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# Effects of Pre-stretching on the Tensile Properties of Knitted Glass Fiber Fabric Reinforced Polypropylene Composite

FAN ZAIXIA, ZHANGYU,\* CHEN YANMO AND LONG HAIRU

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**ABSTRACT:** Weft knitted glass fiber (GF) fabric reinforced polypropylene (PP) composite sheets were fabricated by hot pressing of stacked rib 1:1 knitted fabric preform layers. The knitted preforms were made from GF/PP commingled yarn containing 50 vol% ( $\approx 73$  wt%)GF. Before hot pressing, the preforms were stretched in the wale direction at various ratios. The tensile properties of the pre-stretched GF-PP composites were studied. It was found that there is a critical value of pre-stretch ratio as far as tensile stiffness and tensile strength are concerned. On increasing the pre-stretch ratio within the range of this critical value, both tensile stiffness and tensile strength increase. If the pre-stretch ratio goes beyond this critical value and continues to increase, both tensile stiffness and tensile strength display a tendency of slight decrease because of the break of more glass fibers. The failure strain of the composites decreases with the increase of the pre-stretch ratio because of the decrease of the stretchability of the knitted reinforcements.

**KEY WORDS:** GF/PP commingled yarn, pre-stretch ratio, GF-PP composite, tensile properties.

## INTRODUCTION

**K**NITTED FABRIC REINFORCED composite is a kind of reinforced composite textile structure. The unique interlocked loop structure gives knitted fabric many advantages [1,2]: (1) excellent stretchability and drapability, which allows it to match with any complex shapes very well without folds; (2) excellent shape forming ability, that is, the desired shape (even if double curved shape) can be gained through knitting by the use

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of advanced knitting machines. This technology of shape forming is the so called near-net-shape technology and/or net-shape technology. These advantages of knitted fabric make the knitted fabric reinforced composites possess the following characteristics [1,2]: good drapability, good impact properties, good interlaminar properties, good shapeability, high production rate, short production period, and so on. For many years, knitting technology has been proved to be a cost-effective way of producing composites. However, the same loop structure gives the knitted composites lower tensile stiffness and strength compared to conventional composites. Therefore, many researchers have tried a variety of ways to improve the tensile properties of knitted composites, including the use of floating loops structure instead of simple loops [3], the insertion of straight reinforce fibers and/or yarns into the knitted fabric preform in the wale and/or course direction [4,5], and the pre-stretch of knitted preform uni-axially and/or bi-axially before consolidation [6,7]. Although much research had been done on the effects of pre-stretch on the tensile properties, the pre-stretch ratio along the wale in previous researchers' studies was lower than 50%. The effect of a higher ratio of pre-stretch along the wale on the tensile properties of knitted composites is not known. The primary objective of this article is to study the effect of pre-stretch along the wale, especially the higher ratio one, on the tensile properties of knitted glass fiber fabric reinforced composites made from GF/PP commingled yarn.

