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A study of the tensile behaviour of flax tows and their potential for composite processing

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ABSTRACT

To study the potential of flax tows in composite processing as an alternative to flax spun yarns, a flat flax tow consisting of aligned fibre bundles held together by a natural binder was used and characterised in tension under various conditions. The effect of the gauge length was studied on the dry reinforcement. The experimental results showed that the mechanical properties and failure mechanism varied significantly depending on the gauge length and are discussed in relation to the distribution of elementary fibres within the tow. A characteristic length as from which the mechanical properties are stable has been identified. At this length, the effect of the strain rate on the tensile properties was measured and their sensitivity to the strain rate suggests a viscous effect in the behaviour of the flax tow. To approach process conditions such as wet filament winding, a batch of specimens was impregnated with epoxy prior to tensile testing. The tensile properties under wet conditions were found to be close to the properties under dry conditions and shows that the tow can withstand typical processing tensions. Finally, tensile tests on cured-impregnated tows showed interesting mechanical properties for composite application.

1. Introduction

The environmental issues linked to the scarcity of resources, global warming, and energy consumption have led to the necessity of adopting an eco-design approach in industries. This approach is also relevant to the composite industry. The use of traditional reinforcements for composite materials such as glass fibre create problems in terms of raw materials needed, energy consumption and environmental impact. Glass fibres are produced by combining different quarry products that require a temperature above 1500 °C. Apart from the high energy requirements, the main raw material used for glass fibre production is silica sand. Extensive sand mining has also been shown to produce unexpected socio-ecological impacts [1–3]. In this context, research studies have been conducted to assess the potential of using renewable resource based natural fibre reinforcement for composites, notably as a replacement of glass fibres [4–8]. Natural fibres have interesting properties such as low density, ≈1500 kg/m^3, competitive specific modulus and an affordable price [9,10]. A member of natural fibres family, the flax fibre is of particular interest since it has specific mechanical properties comparable to that of glass fibre [11,12]. After extraction from the stem, the fibres are in the form of fibre bundles or technical fibres having a size of 50–100 μm in diameter [13] and a tensile strength between 600 and 800 MPa [13–15]. The fibre bundles are generally composed of 10–40 elementary flax fibres [11] having an average diameter of 20 μm [16]. Within the fibre bundle, these elementary flax fibres are held together by interfaces for the most part composed of pectin [16]. The length of the elementary flax fibres rarely exceeds 100 mm, the average value being 33 mm [11,16] and its Young's modulus and tensile strength are 40–80 GPa and 600–1800 MPa respectively [11,17,18]. Flax fibres are therefore not homogeneous in size and when produced in the form of a continuous reinforcement such as a yarn or a tow, different constituent scales come into account; viz the fibre bundles and the elementary fibre. These two scales are the object of constant research [11,13–20]. Indeed, understanding these is key to realise the full potential of the use of flax fibres and to interpret the behaviour of derived reinforcements or bio-composites. The upper scale, the flax yarn or tow is comparatively less studied.

For optimised mechanical performance and in the view of a broader application, fibre orientation associated to part geometry is essential. During the manufacturing processes of composite materials such as filament winding, braiding or sheet forming, the reinforcement undergoes deformation and its cohesion is needed to guarantee good quality preforms. To obtain homogeneous reinforcement properties, spun yarns are generally used in order to give

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the latter a better resistance to tension involved during the process or preforming. Flax yarns have successfully been used as material input in pultrusion [21] and filament winding [22]. However, although the use of flax spun yarns is a progress towards the use of renewable based resource, this may not be effective in terms of energy consumption associated to their manufacturing process [23]. Moreover, it has been shown that the use of spun yarns has the tendency to reduce the potential mechanical properties of the composite [24]. The alternative to spinning fibres to produce yarns is to use a binder in order to guarantee the cohesion of a tow. Flax tows are available on the market for composite application in the form of spools or in a woven architecture. It has been shown that complex shapes could be achieved with flax tow based woven fabric by sheet forming process [25–27]. However, despite studies available on yarns based on natural fibres, coir [28], hemp [29], flax [24,30,31], few studies reported the tensile behaviour of flax tows. This is more the case in regards to braiding or filament winding with flax tows.

Our objective in this study is to investigate the potential of the flax tow for composite processing as an alternative to spun yarns. For this purpose, a detailed mechanical characterisation of the dry tow including the effects of the gauge length and strain rate will be presented. A study of the failure modes using digital image correlation as well as the effect of impregnation before curing are also investigated in relation to processing applications such as wet filament winding. Finally, impregnated tows are also characterized after curing by tensile testing in order to estimate the prospective mechanical properties of the bio-composite.

