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

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ABSTRACT

In this paper, the formability of a single layer E-glass non-crimp 3D orthogonal woven reinforcement (commercialized under trademark 3WEAVE® by 3Tex Inc.) is experimentally investigated. The study involves the forming process of the 3D fabric on two complex moulds, namely tetrahedron and double-dome. The tests are assisted by 3D digital image correlation measurement to have a continuous registration of the fabric local deformation. Moreover, the results of bending tests in warp and weft direction are detailed to enlarge the mechanical properties data set of the 3D reinforcement, necessary for understanding its deformability capacities in forming processes. The elevated bending stiffness of the 3D fabric means that use of a blank-holder during forming is not required. The reinforcement has a good drapability and it is able to form complex shapes without defects (wrinkles and fibre distortions). The collected experimental results represent an important dataset for numerical simulations of any complex shape with the considered 3D fabric composite reinforcement.

1. Introduction

Textile reinforcements for composite structures have attracted lots of attention due to their superior shaping characteristics compared with laminates [1]. Textile reinforcements are especially efficient in manufacturing composite structures with complex shapes. Interlacing of warp and weft yarns allows forming complex shapes without defects that are difficult to obtain with unidirectional reinforcements [2].

During manufacturing process, a crucial step is the forming of flat textile reinforcements into a desired (three-dimensional) shape. The shape of the preform is generally obtained by punch and die draping process. After shaping, the reinforcement is injected with resin and consolidated. Forming of double-curved shapes is a critical phase due to in-plane deformations and above all in-plane shear [3]. The deformability of the reinforcement defines the fibre orientations and density, which influences directly the permeability of the preform, and finally the mechanical response of a composite component. Therefore, the knowledge of the behaviour during forming of a dry composite reinforcement is of primary importance to avoid defects (e.g. wrinkling) in complex preforms and to establish the quality of the manufacturing.

In spite of the fast growing interest for 3D orthogonal interlock woven reinforcements in the composites industry for a broad range of applications [4], the behaviour during forming of these reinforcements are not deeply known and investigated. In fact, most of the studies available in the literature (see e.g. [3,5–8]) are dedicated to forming of textile reinforcements with two-dimensional interlacements. In [9,10] experimental data and numerical modelling are detailed for a specific type of angle interlock carbon fabrics. The authors are not aware of similar studies for orthogonal 3D woven reinforcements. Their behaviour, due to a specific geometry of Z-binding and extreme straightness of the stuffing warp and weft yarns [11,12], is quite different from the tight heavily interlaced angle interlock weaves [13].

In this paper, the formability of a single layer E-glass non-crimp 3D orthogonal woven reinforcement (commercialized under trademark 3WEAVE® by 3Tex Inc.), is experimentally investigated. The study involves the experimental simulation of the forming process on two moulds, i.e. tetrahedral and double-dome shape. The tests are assisted by 3D digital image correlation technique to have a continuous measurement of the local deformation during shaping. Particular attention is dedicated to the in-plane shear deformation distribution, being considered the primary deformation mechanism during shaping [14]. The appearance of wrinkles is also related to the bending stiffness of the textile [3,15]. Therefore, bending tests in warp and weft direction are first presented. Blank

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holder is commonly adopted in shaping processes of fabrics with negligible bending stiffness introducing tension in yarns and delaying the out of plane defects. The elevated bending stiffness of the 3D fabric allows excluding blank holders in the forming set-up and delaying the onset of wrinkles in the useful part of the preform.

The present paper continues the study on the deformability of 3D woven fabrics (all done for the same fabric as investigated in this paper), started in [16] with investigation of shear, biaxial tension and compression behaviour of the fabric, continued in [17] with micro-CT observations of change of the fabric internal structure under shear, and in [18] for a comparative analysis of different DIC algorithms for the measurement of fabric 3D deformation.

The experimental results give an important knowledge on the complex double curvature shape formability of the considered 3D fabric composite reinforcement and allow detailed assessment of numerical modelling of these shaping processes. Available numerical modelling based on discrete [19] or continuous [20] approaches can be adopted to predict the forming process of complex shapes assuming the knowledge of the main mechanical features of the 3D textile, as described in Section 4 and in [16], and assessing the accuracy with the experimental forming results presented in Section 5.

