

The experiment of four-point bending behaviours of helicoidally laminated CFRPs

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Abstract. The purpose of this study is to mitigate the brittle behaviour of CFRP. CFRP is a composite material of carbon fibre and a thermosetting resin. As a feature, it has a low density than metallic materials such as steel and aluminium, and it is excellent in specific strength, specific stiffness, and is corrosion resistant. In the civil engineering field, CFRP is expected to be utilized for durability improvement and long life achievement. However, it is necessary to be careful when using it as a primary member, because the behaviour at the time of fracture is very brittle, thereby it is necessary to set a large safety factor at the time of design. One way to achieve the purpose of the current study is to follow a biological structure, so-called biomimetics. In this study, mantis shrimp is selected. The characteristic structure of its forefoot is that chitin fibres are stacked while changing helicoidally their angles. It is said that the forefoot can withstand a thousand times the force of its own weight because of its structure. Helicoidally laminated CFRP is fabricated by processing prepreg sheets of unidirectional carbon fibres. Four laminated structures were examined in which four-point bending experiments were carried out under displacement control of 2 mm/min, and load and displacement were recorded. During the experiments, the specimens were observed until fracture with a video camera. As a result, the brittle behaviour was improved significantly as the orientation angle difference of the fibre sheets decreased.

1 Introduction

Carbon fibre reinforced polymer (CFRP) is a composite of carbon fibre and resin. It is used in various applications because of its high strength and stiffness as well as lightweight compared to metallic materials, and it is also used as a structural material in aircraft and motor vehicles for the purpose of weight reduction. In the recent past, CFRP is now being used in the civil engineering field as well, such as seismic reinforcement of tunnels and bridges. However, for using it as a primary member, we need to set a large safety factor because of the brittle behaviour of CFRP.

On the other hand, fibre reinforced and laminated composite is often observed in biological structures [1-3]. Mantis shrimp uses its forefoot to break a shell for predation [1]. It is known that the surface of its forefoot has a laminated composite of chitin fibres with their angles changing helicoidally [2]. The helicoidal structure contributes to the toughness of its forefoot even against the loading of thousand-fold self-weight [3]. This study focuses on the structure of a biological body from the viewpoint of biomimetics. We fabricated CFRP which consists of a helicoidally stacked laminate and examined the possibility of mitigating the brittle behaviour, which is the disadvantage of CFRP.

Based on the above background, in order to investigate whether the brittle behaviour of CFRP can be mitigated by the imitation of a biological body, helicoidally laminated CFRP was fabricated, and a three-point bending experiment was conducted previously [4,5]. In this study, a four-point bending experiment is conducted for CFRP with the same helicoidal laminate structure. Then, the influence of the loading condition on the load-displacement curve is compared and investigated.

2 Experimental setup

2.1. Prepreg

Table 1 shows the material properties of UD carbon fibre prepreg (manufactured by Mitsubishi Rayon Co., Ltd.) used in this study. Prepreg is a sheet of carbon fibre, the numerical value of the table is the parameter per square meter of the sheet. Curing temperature is 130 degrees Celsius. A number of laminas in each specimen is set as 40 sheets, and the thickness of each specimen is about 4 mm. There are four types of laminate structures: CP (Cross-Ply), SH36 (Single Helicoidal), SH18, and SH9. Their laminate structures are shown in Table 2, and the laminate coordinate system is shown in Figure. 1.

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Table 1. Material properties of UD carbon fibre prepreg (for four-point loading).

	Unit	Measured value
Unit area weight of prepreg	g/m ²	187.3
Unit area weight of fibre	g/m ²	124.3
Fibre content	Wt %	66.4

Table 2. Laminate structures.