2. Experimental program

2.1. Specimen preparation

The flax tow used in this study, manufactured by Groupe Depestele (France), was provided in the form of spools with a linear density of 0.5 kg/km (500 tex). The architecture of the tow, Fig. 1, consists of an assembly of slightly entangled, almost aligned flax fibre bundles along the tow longitudinal axis. The tow's thickness is of 0.16 ± 0.03 mm and its width of 2.20 ± 0.39 mm. The overall cohesion of the tow is guaranteed by a natural binder.

For the tensile tests, specimens of a given length were randomly cut from the spools and glued to a thin aluminium sheet using an epoxy Araldite 2000 + 2013 as shown in Fig. 2. In order to investigate the effect of the gauge length on the tensile properties, six batches of specimens with different gauge lengths were tested (4, 25, 50, 125, 250 and 500 mm) under quasi-static loading. This set of gauge lengths were selected so as to enclose the distribution of the elementary flax fibre lengths within the tow (under 100 mm) and to have some points of measurement far above the maximum elementary fibre length as well. To study the effect of the strain rate on the tensile properties, the gauge length of 250 mm was selected. The choice of the latter is justified by the results obtained on the gauge length effect study and is explained in part 3.2. All the specimens were tested in their "as received" condition without any drying cycle or pre-treatment.

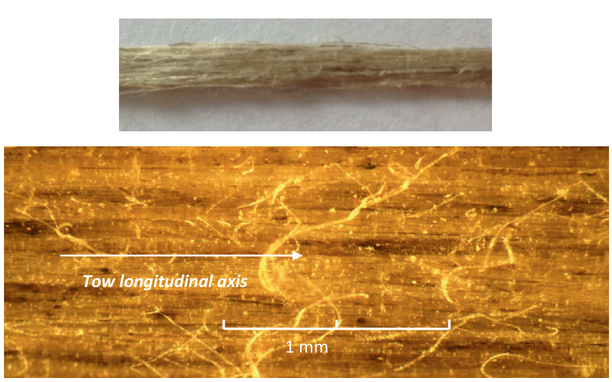

Fig. 1. Flax tow top view (close up).

Fig. 2. Tow specimen for tensile test.

Since we are interested in assessing the potential of this tow for composite preforming processes such as wet filament winding, a batch of 250 mm gauge length specimens were dipped into an epoxy resin bath (SICOMIN SR 1500) and impregnated using a contact process (roller impregnation) prior to tensile testing. Finally, to evaluate the composite properties for our application and to assess the influence of the binder, another batch of 250 mm gauge length specimens were impregnated using the same contact process and allowed to cure at room temperature prior to the tensile test. The tows were not dried nor subjected to any pre-treatments before impregnation. The mass of the specimens were measured before impregnation and after curing to measure the weight fraction of fibres in the specimens.

2.2. Tensile test procedure

All the tensile tests were conducted on an INSTRON 4507 tensile machine with a 10 kN load cell (±2.5 N accuracy). The testing room conditions varied between 20 ± 2 °C in temperature and at 60 ± 5% in relative humidity. Since no specific standard exists for the tensile characterisation of such tows yet, a dedicated protocol developed by the laboratory and validated on the material was used for the purpose of this study. The established protocol shows some similarities with ISO 3341 [32] and ASTM: D2256 standards. The reference strain rate was taken as $6.66 \times 10^{-5}\,s^{-1}$ for the quasi-static tensile tests according to ASTM: D2256 standard. For short gauge length, 125 mm and below, markers were placed along the specimens (Fig. 2) and the displacement during the tensile tests was monitored by image analysis using the mark tracking technique [33]. Other specimens were fitted with a sprayed (black and white colours) speckle pattern so as to follow the displacement field along the tow using digital image correlation. The number of specimens tested per batch was at least 10 as recommended by ISO 3341 international standard test method [32]. To study the strain rate effect on the tensile properties, four strain rates were selected; starting from $1.33 \times 10^{-5}\,s^{-1}$ up to $1.33 \times 10^{-2}\,s^{-1}$ by a step factor of 10.

3. Results and discussions

3.1. Tensile behaviour of flax tow

The typical tensile behaviour of a flax tow with a gauge length of 50 mm is illustrated in Fig. 3. The first non-linear region (at low cross-head displacement) corresponds to the stage where the fibres or fibre bundles within the tow arrange themselves with the loading axis during the tensile loading. Then a linear elastic region is observed where the slope is used to determine the tensile modulus of the tow. This linear elastic part is followed by a non-linear region probably corresponding to random damage of the fibres or interfaces and rearrangements occurring within the tow. The maximum tensile force is taken as the peak point of the curve according