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Quasi-unidirectional flax composite reinforcement: Deformability and complex shape forming

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ABSTRACT

Deformability and complex shape forming of a quasi-unidirectional flax reinforcement for composite materials (commercialized as FLAXPLY UD 180 by LINEO) are experimentally investigated. The first part of the study is focused on the understanding and measurement of the main deformation modes: in-plane tension, in-plane shear, and out-of-plane bending and compression, which are involved during draping of composite reinforcements. The second part is dedicated to the experimental study of a complex 3D shape forming, namely double-dome. The obtained results represent a complete data set for the characterisation of the deformation capabilities of the quasi-unidirectional flax reinforcement during complex 3D shape forming processes and provide benchmarking data for numerical predictions.

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 impregnated with resin and consolidated. In the forming process, the deformability of the reinforcement plays a key role in definition of the fibres' orientations, which influences permeability of the preform and finally defines the mechanical performance of the composite component [1,2]. Therefore, the knowledge of the deformation behaviour of a dry composite reinforcement is important to predict and avoid defects (e.g. wrinkles) in complex preform shapes.

Focusing on continuous fibre materials, the investigations available in the literature [1,2] are mainly dedicated to the deformability and formability of textile reinforcements with 2D interlacements, and recently of textiles with 3D architectures ([3–6]), made of synthetic fibres (i.e. glass, carbon, etc.).

In the last decade the interest in environmentally friendly composites has been rapidly increased. Several works have been published on research dealing with natural fibres, bio-based matrices and their composites (e.g. [7–13]). Natural fibres are particularly attractive for several reasons: they are very popular and abundant in developing countries; they have low cost compared to synthetic fibres; they have good specific mechanical properties and good acoustic or vibrational damping. Moreover, the energy needed for production of natural fibres is much lower than for synthetic fibres and, at last, life cycle analysis (LCA) studies strongly support further development of biomaterials [14]. The main disadvantages of natural fibres as reinforcement of composites are the compatibility between fibre and matrix and their relatively high moisture absorption [11]. In spite of the fast growing interest for natural fibres in the composites industry, the deformability and formability behaviour of natural fibre fabrics as reinforcement are not deeply known and investigated. Only recently, in the authors' knowledge, few investigations on the mechanical properties and complex shape forming of flax woven fabrics have been published ([15–17]).

In this paper, the deformability and formability of a flax fabric adopted as reinforcement in manufacturing complex shape composite components are experimentally investigated. The fabric (commercialized as FLAXPLY UD 180 by LINEO) is a quasi-unidirectional woven fabric with thin twisted weft yarns connecting thick warp yarns using a weft rep weave interlacing pattern. The unbalanced nature of the quasi-unidirectional weave presents additional challenges to the fabric forming [18].

The first part of the study is focused on the measurement of the main deformation mechanisms of the fabric involved in shaping processes: in-plane uniaxial and biaxial tension; in-plane shear; out-of-plane bending and out-of-plane compression. Particular attention is dedicated to the deformation during shear loading, this

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being considered the primary deformation mechanism in reinforcement shaping processes [19]. The tests are assisted by the 2D digital image correlation (DIC) technique to have a continuous measurement of the local deformations on the fabric surface. The peculiarities of the deformation behaviour are highlighted and connected to the quasi-unidirectional construction of the flax fibre fabric.

The second part is dedicated to the experimental study of a complex 3D shape forming process. The drapability of the quasi-unidirectional flax reinforcement was observed using a double-dome punch in an open die forming process. The tests are assisted by 3D digital image correlation technique to have a continuous measurement of the local deformation during shaping, in particular of the shear deformation.

The obtained results represent a complete data set for characterisation of the deformation capabilities of the quasi-unidirectional flax reinforcement during complex 3D shape forming processes and provide benchmarking data for numerical predictions. Based on the present results, in future work available numerical modelling approaches (e.g. [20–22]) can be adopted to predict the forming process of complex shapes assuming the knowledge of the main mechanical features of the quasi-unidirectional flax reinforcement, as described in Section 4, and assessing the accuracy with the experimental forming results presented in Section 5. This investigation can increase the confidence in adopting the flax fibre quasi-UD reinforcement instead of or beside to synthetic fibre woven fabrics in forming complex composite shapes without undesirable defects.