2. Non-crimp 3D orthogonal woven reinforcement

The fabric is a single layer E-glass non-crimp 3D orthogonal woven reinforcement (commercialized under trademark 3WEAVE® by 3Tex Inc.). The fibre architecture of the preform has three warp and four weft layers, interlaced by through thickness (*Z*-directional) yarns (Fig. 1 [21]). The fabric construction results in ∼49%/∼49%/∼2% ratio of the fibre amounts (by volume) in the warp, weft and Z fibre directions, respectively. Its thickness, measured by different techniques, is 2.57 ± 0.42 mm (see [17]). The same 3D glass reinforcement was adopted in the composite experimentally investigated in [21–23]. A detailed description of the 3D orthogonal weaving production process is presented in [24,25]. The fibre material is PPG Hybon 2022 E-glass. Some features of the non-crimp 3D reinforcement are listed in Table 1. The reader is referred to [12] for description of the preform architecture, studied with optical microscopy and micro-CT. Furthermore, biaxial tensile and shear mechanical properties of the E-glass non-crimp 3D orthogonal woven reinforcement are detailed in [16].

3. Experimental methods

3.1. Bending tests

In forming processes of textile reinforcements common defects include wrinkles. They develop as a consequence of the low stiffness in some deformation modes of textiles (e.g. in-plane shear and bending) [15]. A common strategy to prevent wrinkles is the addition of forming constraints, such as blank holders, applying tension to fibres.

Table 1
Properties of the non-crimp 3D orthogonal weave preform. Data provided by 3Tex Inc. [21].

	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

Bending stiffness of a textile plays an important role in its drapability [26], providing stability to in-plane (shear) deformations [27–29]. An increase of this rigidity leads to an increase of the wrinkle size and a decrease of their number [15].

The measurement of the bending behaviour of the single layer E-glass fabric is detailed in the present work to assess its stiffness in comparison to other reinforcements and to motivate the adopted forming set-up without a blank holder.

Two test methods are known to measure the bending stiffness of fabrics [30]: a cantilever bending test, which originates from the work of Peirce [31] (see [32,2]) and the Kawabata test [33]. In the following, bending tests in warp and weft direction of the 3D reinforcement are detailed using the same type of flexometer as the one developed in [2]. The device consists of a metallic part, which enables to place the sample in cantilever configuration under its own weight (Fig. 2) and an optical device acquiring images of the bent specimen. The quasi-static bending tests with different overhanging lengths allow to measure the non-linear moment vs. curvature relationship. The bending length is increased at steps of 50 mm. After each length increment and before taking image for fixing the deformed configuration, the reinforcement relaxes for five minutes reaching a ‘stable’ configuration. The image processing generates digital profiles of bent specimens adopted for curvature and moment evaluations, as explained in Section 4. The samples have a full length of 650 mm and a width of 100 mm.

3.2. Forming tests

In order to experimentally study the forming stage for complex double curvature mould shapes, the set-up illustrated in Fig. 3 was

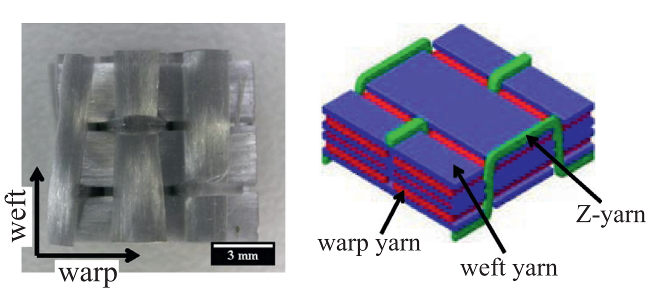

Fig. 1. Architecture of the tows inside the non-crimp 3D orthogonal weave preform [21]: picture (left) and scheme (right) of the unit cell. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

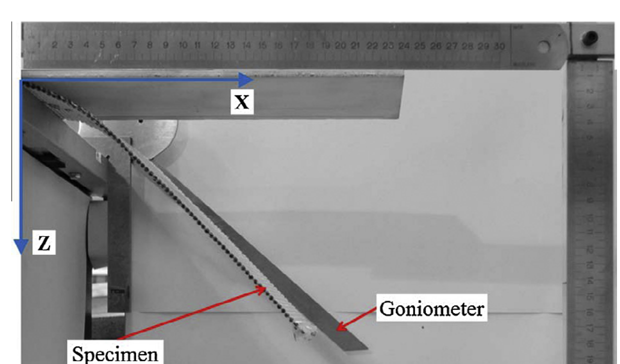

Fig. 2. Bending test set up. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)