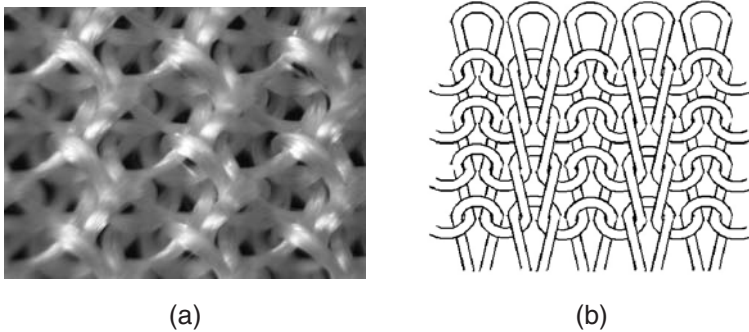
## EXPERIMENTS

### Materials

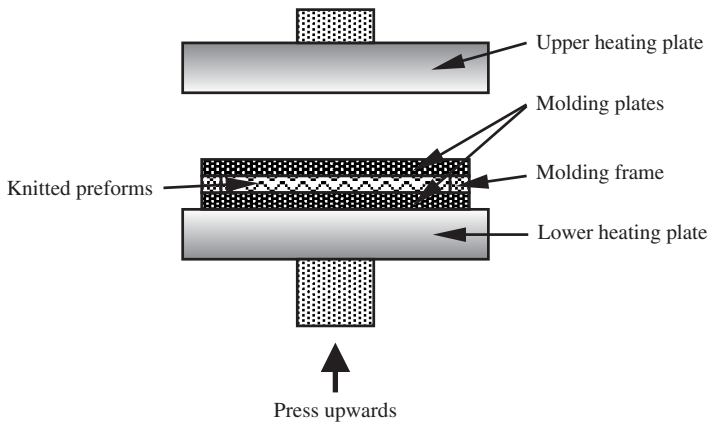
The material used in this investigation was glass fiber/polypropylene (abbreviated as GF/PP below) commingled yarn supplied by Jiangsu Jiu Ding Group. The commingled yarn consisted of two plies of glass fiber filament and two plies of polypropylene filament, and was produced on the special roving frame for glass fiber filament. The linear density of the glass fiber filament and the polypropylene filament were both 330 dtex. Therefore, the content of glass fiber in the commingled yarn was 50 vol% ( $\approx 73$  wt%). The melt flow index (MFI) of the polypropylene resin was 35°/min. The glass fiber filament was sized with PP-suitable sizing and the polypropylene filament was with no sizing.

### Fabrication of Preforms

The weft-knitting technique was used to make preforms from the GF/PP commingled yarns. The weft-knitted structure was produced on the flat



**Figure 1.** Photographs (a) and (b) and schematic of rib 1 : 1 structure.

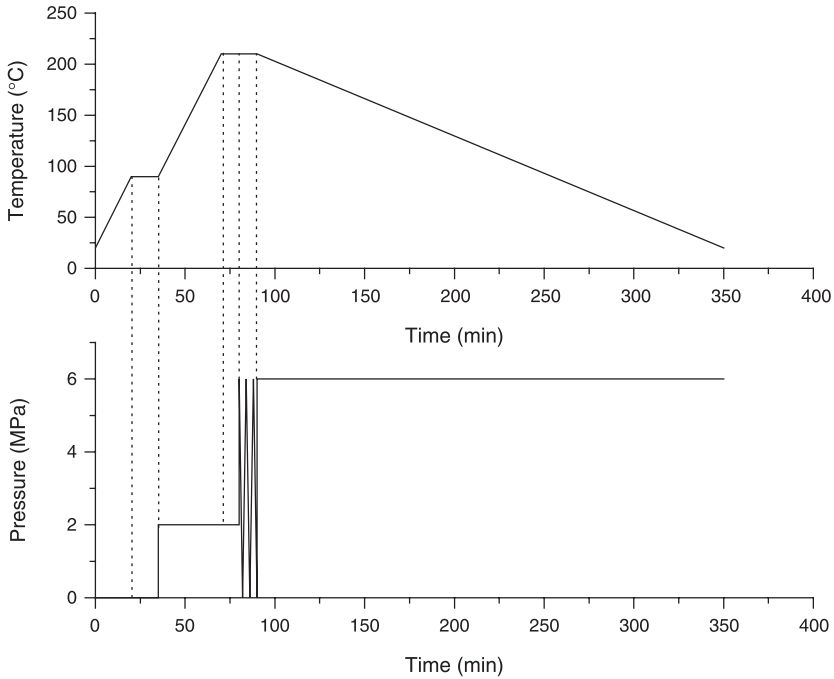


**Figure 2.** Schematic diagram of composite fabrication by a hot press.

knitting machine and was usually called the rib 1 : 1 structure (Figure 1). The fabric had a loop density of 72 loops/cm<sup>2</sup>.

### Fabrication of Composites

Five layers of preforms obtained in the previous section were stacked in the same direction and hot-pressed on the hot-pressing machine to produce the glass fiber knitted fabric reinforced polypropylene composites. Figures 2 and 3 give the schematic diagram of composite fabrication by hot-press, and the pressure and temperature for the fabrication process of GF/PP composites respectively.



**Figure 3.** Temperature and pressure for fabrication process of GF/PP composites made from knitted preforms.

Firstly, the preforms were put into the hot-pressing machine at room temperature without being pressed. Next, the temperature was raised up to 90°C at the rate of 6°C/min to make the polypropylene soften, and this temperature was maintained for 15 min. Then a pressure of 2 MPa was put on the preforms to press them tightly and the temperature was raised to 210°C. When the temperature reached 210°C, a pressure of 6 MPa (oscillating pressure as shown in Figure 3) was applied on the ‘melted preform’ and released many times so as to squeeze out the air trapped inside. This temperature was maintained for about 10 min. Finally, keeping the pressure of 6 MPa, the temperature was dropped down to the room temperature naturally. A composite film with a thickness of about 2 mm was produced from this process.

