Flexural Properties and Low-Cycle Bending Fatigue of Anisotropic Carbon Fiber Mat Reinforced Composites

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Abstract. The carbon fiber/polypropylene (CF/PP) nonwoven fabrics were manufactured by carding process, lay-up process and needle punched process. After hot pressing the nonwoven fabrics, the CF/PP composites were mold. CF/PP composites with carbon fiber lengths of 50 mm and 70 mm was prepared respectively. The 3-point bending test and the low-cycle bending fatigue test (LCBF) at constant stress of 55%, 70% and 85% of original flexural strength were performed. The results showed that the ratio of transverse direction (TD)/ machine direction (MD) flexural modulus of CF50 and CF70 was 1.55 and 2.35, which indicated the composites exhibited anisotropic property. The longer the fibers were, the easier they were to be oriented. The effect of low cycle bending fatigue (LCBF) with 55% and 70% stress level on flexural properties was not obvious. The LCBF of 85% stress level has an obvious influence, and some samples have broken before reaching 30 times of fatigue. Optical observation shows that with the increase of fatigue stress level, the crack becomes deeper, and the bending modulus and strength decrease obviously.

1. Introduction  
Fiber reinforced plastics (FRP) are widely used in engineering fields due to their excellent mechanical properties [1,2]. Compared with glass fiber, carbon fiber has higher mechanical properties and lighter weight, so metal materials are gradually replaced by carbon fiber reinforced composite materials (CFRP) [3,4].

However, thermoplastic resins have the disadvantages of high melt viscosity and have difficulty in impregnating carbon fibers, which affects their mechanical properties. Therefore, in order to improve the impregnation, a new method was used which mixed carbon fiber and thermoplastic resin fiber to prepare a nonwoven fabric intermediate material, and preparing a composite material by hot-press molding. At the same time, during the fabrication process of non-woven fabrics, carbon fibers were arranged in the carding direction, which was expected to improve the mechanical properties of the composite in the carding direction [5].

Flexural properties and fatigue properties are a key indicator to characterize the materials [6]. They are affected by many factors such as reinforcement, matrix, loading method and so on [7,8]. The fatigue of composites is more complex compared to metal because it has different components and anisotropic properties [9,10]. Many researchers have studied the fatigue properties of composites. However, for this anisotropic carbon fiber mat reinforced composites, the relevant research on the
effect of carbon fiber length and orientation on the flexural properties and low cycle fatigue properties was seldom.

In this work, the anisotropic carbon fiber mat reinforced composites were manufactured by carding method and then the hot-pressed molding. The 3-point bending test was conducted to investigate the anisotropic properties of the samples. The low-cycle bending fatigue test were (LCBF) at constant stress of 55%, 70% and 85% of original flexural strength were carried out to obtain the modulus history of fatigue process and compare the residual flexural modulus and strength with un-fatigue samples. The cross section of fatigued and un-fatigued samples was polished to observe micro-damage.

2. Materials and methods

2.1. Material preparation
Carbon fiber/polypropylene fiber composites in this study were fabricated from chopped carbon fiber grade T700SC 12k brought from Toray as reinforcement and polypropylene fiber supplied from Daiwabo Polytec as matrix. The initial carbon fiber length was 50 mm and 70 mm, and the sample were named CF50 and CF70 respectively.

Firstly, as shown in Figure 1, the carbon fibers and polypropylene fibers were blended at a weight ratio at 40:60. Then the mixed fibers were conveyed onto a cylinder which covered in wire. The cylinder and roller over the cylinder rotated rapidly and therefore the fibers were combed along the machine direction and meanwhile the bundles of carbon fibers were separated into individual fibers. After that, the fibers were output as web and laid up. After needle punched process, the CF/PP nonwoven fabrics were fabricated.

The CF/PP nonwoven fabrics were cut into pieces and eight layers of pieces were laminated and hot pressed at 230℃ for 4 min with a hot press machine supplied by Satoh Group. And then after cooling down with circulating water, the specimens were prepared.

The specimens for static 3-point bending tests and low cycle fatigue bending test were cut with a size of 40 mm ×15 mm (thickness ≈ 2 mm).

2.2. 3-point bending tests
The static 3-point bending tests were carried out on a computer controlled universal testing machine (55R4206, Instron) equipped with a 5kN load cell at room temperature. The support span length was 16 times the thickness. The crosshead speed was 2 mm/min.

2.3. Low cycle bending fatigue tests
The low cycle bending fatigue (LCBF) tests were performed to investigate the effect of 30 times different pre-set load on the flexural stress-deflection curve, flexural modulus and flexural strength. The constant cycle stress was calculated and set by the maximum flexural stress in the 3-point bending test. The constant stress of 55%, 70% and 85% of original flexural strength were performed, respectively. The loading and unloading crosshead speed were both 2 mm/min. After 30 times LCBF tests, the specimens were conducted 3-point bending tests to obtain the residual flexural properties.

