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Mechanical properties of flax-fibre-reinforced preforms and composites: Influence of the type of yarns on multi-scale characterisations

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ABSTRACT

As the strongest natural fibres, flax fibres are being used increasingly for technical advanced products such as composites with a view to reducing the impact of the material on the environment throughout its life cycle. In order to improve the understanding of the mechanical properties of flax fibres and their reinforced preforms and composites, multi-scale characterisations are carried out to analyse the tensile properties of flax fibre yarns, fabrics and composites. From three types of yarns, quasi-UD fabrics and composites are manufactured with the same process parameters. Tensile tests are performed at each scale to study the effect on the properties of yarn such as the twist level. At the yarn scale a significant variability of the tensile behaviour is pointed out, as described in the literature. The tensile behaviour of un-impregnated fabrics shows the effect of the weaving process. The tensile results at the composite scale indicate the same trend compared to yarn after the weaving and fabric scales. From the experimental results at different scales an analysis is conducted to explain the tensile behaviour, taking into account the different steps of the manufacturing process. In addition, micro-observations through SEM images will confirm the variability of the tensile behaviour of a single flax yarn and emphasize the strong influence of the twist level on the tensile characterisation at different scales.

1. Introduction

There is a growing interest in the development of natural fibre composites, most likely due to their wide availability, low cost, environmental friendliness, and sustainability. For the past two decades comprehensive research has been conducted on natural fibre composites, and numerous research articles have been published addressing various challenges in the fabrication of composites where the final goal has always been to achieve natural fibre composites with the desired levels of mechanical performance and cost attributes for certain specific industrial uses. Thus, the number of research articles published on natural fibres has reached a new high of 34,385 articles as of March 1, 2015 [1]. From an industrial point of view, the market size for natural fibre composites is projected to reach $5.83 billion by 2019, with a compounded annual growth rate of 12.3% [2]. This should be compared to glass fibre composites which are the largest category of fibre-reinforced composites (with 87% of the market) [2,3]. Among this literature, Shah [4] has shown that natural-fibre-reinforced composites may be potential alternatives to glass-fibre composites in tensile-stiffness-critical applications but not in tensile-strength-critical applications, although a comparably high variation in properties, pronounced humidity absorption and laborious procedures to turn them into continuous structures have limited their widespread usage in mechanically stressed applications [5]. The mechanical properties at the single-fibre and composite stages have been widely described, especially in review papers [3,5–17]. Between these two scales, however, mechanical properties of un-impregnated yarns or fabrics are less studied. Highly ordered textile reinforcements, such as interlaced woven fabrics and unidirectional fabrics made from natural-fibre yarns, perform considerably better than random non-woven mats in natural-fibre composites [18]. Goutianos et al. [19] have found that replacing random mats by woven fabrics has increased the mechanical properties by 3–4 times as well as improved the toughness. Using an Ashby approach, Shah [4,20] has recently suggested that unidirectional fabrics, for instance, provide 2–20 times better (absolute and specific) tensile properties than nonwoven-reinforced composites. The best mechanical properties can generally be obtained for composites when the reinforcement is aligned parallel to the direction of the applied load [20–24]. However, it is more difficult to get alignment with natural fibres than with continuous synthetic fibres [25,26].

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At the yarn scale (based on natural fibres), Goutianos and Peijs [27] have shown that very low twisted yarns exhibit a very low strength when tested in a dry state. In the same study of a wide range of flax textiles based on twisted yarns, they have shown that in terms of composite properties, a high degree of twist (≈20°) in a yarn leads to a decrease in the longitudinal strength and modulus of a UD composite of 20% compared to composites made of zero twist rovings. Baets et al. [28] have found that the stiffness of the fibres/rovings, back-calculated from the composite properties, decreases from 63 GPa to 43 GPa with the introduction of 19° twisted yarns compared to the twistless rovings. Moreover, a higher twist will reduce the permeability of the yarn, which may lead to higher void content and lower composite properties. On the other hand, Rask and Madsen [29] found no direct correlation between the amount of twist and the decreasing tensile properties, but the effect on the voids content of the composite manufactured is significant. Ma et al. [30] have studied the effect of different twist levels (20, 60 and 150 turns per meter, tpm) on the tensile strength of un-impregnated sisal yarns (with a linear density of 1250 tex) which first increased and then started to decrease when a critical twist level (90 tpm) was reached. Zhang and Miao [31] produced a wrap yarn with untwisted flax fibre, and its reinforcing composites possessed higher flexural strength and modulus (145 MPa and 15 GPa respectively for 31% fibre volume fraction) than those of the twisted yarn-reinforced composites. For untwisted flax yarns of 500 tex and twisted (between 11° and 13°) sisal yarns (of 230 tex), respectively, the effect of the gauge length on tensile properties of un-impregnated yarns has been studied by Moothoo et al. [32] and most recently by Belaadi [33]. These authors have pointed out the high non-homogeneity of yarns during tensile tests. At the level of un-impregnated fabrics, weaving fibre bundles into fabrics for easier handling, for example, introduces fibre crimp which reduces the mechanical properties of the reinforcements. Other textile variabilities such as yarn spacing, yarn path waviness, and wrinkling can also significantly influence subsequent properties [34]. Misnon et al. [35] have shown that for two woven hemp fabrics with the same textile properties (crimp, areal density, linear density of yarns, warp/weft density) the differences in their tensile strengths and tensile moduli are insignificant. Some characterisation at the level of flax-based woven fabrics are presented in [36–38] for the shape forming.

