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Prestressed natural fibre spun yarn reinforced polymer-matrix composites

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ABSTRACT

We report that a prestressing technique similar to that traditionally used in prestressed concrete can improve the mechanical performance of flax fibre spun yarn reinforced polymer-matrix composites. Prestressing a low twist yarn not only introduces tension to the constituent fibres and compressive stress to the matrix similar as in prestressed concretes, but also causes changes to the yarn structure that lead to the rearrangement of fibres within the yarn. Prestressing increases the fibre packing density in yarn, causes fibre straightening, and reduces fibre obliquity in yarn (improved fibre alignment along yarn axis). All these changes contribute positively to the mechanical properties of the natural fibre yarn reinforced composites.

1. Introduction

There has been growing interest in the use of natural fibres as reinforcements for polymer-matrix composites (PMCs) because of a number of factors, including increasing environmental concerns and long term sustainability of resources, recyclability, biodegradability and weight-specific performance. Natural fibres extracted from plants, such as flax and hemp, are increasingly being used as an eco-friendly alternative to glass fibres traditionally used in composites for engineering applications.

Natural fibres extracted from plants have relatively short length, known as staple fibres in the textile industry. Staple fibres cannot be directly processed into continuous length of highly structured preforms for use in polymer-matrix composites using commercial textile processes, such as weaving, braiding and knitting. Currently, natural fibres are mainly used as random dispersion in injection/extrusion moulding compounds or as random nonwoven mats for lamination and resin infusion. Randomly oriented composite structures possess much lower mechanical properties than those made with oriented structures [1], therefore they are not suitable for use in structural applications where mechanical performance is of primary importance. For the production of structured composites, natural fibres need to be spun into yarns for further processing into structured preforms using technologies that are currently used for forming preforms from carbon and glass fibre rovings (for example, weaving and braiding).

The conventional yarn production methods for staple fibres produce a twisted yarn structure. Fibres in a twisted yarn are poorly aligned. The detrimental effect of twist in staple fibre spun yarn reinforced composites has been well recognized [2–4]. However, a minimum level of twist has to be used in order to provide the yarn strength required for yarn handling in composite production. This minimum twist is still significant to the detriment of mechanical properties of the final composites. We recently proposed the use of two-ply yarns [3] to reduce the fibre misalignment without negative effect to the yarn strength. Ideally, yarns in structural composites should be twistless so that all fibres are perfectly aligned to the yarn axis [5]. In practice, fibres in the twistless yarn are still not perfectly aligned because the yarn body follows a somewhat tortuous path due to the tension and torque balance between the flax fibre body and the fine wrapping filament [6]. Weaving can cause further fibre misalignment due to the presence of yarn crimps in the resulting fabrics. To eliminate these structural defects and the expensive spinning and weaving process that are inherent to twisted and twistless yarns, we proposed a modified nonwoven process to produce highly aligned natural fibre tapes (or mats) [1]. However, we found that the composites made from the highly aligned nonwoven mat had a lower initial modulus than that from the unidirectional woven fabric and attributed this to the absence of fibre pre-tensioning introduced during the spinning and weaving operations, which has prompted this investigation on prestressing a low twist yarn during composite fabrication.

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Prestressing is a technique used widely in civil engineering to enhance the mechanical properties of reinforced concrete that is cast around tensioned tendons (usually steel bars). The cured concrete adheres and bonds to the steel bars and when pretension on the tendons is subsequently released, it is transferred to the concrete as a compressive stress which balances the tensile stress that the concrete compression member would otherwise experience due to external load. Mechanical properties of polymer-matrix composites can also be improved using prestressing. Fibre prestressing in relation to polymer-matrix composites manufacture falls into two general categories: (1) fibres are prestressed first and then processed into composites without the application of tension, and (2) an external tension is maintained on fibres during the curing process as composites are formed.

In the first category, prestressing serves two possible purposes. Firstly, prestressing breaks weak fibres and thus reduces the number of weak spots and the dynamic effect of weak fibre failure on its adjacent fibres in the composite [7,8]. Secondly, viscoelastic fibres retain some tension after external load is released gradually. This residual fibre stress can be exploited for making prestressed composites in a two-step process: first prestressing the fibres, and then using the fibres in a polymer-matrix composite immediately after the prestress on fibres is released and the viscoelastic fibres relax. The residual fibre tension transfers into compression stress to the polymer composite as the matrix solidifies [9,10]. The matrix compressive stresses impede crack propagation and reduce composite strain resulting from external tensile and bending loads for typical glass fibre/epoxy composites [11,12].

