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Effect of linear density and yarn structure on the mechanical properties of ramie fiber yarn reinforced composites

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Effects of linear density and yarn structure on both static and dynamic mechanical properties of ramie fiber yarn reinforced composites (RYRCs) were investigated. The failure mechanisms of RYRCs were analyzed with the aid of ultrasonic C-scan and Scanning electronic microscopy (SEM). The results showed that the tensile strength of RYRCs increased gradually with increase of the linear density of the single yarns. The maximum tensile strength was obtained when the linear density reached 67.3 tex. However, a downtrend of the tensile strength was observed with further increase of the linear density of ramie single and plied yarns. The interlaminar fracture toughness was relatively high for RYRCs made from yarns with lower linear density due to the extensive fiber bridging observed during the double cantilever beam test. Meanwhile, the linear density and structure of ramie yarn had remarkable influence on the failure mode of RYRCs during the drop weight impact test.

1. Introduction

Plant fibers, such as flax [1], ramie [2], jute [3], and palm [4], have been widely used as composite reinforcements in fields as diverse as sporting goods, automotive, and aerospace over the past few decades [5,6]. The promotion of environmentally friendly plant fibers could make a great contribution to carbon emission reduction than traditional synthetic fibers [7]. Meanwhile, plant fibers reinforced composites (PFRCs) possess relatively high specific mechanical properties and superior functional properties (sound absorption, thermal insulation and damping properties) [8–10]. The low price and abundant availability of plant fibers make PFRC an ideal alternative for synthetic fiber reinforced composites.

Plant fibers are mainly extracted from the stems, leaves or fruits of plants, which make these fibers discontinuous due to the limited length of plant organs [11]. However, the continuous fibers are essential for manufacturing high performance composite materials. Continuous plant fiber yarns have been first applied in textile industry by ring spinning [12]. The mechanical behaviors of plant fiber yarns have been extensively investigated in numerous studies [13–15], which mainly focused on the textile application. As to composite reinforcements, in recent years researches have been looked into the potentials of aligned plant fiber yarn reinforced composites. Madsen and Lilholt [16] reported the values of axial stiffness and strength of the unidirectional flax yarn reinforced polypropylene composites with a fiber weight fraction varied from 56% to 72%, this being in the range of 27–29 GPa and 251–321 MPa, respectively. Pinto et al. [17] investigated the tensile strength and modulus (76.6 MPa and 11.9 GPa, respectively) of the unidirectional jute yarn reinforced epoxy composites. Using flax/polypropylene commingled wrap yarns, Zhang and Miao [18] reported the flexural strength of 145.6 MPa and modulus of 15.3 GPa for 31.4% fiber volume fraction composites. All these examples implied that the mechanical performance of the PFRC could be further improved by the optimization of plant yarn structures which will not be served for textile applications, but for composite reinforcements.

Twist degree and linear density of plant fiber yarns are the two essential factors which should be considered for optimizing the structure of plant fiber yarns. Effects of fiber twist of plant yarns on their reinforced composites received great attention by many researchers [11,12,18,19]. It was found that the twist of fibers could reduce the orientation efficiency of plant fibers and impair the permeability of plant fiber yarns, which led to detrimental effects on the mechanical properties of PFRC. Considering the strength of the yarns required for composites manufacturing process, a minimum suitable twist level of plant fiber yarns was proposed by some researchers [11,12,19].

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Table 1
Basic parameters of the single and plied ramie yarns.

Group	Linear density (tex)	Surface twist angle (°)
SRY16	15.8 ± 0.6	20.6 ± 1.6
SRY27	26.7 ± 1.8	19.8 ± 2.2
SRY67	67.3 ± 1.4	20.3 ± 1.8
SRY202	202.3 ± 2.5	22.5 ± 3.4
PRY64	(63.5 × 2) ± 3.1	10.8 ± 3.6
PRY182	(182.4 × 2) ± 3.8	11.9 ± 4.8

However, there are few works concerning the influence of linear density of plant fiber yarns on the mechanical properties of these fiber yarns reinforced composites. For carbon or other synthetic fibers, more attention was paid to the effect of fiber tow size on the mechanical performance of these composites. Jacob et al. [20] reported that an increase in tow size of chopped carbon fiber caused a decrease in the tensile properties and specific energy absorption of CFRP, due to the emerging of defects and voids in the composites. By contrast, plant fibers are typical products of natural resources and the spinning processes of plant fiber yarns is the substantial distinction to the manufacturing methods for continuous synthetic fiber yarns. Madsen et al. [21,22] chose two hemp fiber yarns with different linear density as composite reinforcements to comprehensively investigate the effects of yarn type, fiber volume fraction, matrix type, processing temperature and conditioning humidity on the axial tensile properties of the corresponding composites. Referring to the influence of linear density, the relatively similar selected yarns (46.5 tex and 52.9 tex) made the results have limited meaning on the selection of optimized linear density of plant fiber yarns.

