

A method for plaiting polymer fibre around natural yarn to form a composite fabric

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Abstract

A method has been developed for plaiting polymer fibre around natural yarn using a sewing machine to form a composite fabric. It was tested using polypropylene (PP) fibre and cotton yarn. An investigation of the relationship between the PP weight ratio and the number of PP fibres in the composite fabric revealed that the weight ratio can be easily controlled by adjusting the number of core PP fibres. The developed composite fabric was heat moulded to form fibre-reinforced polymer (FRP). Comparison of the stress–strain curve and tensile strength of this FRP with those of FRP made with conventional fabric revealed that, although the tensile strength of the FRP formed using the composite fabric was smaller than that of the conventional FRP, the strain of the developed FRP was larger because of delamination at the PP-cotton yarn interface. The developed FRP was improved by covering its top and bottom surfaces with a thin PP sheet before heat moulding. This prevented stress concentration, resulting in a 30% increase in tensile strength. Use of this FRP formed material using composite fabric is an effective approach to forming composite materials having high strain performance and tensile strength.

Keywords: fibre-reinforced composites, composite yarn, polypropylene, cotton, static tensile test, stress–strain curve.



1 Introduction

Materials made of thermoplastic resin and natural fibres have attracted much attention as environment-friendly materials because they can be easily disposed of using only an incinerator. Moreover, fabrics woven using composite yarn made of natural yarn and resin fibre should have higher strength. However, the methods proposed so far for forming composite yarns (such as fusion, powder, and solvent [1]) are not cost effective [2, 3]. There is thus a need for novel materials with high recyclability and easy disposability.

Several kinds of natural fibres have been used as a reinforcing material in the quest for better composites [4, 5]. Cotton yarn is particularly attractive because it has higher heat resistance than other fibres such as jute, hemp and bamboo. High heat resistance is especially important for composites made using thermoplastic resin because they are fabricated at high temperature. While composite fabric has been shown to have sufficient strength for practical application, impregnation of the resin into the fabric is problematic, especially for thermoplastic resin with high viscosity.

A method for plaiting polymer fibre around natural yarn has been developed using a sewing machine to form a composite fabric. It was tested using polypropylene (PP) fibre and cotton yarn. The relationship between the PP weight ratio and the number of PP fibres in the composite fabric was first investigated and it was found that the weight ratio can be easily controlled by adjusting the number of core PP fibres. A fibre-reinforced polymer (FRP) was then formed using the composite fabric and heat moulding. Examination of its stress-strain curve and tensile strength with those of FRP made with conventional fabric revealed that, although the tensile strength of the FRP formed using the composite fabric was smaller than that of the conventional FRP, its strain was larger because of delamination at the PP-cotton yarn interface. Covering the top and bottom surfaces of the laminated composite fabric with a thin PP sheet before heat moulding reduced the stress concentration, resulting in a 30% increase in tensile strength.

Use of this plaiting method should be easy to implement because it requires only the addition of a small sewing machine. Moreover, the moulding conditions are easy to control because the amount of PP fibre can be easily adjusted by changing the plaiting pitch and the number of PP fibres.

2 Fabrication and structure of composite yarn and composite fabric

2.1 Composite yarn

The structural model of the developed composite yarn is shown in fig. 1(a). To increase the matrix polymer content, some matrix fibres, the 'core matrix fibres', are arranged in parallel along the reinforcing yarn, as shown in fig. 1(b). The matrix fibres are plaited around the centre of the reinforcing yarns, as illustrated in fig. 1(c), by using a mellow sewing machine. The twisted cotton yarn, made

with four tenth-string single yarns was used as the reinforcement yarn at the centre. Monofilament PP fibres (300D) were used as core fibres. Their mechanical properties are listed in table 1. The fibre diameter, plaiting pitch L , and the number of reinforcing PP fibres can be freely selected, meaning that the composite moulding conditions are easy to control. A photograph of the composite yarn is shown in fig. 1(d): on the left, the composite yarn is shown with only cotton yarn at the centre; on the right, the yarn is shown with three core PP fibres at the centre along a cotton yarn.

Table 1: Mechanical properties of PP fibre (300D).