In the second category, tension is applied to fibres during resin curing. In the final composite material, the fibres are under tensile stress and the resin is under compressive stresses, similar to what happens in prestressed concretes mentioned earlier. Using the single fibre fragmentation technique, Scherf and Wagner [13] demonstrated that shear strength at carbon fibre– epoxy interface increases with increasing level of stress applied to fibre during curing. It has also been reported that the strain induced by fibre pretension in the composites can reduce the effect of thermal residual stresses resulting from the curing process [14]. In this paper, we will only refer this category of composites (i.e., fibres are tensioned during resin curing) as prestressed composites.

Two strengthening mechanisms for prestressed glass fibre reinforced polymer composites were proposed [12]. First, fibre prestressing places the matrix under compression residual forces, which retard crack opening mechanism in matrix and cancel out some part of the shear forces at the interface and the tensile forces in the matrix under external load. Second, prestressing stretches the fibres so that resin is cured around a straight and taut fibre, and therefore the fibres in the final composites contribute to carrying the load instantaneously and simultaneously.

The objective of this investigation is to understand how prestressing of a natural fibre spun yarn during resin curing affects the mechanical performance of the final natural fibre reinforced polymer-matrix composites. Unlike carbon fibre and glass fibre, which are typically twistless rovings, the natural fibre spun yarn has a twisted structure held together by fibre-to-fibre friction. The yarn structure and stress conditions undergo changes when a fixed strain on the yarn is maintained over the period of time required for resin curing.

2. Experimental

2.1. Flax fibre and yarn

Flax sliver with a linear density of 14 ktex (1 ktex = 1 g/m) was purchased from a textile mill in China. The sliver was spun into yarns on a lab scale Caipo SRL ring spinning machine. Preliminary spinning trials showed that the minimum twist level achievable with this flax fibre on the spinning machine without significant fibre loss and frequent yarn end breaks during spinning was a twist multiplier (TM) of 3.8. $TM = T/N_e^{1/2}$, where T is the number of twist turns per inch of yarn and N_e is the yarn count according to the English cotton system. Twist multiplier is directly related to the yarn surface fibre twist angle and is preferred for comparing the level of twist in yarns of different counts. All the yarns reported in this investigation were spun to this minimum twist multiplier of 3.8.

2.2. Testing of fibre and yarn

All the fibre and yarn samples were conditioned for 24 h at 20 °C and 65% relative humidity before testing. Tensile tests of the flax fibre were carried out on a Favimat™ single fibre tensile testing machine. The gauge length used was 10 mm and the crosshead speed was 1 mm/min. 95 fibres were tested. Tensile tests of the flax yarns were performed on Instron 5567 tensile testing machine using a 100 N load cell according to ASTM D 2256. The gauge length was set at 500 mm and the crosshead speed at 200 mm/min. 30 yarn specimens were tested.

Stress relaxation test on the flax yarn was carried out using the same Instron tensile testing machine. The yarn specimen was first elongated to the predetermined strain (for example, 0.03). The crosshead of the tensile testing machine was then stopped and held in position. The decay of force in the yarn was recorded over a period of one hour. The test was repeated on at least 5 specimens at each prestressing level.

2.3. Composites manufacturing

The composites fabrication procedure is illustrated in Fig. 1(a).

The flax yarn was first prepared into hanks (100 rounds of 1 m-long loops, see Fig. 1b) on a laboratory hanking machine. Our previous work showed that fibre moisture content can have a significant adverse effect on the interfacial shear strength of natural fibre/polymer composites [15,16]. To eliminate this effect, the yarn hanks were dried in a convection oven at 100 °C for 5 h before being used for composites fabrication. Unsaturated polyester resin F62333 and MEKP Interox NR20 hardener supplied by FGI Australia were used as matrix. The ratio between hardener and resin was 1.5%.

An open-ended two-part leaky mould [17] was used to produce composites from the prepared hanks of parallel yarns. The leaky mould was placed inside a steel channel frame fitted with a fixed pin and a movable pin, as shown in Fig. 1(b). The yarn hank was loaded (prestressed) between the two pins. Before the application of tension (prestressing), the part of the yarn hank in the range of the leaky mould was impregnated with the resin system using a brush (fibre and resin in approximate 50/50 ratio by weight), with the two ends of the hank near the pins being kept dry. The movable pin was then pulled by the screw mechanism to apply a predetermined level of strain to the yarn hank. The leaky mould was closed and the device was moved into a hydraulic press. A constant force (45 kN) was applied to the leaky mound while the resin was cured for 24 h at room temperature. As shown in Fig. 1(c), the large applied force ensures a constant gap height (3 mm) between the top die and the bottom die, which determines the sample thickness. The tension applied to the yarn hank was then removed by releasing the screw mechanism and the composites specimen was taken out from the mould. The specimen was post cured at 80 °C in a convection oven for two hours. The dimensions of the manufactured composites were 265 mm × 35 mm × 3 mm.