Name	Stacking sequence
CP	[0/90] ₂₀
SH36	[0/36/72/108/144] ₈
SH18	[0/18/36/54/72/90/108/126/144/162] ₄
SH9	[0/9/18/27/36/45/54/63/72/81/90/99/108/117/126/135/144/153/162/171] ₂

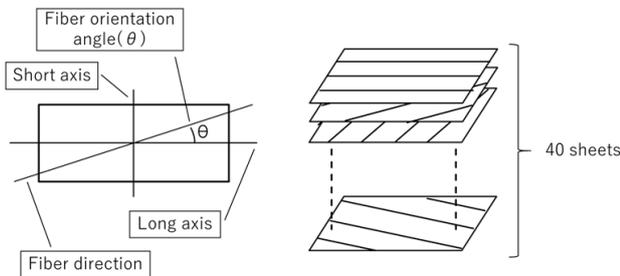


Figure 1. Laminate coordinate system.

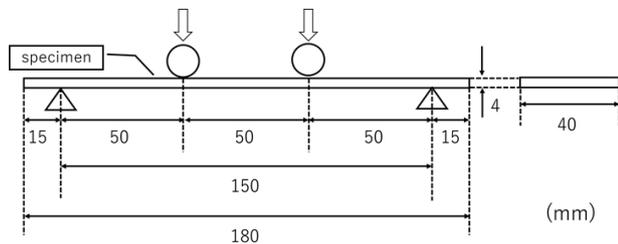


Fig. 2. Loading conditions (four-point bending).

2.2. Molding procedures

CFRP was moulded by heating with an autoclave process, where all the processes below were conducted by ourselves. First, an electric oven (size is 1000 mm by 1000 mm by 600 mm) was made. Then the nichrome wire was placed in the oven for heating, and it was connected to the transformer for a varying level of heating. A hole was made in the oven wall by inserting a

thermometer which was to measure the temperature inside the oven. UD prepreg was cut into predetermined size sheets by a cutter to prepare laminas. In the case of CP, a prepreg was cut into a 200 mm by 200 mm square, while, in the case of SH, a prepreg was cut into 290 mm by 290 mm square. Cut prepreg sheets were handled with vinyl gloves and stacked without trapping air bubbles. If air bubbles were trapped, they were removed by pushing out along the fibre direction. Next, the laminated prepreg sheets were covered by a vacuum bag, breather fabric, and perforated release film. At this time, the vacuum bag was closed by sealant tape so that the air does not enter to the bag, then the inside of the vacuum bag was made a vacuum. The bag was sandwiched with steel plates, and this sandwiched bag was pressed by using a pressurizing tool. The entire assembly was put in the oven for heat hardening. Until the temperature in the oven would reach 80 degrees Celsius, the temperature in the oven was adjusted at the heating rate of 1 degree Celsius/min. And then, the temperature was maintained at 80 degrees Celsius for one hour. Next, until the temperature in the oven would reach 130 degrees Celsius, the temperature in the oven was adjusted at the heating rate of 1 degree Celsius/min. After reaching 130 degrees Celsius, the temperature was maintained at 130 degrees Celsius for two hours. After that, the specimen was allowed to cool down by the room temperature.

2.3. Specimen

The fabricated CFRP laminate was cut into four specimens. The dimensions of each specimen are 180 mm long, about 4 mm thick, and 40 mm wide. Figure. 2 shows the dimensions of the specimen.

2.4. Loading conditions

The outline of the loading experiment is shown in Figure 2. In the experiment, a four-point bending load was applied. The distance between support points was 150 mm, and the distance between support point and loading point was 50 mm. The loading machine (SHIMADZU AG-1 250 kN) was used under displacement control, and the displacement speed was 2 mm / min. A load cell (SHIMADZU SFL-250 kN AG) was used to measure the load. A load-displacement curve was then obtained after the experiment. In addition, a video was recorded on the side surface of the specimen during the experiment.

3 Experimental results

Experimental results are shown by load-displacement curves with displacement (mm) on the horizontal axis and load (kN) on the vertical axis. It must be noted that the point at which the maximum load was measured is mentioned below as (maximum load, displacement).