Before hot-press, all of the five layers of preforms were pre-stretched on a homemade stretch frame (shown in Figure 4) along the wale.

Strong cloth that was not easy to elongate and which can resist high temperatures was used as stretching cloth. The stretching cloth was sewed to both ends of the preform. One end of the preform was fixed to

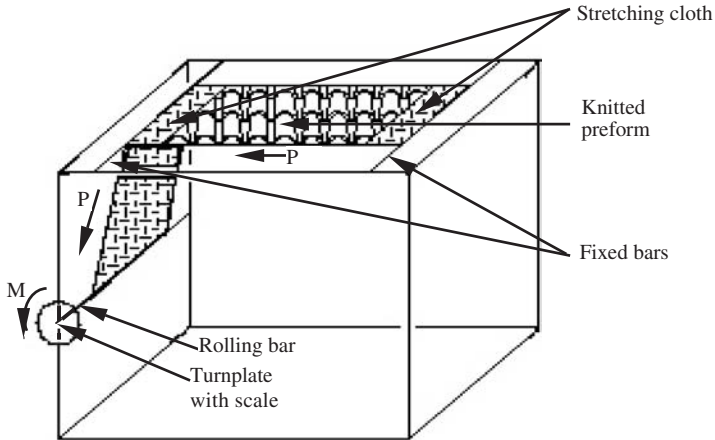


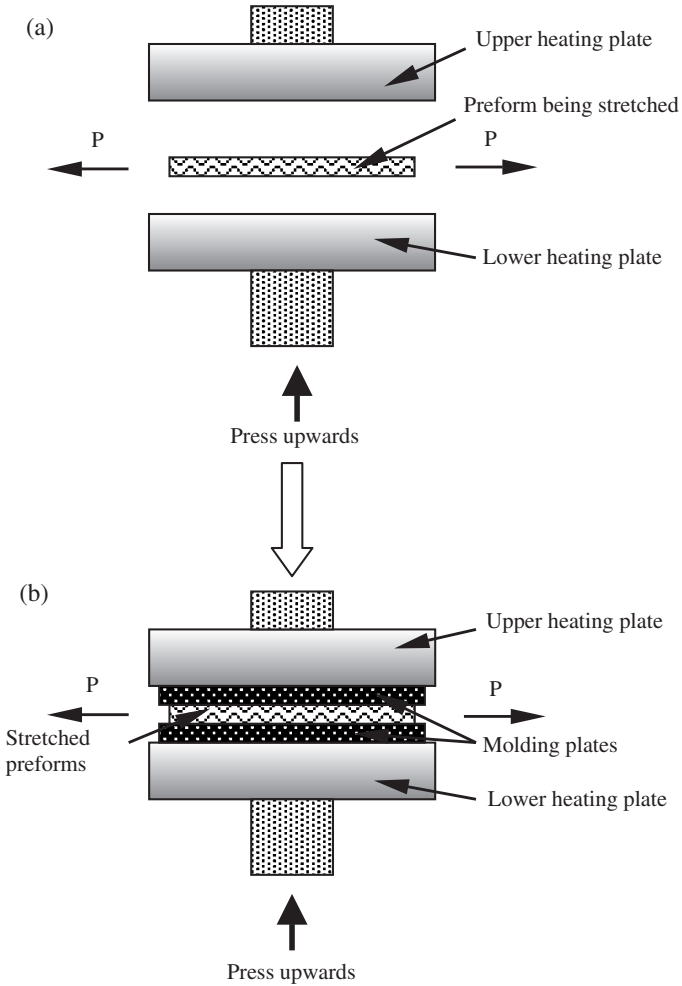
Figure 4. Schematic of the homemade stretch frame.

the back fixed bar, and the other end went across the front fixed bar and fixed to the rolling bar. The rolling bar was connected to a turnplate with scale. Turning the turnplate would stretch the preform out by winding the front stretching cloth to the rolling bar. Compared with the elongation of the preform, the stretching cloth can be neglected because it was not easy to elongate. Therefore, the distance that the turnplate turned can be taken as the stretched-out length of the preform. Keeping the preform stretched and hot-pressed, pre-stretched composite would be produced. The whole fabrication process of pre-stretched composites consists of two steps—stretching step and hot-pressing step—as shown in Figure 5 (a) and (b).

