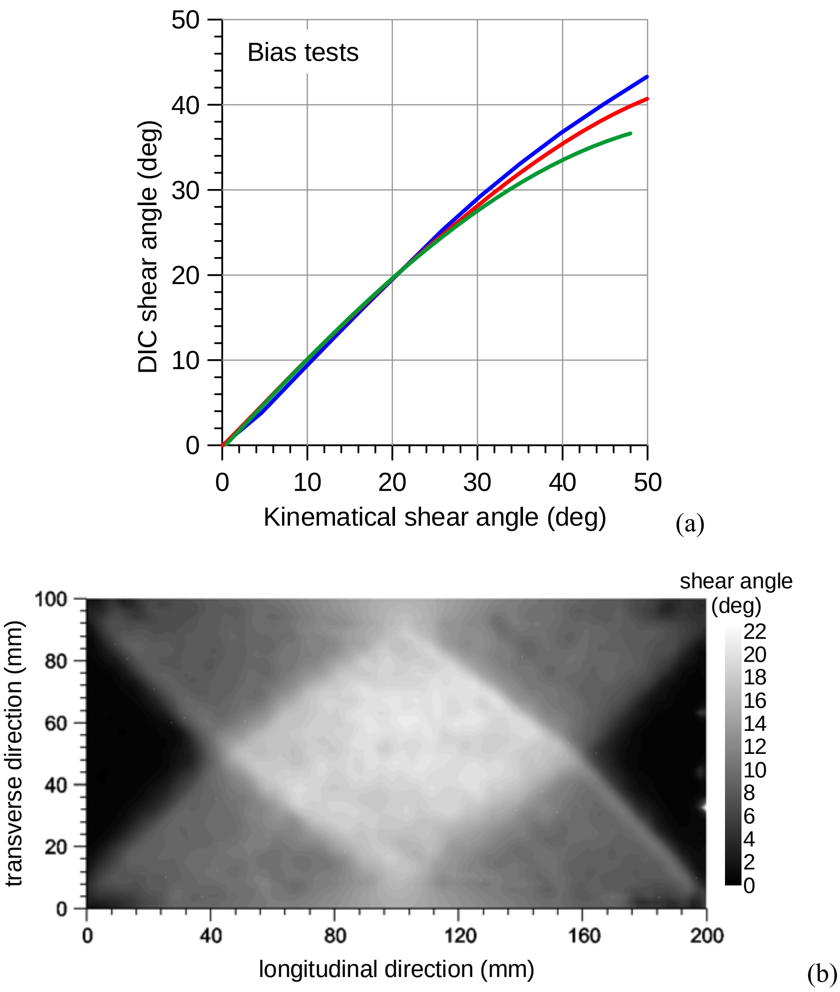


Figure 6. Bias test. (a) Comparison of measured and theoretical shear angle; (b) contour plot of the measured shear angle distribution.

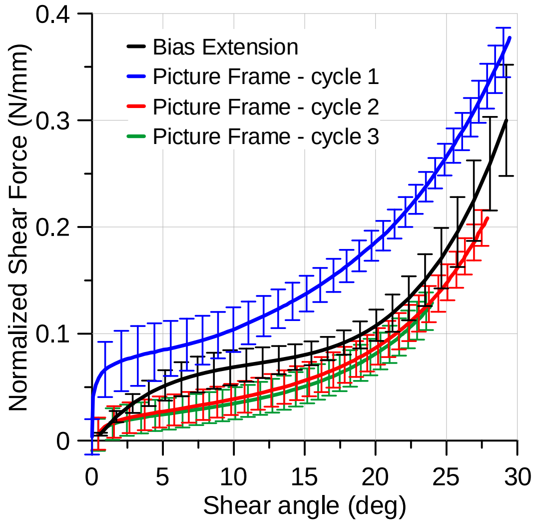


Figure 7. Bias extension and picture frame tests comparison. Average normalized shear force vs. shear angle curves. Error bars give the standard deviation.

5. Conclusions

The experimental study presented in this paper was focused on understanding the deformability of a single layer non-crimp 3D orthogonal weave E-glass composite reinforcement, commercialized under trademark 3WEAVE® by 3Tex Inc. The attention was focused on the in-plane biaxial tension and shear behaviour.

Biaxial tests have been performed for different velocity ratios k. The negligible yarn crimp of the 3D reinforcement seems to produce a reduction of the initial nonlinear strain range compared to 2D reinforcements available in the literature.

Uniaxial bias extension and picture frame tests have been performed to investigate the shear behaviour. The theoretical hypotheses of the energy based normalization procedure adopted have been verified for the considered 3D woven fabric. The measured shear angle is in good agreement to the kinematic theoretical assumptions up to $\approx 30^{o}$ and the hypothesized distribution of shear angle on the fabric surface was exactly observed during the experiments. These observations demonstrate that the theoretical kinematism can be considered for the present 3D reinforcement as well.

The obtained experimental results represent a data set for the simulation of forming processes with such single layer non-crimp 3D orthogonal weave E-glass composite reinforcement.

Acknowledgements

3Tex Inc. is acknowledged for manufacturing and supplying the non-crimp 3D orthogonal weave E-glass reinforcement (3WEAVE®).

References

[1] Boisse P., “*Composite reinforcements for optimum performance*”, Woodhead Publishing Limited, Oxford (2011).

[2] Bogdanovich A.E. and Mohamed M.H., Three- Dimensional reinforcement for composites. *SAMPE Journal*, **45**, pp. 8-28 (2009).

[3] Carvelli V., Gramellini G., Lomov S.V., Bogdanovich A.E., Mungalov D.D., Verpoest I. Fatigue behaviour of non-crimp 3D orthogonal weave and multi-layer plain weave E-glass reinforced composites. *Composites Science and Technology,* **70**, pp. 2068-2076 (2010).

[4] Mohamed M.H., Zhang Z.H. *Method of forming variable cross-sectional shaped three-dimensional fabrics*. US Patent 5085252 (1992).

[5] Harrison P., Clifford M.J. and Long A.C. Shear characterization of viscous woven textile composites: a comparison between picture frame and bias extension experiments. *Composites Science and Technology,* **64**, pp. 1454-1465 (2004).

[6] Launay J., Hivet G., Duong A.V. and Boisse P. Experimental analysis of the influence of tensions on in plane shear behaviour of woven reinforcements composites. *Composites Science and Technology,* **68**, pp. 506-515 (2008).

[7] Lomov S.V., Willems A., Verpoest I., Zhu Y., Barbuski M. and Stoilova Tz. Picture Frame test of woven composite reinforcements with a full-field strain registration. *Textile Research Journal,* **76**, pp. 243-252 (2006).

[8] Lebrun G., Bureau M.N., Denault J. Evaluation of Bias-extension and Picture frame Test methods for the Measurement of Intraply Shear Properties of PP/glass Commingled Fabrics. *Composites Structures,* **61**, pp. 341-352 (2003).

[9] Cao J., Cheng H.S., Yu T.X., Zhu B., Tao X.M., Lomov S.V., Stoilova T., Verpoest I., Boisse P., Launay J., Hivet G., Liu L., Chen J., De Graaf E.F., Akkerman R. Characterization of mechanical behaviour of woven fabrics: Experimental methods and benchmark results. *Composites Part A,* **39**, pp. 1037-1053 (2008).

[10] Grosberg P., Park B.J. The mechanical properties of woven fabrics. Part V. The initial modulus and the frictional restraint in shearing of plain woven fabrics.. Textile Research Journal, **36**, pp. 420-431 (1966).