Therefore, fully understanding the effects of linear density of plant fiber yarns on the mechanical properties of these fiber reinforced composites is important for selection and optimizing the structures of plant fiber yarns as composite reinforcements. In this work, six types of ramie fiber yarns were selected to make ramie fiber reinforced composites. Preliminary tensile tests were conducted on single ramie fiber extracted from different ramie yarns in order to investigate the influence of spinning processes on single ramie fiber. Unidirectional tensile and interlaminar properties of these composite laminates were studied. Meanwhile, drop weight impact (DWI) tests were also conducted since there was a noticeable lack of DWI data on PFRC which seriously limited their prospective applications in impact critical components. Scanning electronic microscopy (SEM) and Non-destructive C-scan photographs were used to characterize and analyze the fracture surfaces and failure mechanisms of RYRCs made from ramie fiber yarns with different linear density.

2. Experimental

2.1. Materials

Six types of ramie fiber yarns selected by this research were obtained from Hunan Dongting Maye Co., Ltd. (China), including four types of ramie single yarn and two types of plied yarns which were the commonly used yarn styles in the textile industry for increasing the strength of the yarns [23]. The ramie yarns with different linear density and structure were manufactured by using the same grade of ramie fibers to avoid the effects of other factors besides linear density. The linear densities of ramie yarns were measured from the dry weights of 10 m yarn samples from different bobbins. Subsequently, the six batches of ramie yarns were denoted as SRY16, SRY27, SRY67, SRY202, PRY64 and PRY182, where SRY meant single ramie yarn, PRY meant plied ramie yarn and the numbers referred to the corresponding meant linear densities. The surface twist angles of ramie yarns were obtained by measuring angels between different ramie fibers and axial of yarns in SEM photos with the aid of MiVnt software from Shanghai Optical Instrument Factory (China). In this research, 30 different parts of the yarn surface were randomly selected to measure and calculate the average surface twist angle for each type of yarn.

The linear density and twist angle of the selected six types of ramie yarns are listed in Table 1. It can be found that the linear densities of different types of ramie yarns were very distinct. However, if the deviations were taken into consideration, the twist

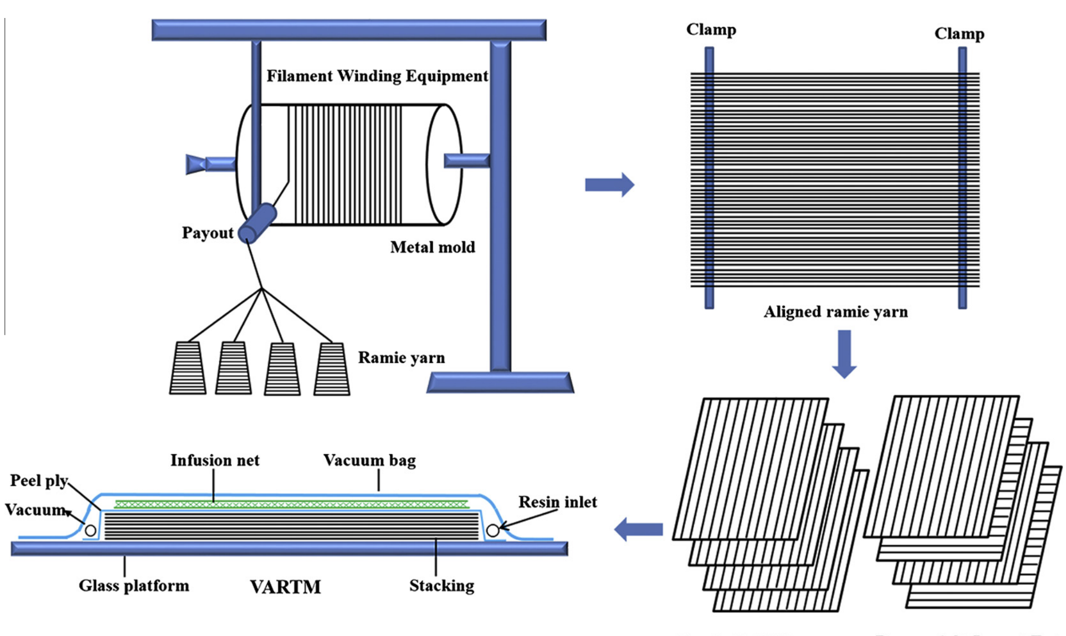

Fig. 1. Schematic drawing of fabrication process for composite laminates. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)