In order to study the effect of pre-stretch ratio ( $R$ ), which was defined as the proportion of the stretched-out length ( $\Delta l$ ) to the original length ( $l_0$ ) (Equation (1)), on the tensile properties of the composites, nine groups of composites numbered I, II, III, ..., IX were made from preforms with different pre-stretch ratios of 0, 5, 10, 20, 30, 40, 50, 60, and 80%. The corresponding relationship between the serial number and the pre-stretch ratio is shown in Table 1.

$$R = \frac{\Delta l}{l_0} \times 100(\%) \quad (1)$$

Here,  $R$  refers to the pre-stretch ratio of the preform,  $\Delta l$  is the stretched-out length of the preform, and  $l_0$  means the original length of the preform.



**Figure 5.** Fabrication process of pre-stretched composites: (a) step 1: stretching and (b) step 2: hot pressing.

**Table 1.** Relationship between serial number of composite samples and pre-stretch ratio of preforms.

| Serial number             | I | II | III | IV | V  | VI | VII | VIII | IX |
|---------------------------|---|----|-----|----|----|----|-----|------|----|
| Pre-stretch ratio $R$ (%) | 0 | 5  | 10  | 20 | 30 | 40 | 50  | 60   | 80 |

## Tensile Tests

The composite films were cut into tensile specimens of dimension  $250 \times 25 \times 2 \text{ mm}^3$ , along the warp direction of the knitted fabric. At least five pieces of specimens were prepared for each group of composites with different pre-stretch ratios. The tensile tests were carried out at room temperature on the computer controlled model WDW-20 Hualong Electron Universal Test Machine, at a crosshead speed of 10 mm/min.

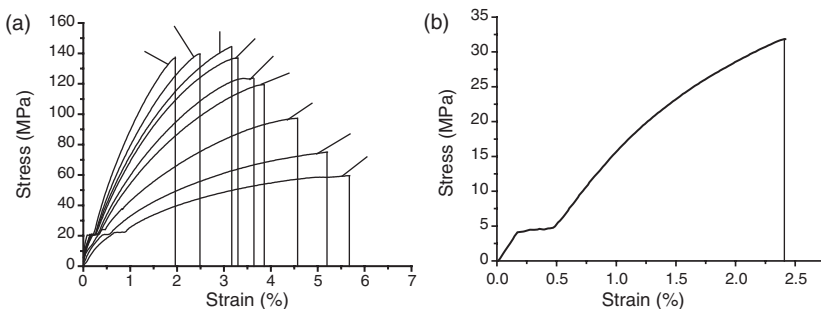
## Scanning Electron Microscopy

The cross-sections of the composite films made from a single layer of preform with different loop densities were examined by scanning electron microscopy using JEOL, Model JSM-5600 at 30 kV accelerating voltage. All samples were coated with gold and examined at a magnification of  $100\times$  or higher.

## RESULTS AND DISCUSSION

### Tensile Stress–Strain Curve

Although fabricated from preforms with different pre-stretch ratios, the nine groups of composites displayed very similar tensile stress–strain curves as shown in Figure 6(a). This similarity in tensile stress–strain curve of the nine groups of composites indicates the fact that the failure mechanism for composites made from preforms pre-stretched in different ratios is the same, that is, pre-stretching of the preform had no influence on the tensile failure



**Figure 6.** Typical stress–strain curve of: (a) GF/PP composites made from pre-stretched preform and (b) PP matrix.



mechanism of the composites. Figure 6 (b) shows the typical tensile stress–strain curve of polypropylene matrix. As can be seen from Figure 6(a) and (b), the typical tensile stress–strain curve of GF/PP composites is similar in shape to that of pure polypropylene, which is a kind of thermoplastic material. And this implies the fact that the GF/PP knitted composites possess thermoplastic properties. In other words, the GF/PP knitted composites belong to thermoplastic materials.