Density	Bend		Pull			Deflection temperature under load	Rockwell hardness
	Modulus	Strength	Modulus	Yield stress	Stress		
0.9[g/cm ³]	1500[MPa]	43[MPa]	1500[MPa]	34[MPa]	100[Mpa]	100[°C]	100

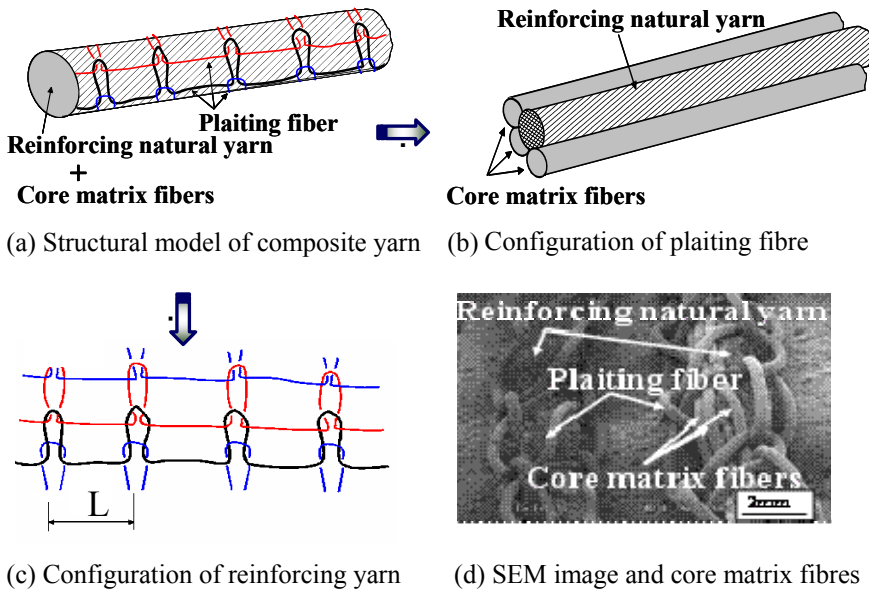


Figure 1: Composite yarn.

To investigate the relationship between the weight ratio of the PP and the number of core PP fibres, five composite yarn samples were prepared with the number of core PP fibres ranging from one to five. The plaiting pitch was set to 3.9 mm. The weight ratio of the PP in the composite yarn was measured by dissolving the cotton yarn using 70% sulphuric acid. The change in the weight ratio with the number of core PP fibres is shown in table 2.

Table 2: Weight ratio of PP and cotton.

The number of core PP fibers	1	2	3	4	5
Cotton [wt%]	49.95	45.79	41.85	38.96	36.89
PP [wt%]	50.05	54.21	58.15	61.04	63.11

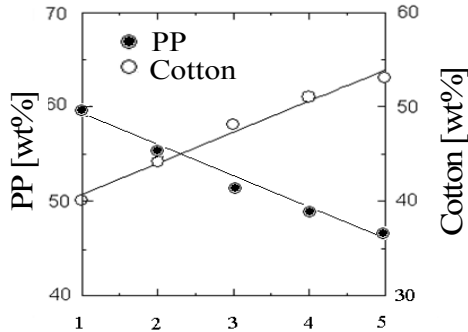


Figure 2: The number of core fibres.

As shown in fig. 2, the number of core PP fibres and the PP weight ratio had an almost linear relationship. This means that the weight ratio can be easily controlled by adjusting the number of core PP fibres.

The composite yarn fabricated using our plating method has four key features.

- Different types of reinforcement yarns and plaiting fibres can be used.
- The matrix content can be easily adjusted due to the easy adjustability of the plaiting pitch, the number of core matrix fibres, among others.
- Composite fabrics with various weave patterns (plain, braid and 3D) can be easily fabricated.
- Composite fabrics woven using the developed composite yarn should have high strength and good flexibility, making them suitable for various applications.

2.2 Composite fabric

Composite fabric was fabricated by weaving the composite yarn using a weaving machine. The number of core PP fibres was 1, 3 or 5, the weave pattern was plain, while the warp and woof were, respectively, set to 12 and 11 per inch. The thickness was 0.8 mm for the fabric woven with cotton yarn only and 1.5 mm for fabric woven using the composite yarn.

3 Moulding method for FRP plate

To form a fibre-reinforced plastic (FRP) plate, three composite fabrics were stacked in a laminate structure in a mould die and heated with a hot press. Lubricant was previously coated on the top and bottom surfaces of the die to prevent the PP from adhering to it. The moulding temperature, pressure and time

were set to 190°C, 1.5 MPa, and 7 minutes, respectively. After heating, the die was kept at room temperature for ten minutes.

To compare the mechanical properties of the developed fabric FRP with those of a conventional fabric FRP, fabric FRP was prepared using cotton fabrics and thin PP sheets. The cotton fabrics were arranged in a plain weave pattern, and the PP sheets were stacked in a laminate structure, as illustrated in fig. 3. The sheets were 0.11, 0.16, and 0.2 mm thick. The FRPs made using the developed fabric are identified as P1, P2, and P3, as listed in table 3. Those made using the conventional fabric and a PP sheet are identified as S1, S2, and S3, as listed in table 4. For instance, test specimens S1 and P1 were moulded using the same PP weight ratio. The FRP plates were all 240 × 240 mm. The moulding conditions were the same for both types of FRP.