Bensadoun et al. [39] have reported on the evolution of tensile moduli and tensile strength for nine flax-fabric architectures (mat, plain weave, twill, quasi-UD, UD...) with different areal densities, (moduli between 7.3 GPa for Random mat to 26 GPa for UD and strength of 84 MPa to 249 MPa). Additional information (especially on the twist level of flax yarns) can be found in her Phd thesis [40], where tensile results conducted on composites reveal that differences in strength can reach 30% (in warp direction) or 23% (in weft) between a high-twist plain weave and a medium-low-twist twill. Associated to these experimental studies, Shah et al. [41] have proposed a mathematical model, based on the rule of mixture, able to predict the effect of yarn twist on the tensile strength of aligned plant-fibre composite. In this paper, they introduced the notion of the limit of twist level from where the yarn strength decreases. A multi-level approach (tensile behaviour of un-impregnated yarns and fabrics and composites) has been proposed recently by Blanchard et al. [42], and they have shown that the wide variability in terms of tensile properties recorded at the scale of flax-fibre yarns decreases at the scale of fabrics and composites. In many of these experimental studies, the properties of flax fibres are back-calculated from results obtained on impregnated composites and using micromechanical equations as the law of mixture. Even if it is not a problem for stiffness where the influence of matrix and interface are negligible, the fibre misorientation, the fibre volume fraction and the fibre-matrix adhesion have to be considered for the strength measured. Consequently, this paper is focused on a multi-level approach to discuss the mechanical properties of yarns, fabrics and composites based on flax fibres. From three flax-fibre yarns with the same linear density, but different level of twist, three quasi-UD have been woven then three composites have been manufactured with the same process parameters. The aim of the study is to characterise the tensile properties at each scale (yarn, fabric and composite) and to analyse the influence of the type of yarn and of the weaving process on the tensile results.

2. Materials and methods

2.1. Flax yarns

Different process steps are followed to obtain either short or long flax fibres [19,43–45]. As flax fibre is a non-continuous fibre, also called natural staple fibre, the range of fibre length is 30–100 mm. For that reason, in the textile industry, flax fibres are graded as long staple fibres with a length exceeding 60 mm [45,46]. The preparation for the spinning process for flax fibres starts from with the retting and the scutching between flax seeds and straws. Then the fibres are hackled and drawn in order to obtain a continuous untwisted bundle of soft fibres.

The raw flax fibres come from France and have an average diameter of 20 μm. The yarns used in the study contain flax fibres from the same bundle and have undergone the same preparation process, but the difference was introduced with the spinning process (dry or wet spinning). Consequently, the twist angle can be changed between a low-twisted and a high-twisted yarn [27,28,39,41]. Three different yarns were used in the study:

Yarn 1 denoted Y1 is a low-twist yarn which has mainly long scutched hackled fibres. It was manufactured with the wet-spinning process. This operation consists of soaking the bundle of fibres in water (60–70 °C) to have more flexible fibres. Afterwards, the fibres are drawn and twisted until a thinner yarn is obtained. The quality of these fibres is higher and thus costly. The bundle of fibres can be hackled directly, as they are already aligned. The long hackled fibres are used very often in yarns to obtain a weave and a unidirectional fabric.

Yarn 2 denoted Y2 is a tow flax yarn. By definition, it contains shorter flax fibres compared to long flax fibres and it is obtained with the dry-spinning process. The yarn is highly twisted in order to obtain the same linear density as Y1. The yarn obtained is thicker than the wet-spun yarn. Regarding fibre characteristics, the morphology and appearance of flax tows are different from long hackled ones as the fibres are entangled and contain shives. Consequently, the tow flax fibres need more cleaning and hackling. They are usually used for their cheap cost and for their low mechanical performance. But, as demonstrated by Martin [44], although the initial quality of raw flax tows is low, once aligned and cleaned they became similar to scutched flax in terms of high mechanical performance. For that reason, the use of tow flax yarn fibres can be very interesting for technical applications; hence our choice to compare between these two types of fibre in Y1 and Y2 (long hackled fibre yarn vs. tow yarn) at the yarn, fabric and composite scales.

Yarn 3 denoted Y3 is a roving yarn. It is used more often for technical applications: the fibres are collected into a parallel strip with a low twist in order to maintain them in the same direction for better mechanical properties and resin impregnation at the composite scale. Unlike the glass fibre rovings where the fibres are kept parallel and flat, the flax roving are twisted, even if this is with a low twist, to gain the strength needed to help the weaving process.