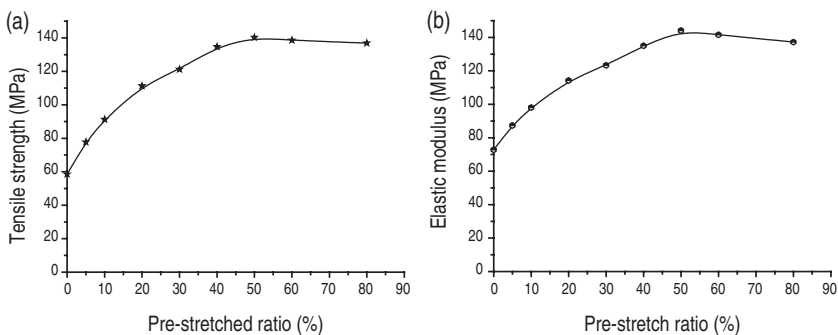
### Tensile Stiffness and Tensile Strength

The tensile stiffness determined by averaging the slope value of the initial linear section before yield section in the strain–stress curve, and the tensile strength of GF/PP knitted composites made from preforms with different pre-stretch ratios are shown in Figure 7 (a) and (b) respectively.

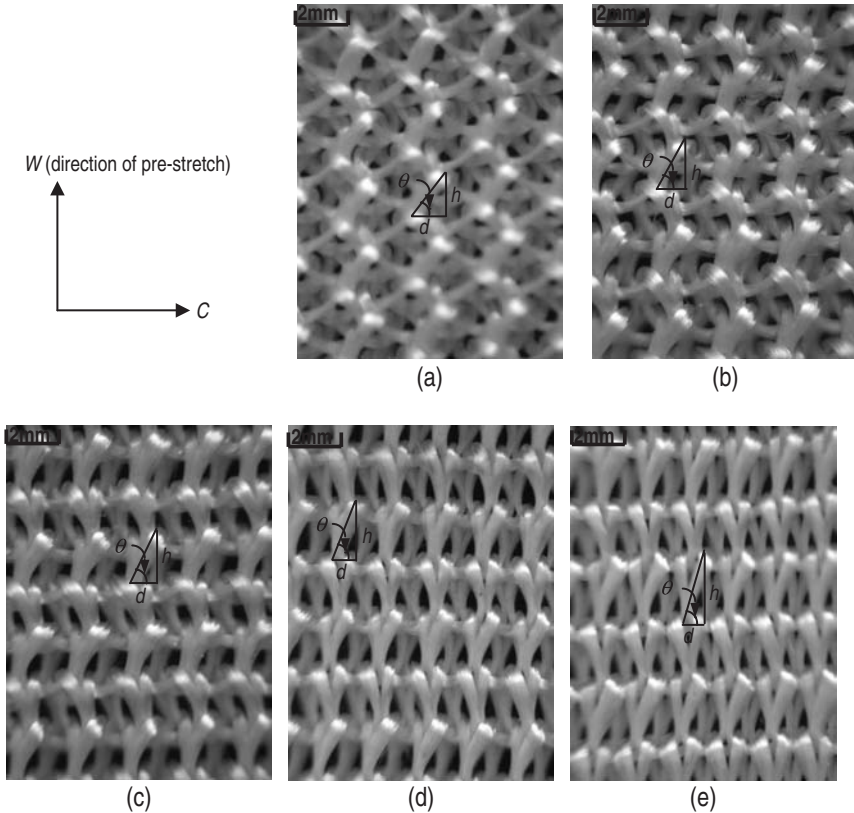
As can be seen, both tensile stiffness and tensile strength of the composites increased as the pre-stretch ratio increased from 0 to 50%. However, on increasing the pre-stretch ratio further (from 50% to 60% and 80%), neither the tensile stiffness nor the tensile strength increased. Instead, both of them showed a slight drop-down.

Figure 8 (a)–(e) gives the photo of preform pre-stretched by 0, 20, 40, 60, and 80%, respectively.