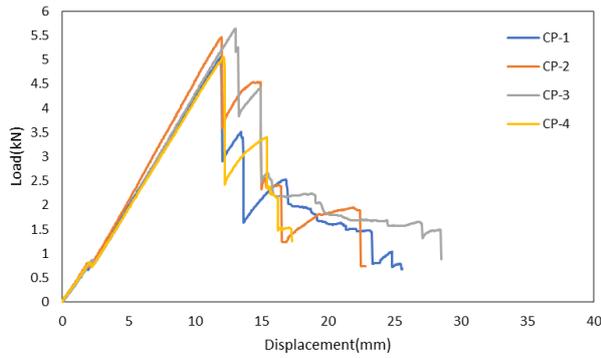


Fig. 3. Load-displacement curves of CP (four-point)

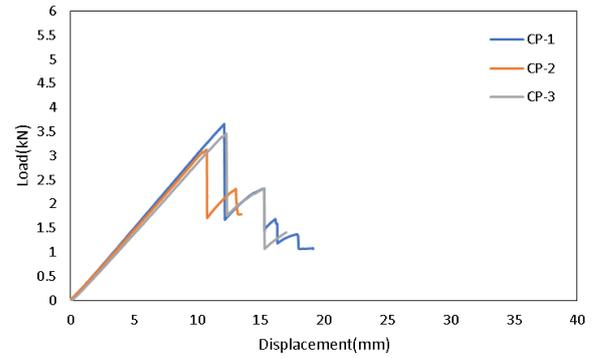


Fig. 7. Load-displacement curves of CP (three-point)

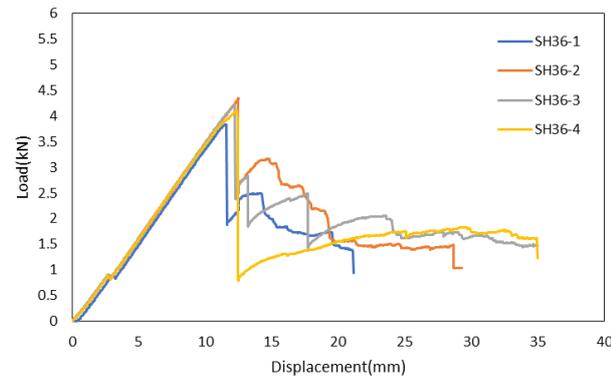


Fig. 4. Load-displacement curves of SH36 (four-point)

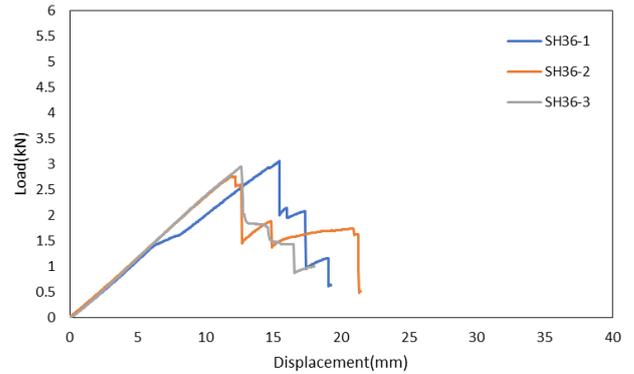


Fig. 8. Load-displacement curves of SH36 (three-point)

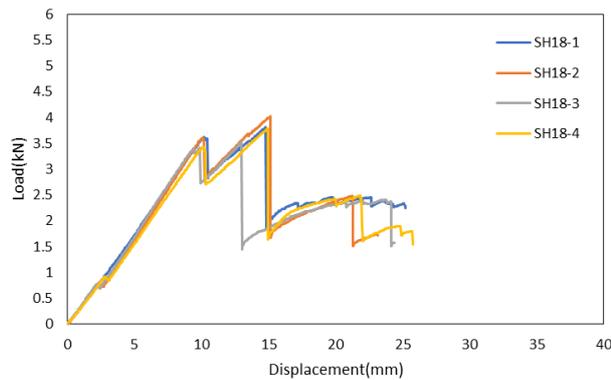


Fig. 5. Load-displacement curves of SH18 (four-point)