2.4. Optical observation
The broken samples not undergone LCBF and undergone LCBF loading were observed by an optical microscope. To observe clearly, the cross section of samples cut perpendicular to the loading direction
was solidified in a cube filled with epoxy and polished with sandpaper (400 grit, 800 grit, 1200 grit and 1500 grit) and then aluminum powder.

3. Results and discussion

3.1. Flexural properties

Figure 2 shows the representative flexural stress-deflection curves of CF50 and CF70 in the MD and in the TD. Figure 3 shows the (a) flexural modulus, and (b) flexural strength. For CF50 and CF70, the flexural modulus and flexural strength in the MD were higher than those in the TD. For CF50, the MD/TD ratio of flexural modulus and strength was 1.55 and 1.08, while for CF70, the MD/TD ratio was 2.35 and 1.45. The differences of flexural properties in the MD and in the TD indicated the samples exhibited obvious anisotropy. It could be seen that the longer carbon fibers were, the more obvious anisotropic flexural properties were.

3.2. Flexural modulus and curves during low cycle bending fatigue tests

The flexural modulus history of 30 times LCBF tests with constant cycle stress are shown in Figure 4. During the LCBF tests at constant stress of 55% and 70%, the flexural modulus did not change obviously for CF50 and CF70 in the MD and in the TD. However, at the constant stress of 85%, the flexural modulus showed the decreasing tendency in each kind of samples. Some samples broken before reaching 30 cycles, which indicated the 85% stress level caused great damage to the samples.

The typical flexural stress-deflection history (e.g. CF70-MD) of 30 times LCBF tests with constant cycle stress are shown in Figure 5. During the LCBF tests at the constant stress of 55% and 70%, there was a certain difference in deflection between the first cycle and the second cycle, which indicated that at the 55% and 70% stress level, the first cycle will slightly damage the specimen, resulting in the deflection not returning to 0 when the bending load returns to 0. The flexural stress-deflection curves
of the second and subsequent cycles almost overlapped, which indicated at the 55% and 70% stress level, the specimens did not damage obviously. At the (c) 85% stress level, it can be seen from the figure that the curve of each cycle loading did not have a high degree of coincidence as in the 55% and 70% stress level fatigue. As the cycle times increased, the slope of the curve decreased. In addition, some samples suffered greater damage during LCBF fatigue, so they failed before reaching 30 cycles. The stress level of 85% had a great influence on the bending fatigue performance of the sample.

3.3. Residual strength after fatigue

Figure 6 shows the comparison of flexural modulus and flexural strength of fatigued and un-fatigued samples. The effect of low cycle bending fatigue (LCBF) with 55% stress level on flexural properties was not obvious. After fatigue, the decrease rate of flexural modulus and strength was less than 5%. After LCBF with 70% stress level, the decrease rate of flexural modulus was usually below 5%, and the maximum decrease rate was approximately 9%. The about 10% declines in flexural strength also indicated the effect of this load level on the flexural properties was slight. The LCBF of 85% stress level has an obvious influence. The decrease rate of flexural modulus was more than 10%, the maximum could be 27%, and the decrease rate of bending strength was about 15%.

3.4. Optical observation of fracture behavior

Figure 7 shows the typical cross section of fatigued and un-fatigued samples after bending tests. For the un-fatigued sample, it could be seen wrinkles, but the cracks are not very obvious, and the crack depth was relatively shallow. After 55% stress level LCBF fatigue, the crack depth of the sample was not deep. After LCBF fatigue at 70% stress level, the crack became deeper. There were obvious traces of damage appeared at the bottom of the specimens, and there were debonding of fibers and resins and greater damage to the resins, indicating that bending fatigue at 70% stress level affects the samples. After LCBF tests at 85% stress level, the cracks were more obvious and the crack depth was deeper. There were delamination, resin and fiber debonding, resin destruction, and damage at the bottom.
4. Conclusions
In this work, carbon fiber reinforced composites were prepared. 3-point bending tests and low cycle bending fatigue tests were employed to investigate the flexural properties and fatigue mechanism. The optical observation of the cross section was to identify micro-damage. The results can be summarized as follows:

(1) The results show carding method can be an effective method to make anisotropic CF/PP composites. The ratio of flexural strength of carding direction and the other direction could be controlled between 1.08 to 1.45, which indicated the anisotropic properties could be controlled.

(2) Compared with CF50, in the samples of CF70, the carbon fibers were arranged more in the machine direction. Therefore, the anisotropy was more obvious with the increasing of carbon fiber length.

(3) The effect of low cycle bending fatigue (LCBF) with 55% and 70% stress level on flexural properties was not obvious. The LCBF of 85% stress level had an obvious influence. The decrease rate of flexural modulus was more than 10%, and the decrease rate of bending strength was about 15%.

(4) Optical observation shows that with the increase of fatigue stress level, the crack becomes deeper, and the flexural modulus and strength decreased obviously.

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