Table 3: Identification of FRPs formed using composite yarn.

Test specimens	The number of core PP fibers
P1	1
P2	3
P3	5

Table 4: Identification of FRPs formed using PP sheet and conventional fabric.

Test specimens	Thickness of PP sheet [mm]
S1	0.11
S2	0.16
S3	0.2

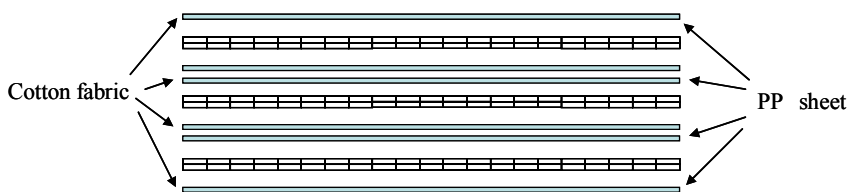


Figure 3: Construction of conventional fabric FRP.

4 Static tensile test

4.1 Specimens

The FRP plates were cut into specimens 25 mm (12 warp) in width and 200 mm in length with a diamond cutter for static tensile testing. Aluminium tabs, 50 × 25 mm) were attached to both ends of each specimen (as shown in fig. 4).

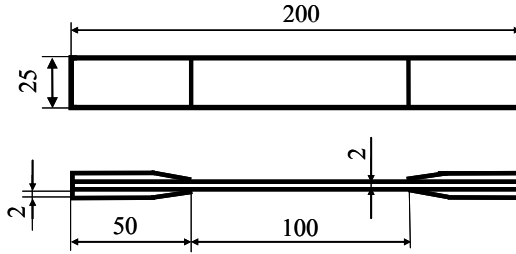


Figure 4: Test specimens for tensile test.

4.2 Conditions

An automatic tensile tester with displacement control was used. The tensile speed was set to 5 mm/min. The room temperature and humidity were 20°C and 65%, respectively. The number of test samples was six for each specimen. The fracture faces after the tensile test were observed using a photon microscope (VQ-Z50, Keyence).

5 Results and discussion

Figure 5 shows the tensile stress–strain curves for specimens P1, P2, P3, S1, S2, and S3, and fig. 6 shows the tensile strength for each specimen.

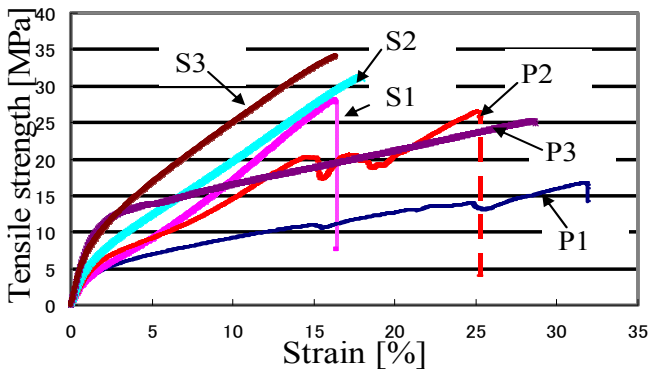


Figure 5: Tensile stress–strain curves for each FRP specimen.

As shown in fig. 5, the tensile strain for P2 was low, about 15–20%. Such a decrease for S2 is not evident. As shown in fig. 6, the tensile strength increased with the PP resin content. Since the cotton yarn content was the highest in P1 and S1, P1, S1, P2, and S2 had insufficient resin content to have a noticeable composite effect.

SEM photographs of a cross-section of P2 and S2 at a point where the strain was 15–20% are shown in fig. 7. With the P2 specimen, delamination occurred

at the boundary between the PP and cotton yarn. As a result, although the tensile strength of the developed FRP was lower than that of the conventional FRP, its maximum strain was larger. The developed FRP thus has better strain performance than the conventional FRP. The tensile stress was lower in the P3 specimen. This is because P3 had sufficient resin to have a noticeable composite effect.

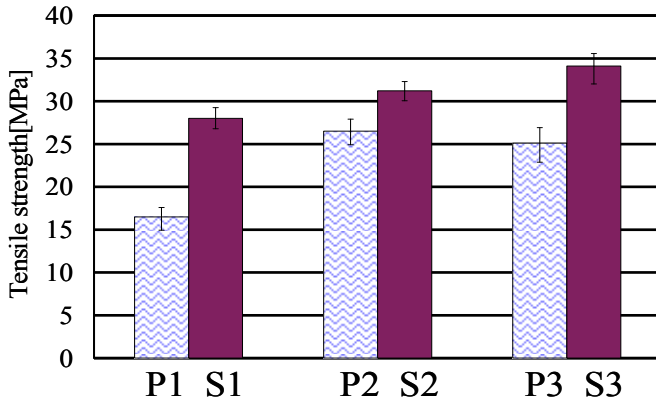


Figure 6: Tensile strength for each FRP specimen.