2. Material

The fabric is a quasi-unidirectional flax reinforcement (commercialized as FLAXPLY UD 180 by LINEO). The fibres architecture of the preform has 95.5% of the fibres (by weight) in warp direction and 4.5% in weft. The flax fibre density is 1.4 g/cm^3. The fabric has a weft rep weave 4/4(4), i.e. each weft yarn goes up and under 4 warp yarns (see Fig. 1). Some measured features of the reinforcement are listed in Table 1.

3. Experimental methodologies and devices

Biaxial tensile tests at different velocity ratios at two axes were performed to gather information on the initial non-linear stiffening due to the very 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 flax preform. During these tests, images were recorded by a digital camera for image correlation analysis by Vic-2D software [23]. For this purpose the specimen surface was speckled with black acrylic paint for strain

Table 1
Measured properties of the quasi-unidirectional flax reinforcement.

	Fabric plies	1
	Areal density (g/m^2)	180
Warp	Insertion density (ends/cm)	42.5
	Linear density of yarns (tex)	41.6
Weft	Insertion density (picks/cm)	3
	Linear density of yarns (tex)	27.7

components measurements with a digital image correlation system [24]. The procedure followed for image analysis is detailed in [25].

Out-of-plane deformability behaviour was investigated with bending and compression tests.

Bending stiffness of a textile plays an important role in its drapability [26] and transverse compression is one of the main deformation modes [27] during the compaction stage of resin infusion processes due to the applied vacuum and possible additional pressure, which modifies the final material thickness.

Furthermore, the forming stage using a complex double curvature mould was experimentally investigated for two orientations of the fibres, assuming a punch with double-dome shape and measuring the full field displacement with three dimensional image correlation analyses by MatchID3D software [28].

The tests were performed in the labs of Politecnico di Milano and KU Leuven.

3.1. Biaxial tension tests

Biaxial and uniaxial tension tests were performed on square specimens of the fabric, using a biaxial testing machine in KU Leuven equipped with two independent orthogonal axes (Fig. 2), with grips of length 190 mm. Velocity of the two loading axes was set in the range 1–2 mm/min to have different warp to weft velocity ratios (k = warp velocity/weft velocity). It should be underlined that the velocity ratio (imposed by the device) does not coincide with the strain ratio in the centre of a specimen under biaxial loading. Four load cells of 5 kN were used to measure the force applied to each side of the specimen. 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. 2.

3.2. In-plane shear behaviour

Two tests are generally performed for in-plane shear characterisation of engineering fabrics, namely uniaxial bias extension and picture frame test (see e.g. [2,29]). Most of the studies concerning shear testing of fabrics ([29,30]) include normalization procedures for the bias force, based on the energy approach proposed by Harrison et al. in [30]. The normalization procedures provide the

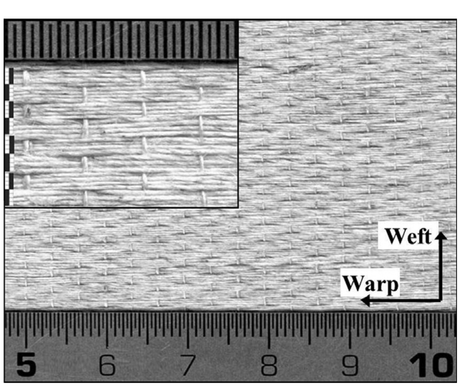

Fig. 1. Quasi-unidirectional flax reinforcement (LINEO – FLAXPLY UD 180).

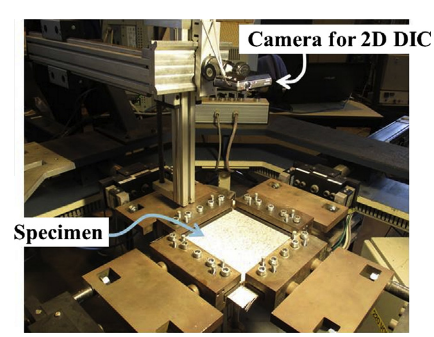

Fig. 2. Uni/biaxial tension test. Biaxial tensile machine and test set-up.