From these photos, it can be seen that, the loop configuration changes greatly with the increase in the pre-stretch ratio. Under wale tension, more and more yarns skip from needle loops and sinker loops to loop ribs, resulting in an increase of loop height  $h$ , but a decrease in loop distance  $d$ . This transfer of yarns in loops, on the one hand, causes the loop ribs to elongate and orient in the wale direction gradually, which is reflected by the



**Figure 7.** (a) Tensile strength and (b) tensile stiffness of GF/PP composites with different pre-stretch ratio.



**Figure 8.** Photos of preform pre-stretched in ratio of (a) 0%; (b) 20%; (c) 40%; (d) 60%; and (e) 80%.

increase in  $\theta$ , the angle between the loop rib and the course direction. This means, more and more glass fibers align in the wale direction, that is, the orientation degree of glass fibers in the wale direction increases. The increase in the orientation degree of glass fibers in the wale direction contributes to the enhancement of both the tensile stiffness and tensile strength of the composites. On the other hand, this transfer of yarn in loops causes the curvature radius of the needle loops and the sinker loops to increase. Increase of the curvature radius of the needle loops and the sinker loops leads to more and more glass fibers breaking at needle loops and/or sinker loops because of their brittleness. The breakage of glass fibers has a negative effect on the increase of tensile stiffness and tensile strength of the composites. In order to validate this conjecture about the break of glass

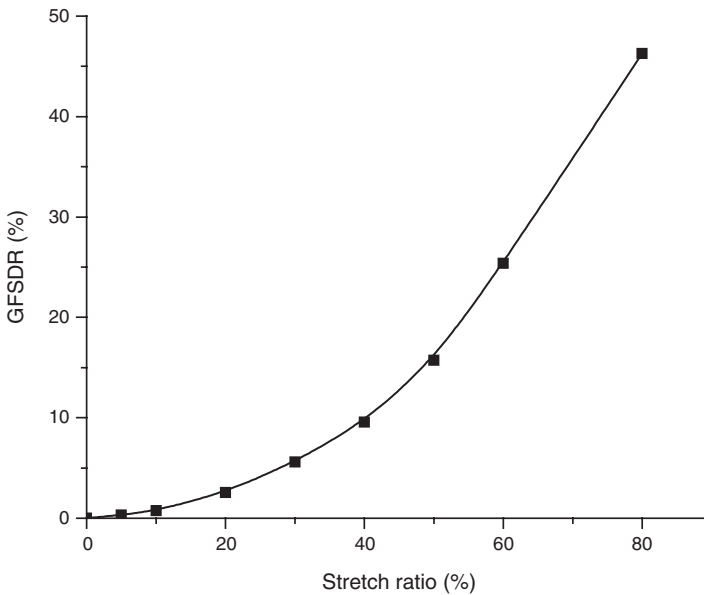
fiber while pre-stretching, the degree of glass fibers' break caused by stretch was investigated and *glass fiber strength damage ratio (GFSDR)* was introduced to express this break degree quantitatively. *GFSDR* was defined as the proportion of the strength of the glass fiber bundle unraveled from the stretched preform ( $T_1$ ) to that of the glass fiber bundle unraveled from the un-stretched preform ( $T_0$ ) (see the equation below):

$$GFSDR = \frac{T_1}{T_0} \times 100(\%) \quad (2)$$

Here,  $T_0$  and  $T_1$  refer to the tensile strength of the glass fiber bundle unraveled from the stretched preform and that of the glass fiber bundle unraveled from the un-stretched preform, respectively.

The relationship between *GFSDR* and the stretch ratio of the preform is given in Figure 9.

It can be seen clearly from Figure 9 that the strength of the glass fiber bundle in the preform decreased greatly as the stretch ratio increased. When the preform was stretched by 80%, the glass fiber bundle in it lost nearly 50% of its original strength. This indicated that the glass fiber break did occur with preform stretch and the break degree of glass fibers increased



**Figure 9.** The relationship between *GFSDR* and the stretch ratio of the preform.

rapidly with the increase in the stretch ratio. This was definitely disadvantageous to the increase in the tensile stiffness and tensile strength, while the pre-stretching method was used to increase the tensile properties of the composites.