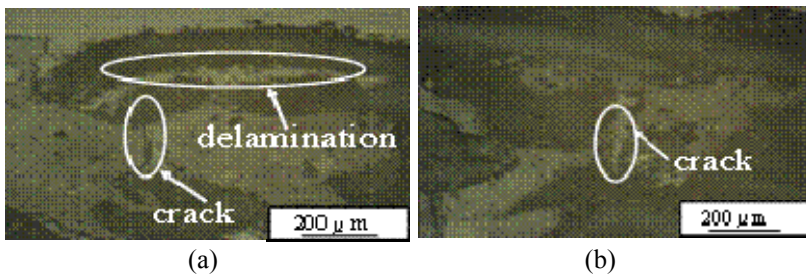


Figure 7: SEM images of the FRPs in cross-section after tensile test. (a) P2 specimen, developed FRP with composite yarn. (b) S2 specimen, conventional FRP with cotton fabric and PP sheet.

Next the focus was on the unevenness on the FRP surface because the developed FRP had more unevenness than the conventional FRP. The large unevenness on the developed FRP surface was due to the PP not uniformly covering the FRP surface, resulting in stress concentration somewhere near the surface. To increase the maximum tensile strength of the developed FRP, the top and bottom surfaces of the composite fabric in laminate was covered with thin PP sheets before heat moulding. This changed the PP weight ratio (as shown in table 5).

Table 5: Weight ratio of PP and cotton.

The number of core PP fibers	1	3	5
Cotton [wt%]	40.05	32.42	27.78
PP [wt%]	59.95	67.58	72.22

The stress–strain curves of the improved FRP are shown in fig. 8; the improved FRPs are identified as “PS”. For instance, the specimen with PP sheets added to the surfaces of P1 is “PS1”. Fig. 9 shows the tensile strength of the P- and PS-type specimens. Adding the sheets was effective in reducing the stress concentration, and the tensile strength was improved by about 30% for PS1.

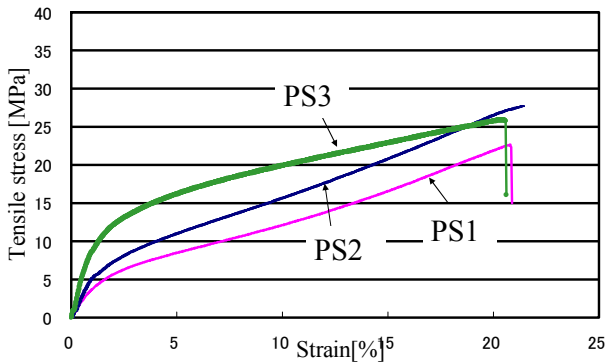


Figure 8: Tensile stress–strain curves of FRP after adding PP sheet to top and bottom surfaces.

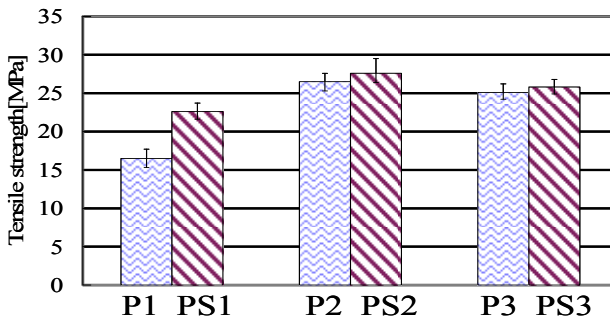


Figure 9: Tensile strength before (P) and after (PS) adding PP sheets to surfaces.

A check for delamination after tensile testing showed that the FRP formed using the composite yarn had high strain performance. Moreover, adding the PP sheets to the surfaces of the composite fabric before heat moulding effectively improved tensile strength.

Future work includes identifying the optimum conditions (number of core PP fibres and pitch of plaiting fibres) for moulding composite materials with high strength.

6 Main results

- (1) The cotton content in the composite yarn had an almost linear relationship with the number of core PP fibres.
- (2) The composite fabric made using cotton/PP composite yarn was flexible.
- (3) The strain of the FRP plate made using the composite fabric was larger than that of one made using a PP sheet because using the composite fabric has caused flaking off.
- (4) The unevenness of the FRP surface decreased the tensile stress. Reducing the unevenness by using a PP sheet increased the tensile strength by about 30% for the P3 specimens.

Acknowledgements

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