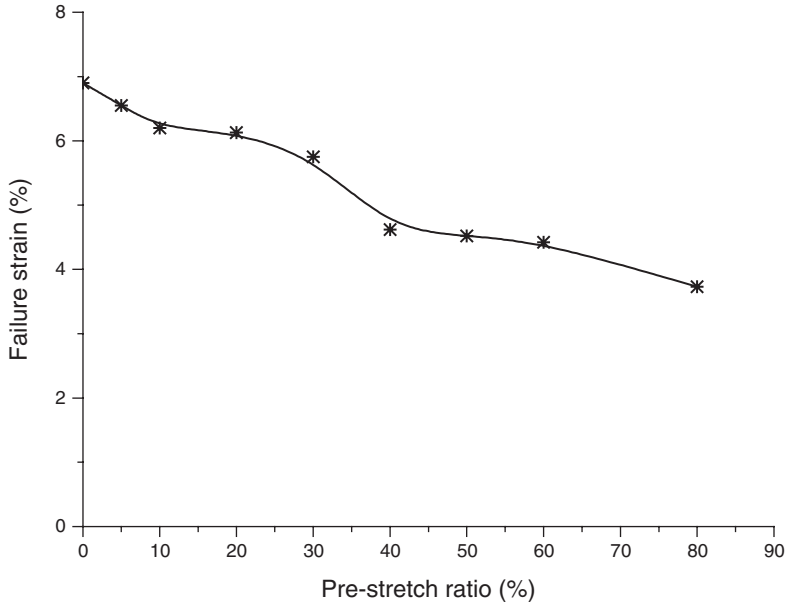
Therefore, pre-stretching the preform has both positive and negative effects on the tensile stiffness and tensile strength of the composites. There is a certain critical value  $R_0$  of pre-stretch ratio  $R$ . When  $R = R_0$ , the increment of the tensile stiffness and tensile strength brought by the positive effect of pre-stretching equals their decrement caused by the negative effect of pre-stretching. Thereby, if  $R < R_0$ , the increment brought by the positive effect of pre-stretching is larger than the decrement caused by the negative effect of pre-stretching, the tensile stiffness and tensile strength of the composites increase with the increase of pre-stretch ratio; and if  $R > R_0$ , i.e., if the decrement exceeds the increment, the tensile stiffness and tensile strength of the composites will not only not increase, but also decrease slightly as pre-stretch ratio increases.

$R_0$  varies with a lot of factors, such as the properties of glass fibers, loop structure, and geometric variables – including loop density, loop height, loop distance, and so on – of the preform, etc. The more brittle and weaker the glass fibers are, the smaller  $R_0$  is. If the loop structure of the preform causes the glass fiber to be badly curved,  $R_0$  will be lowered. Higher loop density of the preform results in smaller  $R_0$ . The one that has the longer loop height and shorter loop distance will show smaller  $R_0$ , if the two preforms have the same loop density and wale pre-stretch is applied. As far as the preforms in this research are concerned, it can be seen from Figure 6 that, this value of  $R_0$  is about 50%. It can also be seen from Figure 6 that the decrease tendency of both tensile stiffness and tensile strength is not very obvious, although this phenomenon should not be neglected. And if the pre-stretching method is used to improve the tensile stiffness and tensile strength of the knitted composite, it is better to find out this value of  $R_0$  and to make sure that the knitted preform is pre-stretched within the range of this critical value.

### **Failure Strain**

Figure 10 shows the relationship between pre-stretch ratio of the preform and the failure strain of the composites.

It can be seen from Figure 10 that the failure strain of the composites basically displays a tendency to decrease with the increase in pre-stretch ratio. This is mainly because the stretchability of the knitted reinforcements in the composites decrease with the increase of pre-stretch ratio. Although it is mentioned in the previous section that, more glass fibers break with the



**Figure 10.** Failure strain of composites made from preforms pre-stretched in different ratio.

increase of pre-stretch ratio as is known, the break of glass fibers results in the formation of many short glass fibers. These short glass fibers may contribute to the increase in the failure strain of the composites to some extent. But this effect of broken glass fibers is negligible compared with that of the decrease of the stretchability of the reinforcements. Therefore, the failure strain of the composites basically decreases with the increase of the pre-stretch ratio.

## CONCLUSIONS

The effects of pre-stretching on the tensile properties of the composites made from GF/PP commingled yarn preforms are discussed in this article. As far as tensile stiffness and tensile strength are concerned, there is a critical value of pre-stretch ratio. On increasing the pre-stretch ratio within the range of this critical value, both tensile stiffness and tensile strength increase. If the pre-stretch ratio goes beyond this critical value and continues to increase, both tensile stiffness and tensile strength display a tendency to slightly decrease because of the breakage of more glass fibers. The failure strain of the composites decreases with an increase in the pre-stretch ratio because of the decrease in the stretchability of the knitted reinforcements.

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