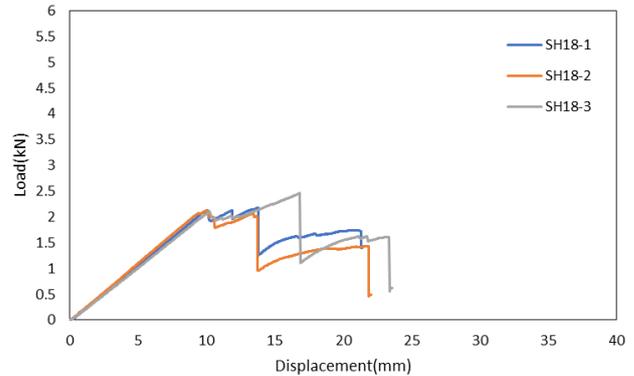


Fig. 9. Load-displacement curves of SH18 (three-point)

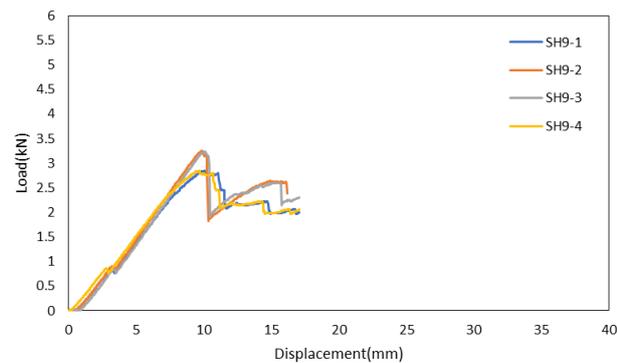


Fig. 6. Load-displacement curves of SH9 (four-point)

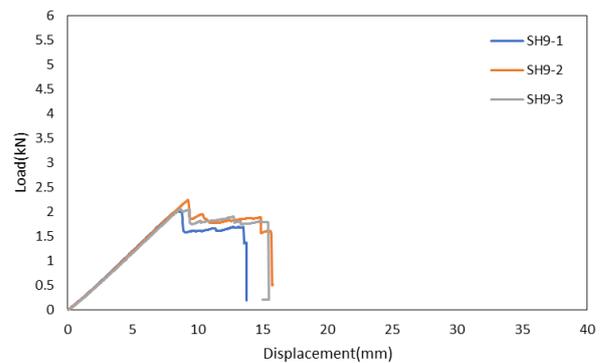


Fig. 10. Load-displacement curves of SH9 (three-point)

3.1. CP

Figure 3 shows the load-displacement curves of CP. The maximum load and corresponding displacement of four specimens were (5.06, 12.05), (5.47, 12.05), (5.65, 13.02), (5.05, 12.27), and the average was (5.31, 12.35). In each of the specimens, after the maximum load was achieved, the residual load was not kept, and the load quickly declined.

3.2. SH36

Figure 4 shows the load-displacement curves of SH36. The maximum load and corresponding displacement of four specimens were (3.84, 11.2), (4.35, 12.75), (4.20, 12.24), (4.10, 12.39), and the average was (4.12, 12.15). The maximum load became smaller than that of CP. Similarly to CP, the shape of curves did not show the residual load after achieving the maximum load, and the declining portion showed several load drops. SH36-3 and 4 showed their residual load maintained for a longer period after a big load drop.

3.3. SH18

Figure 5 shows the load-displacement curves of SH18. In this laminate structure, the peak load was measured once, and then the second peak load equal to or higher than the first one was also observed. The initial peaks were (3.62, 10.27), (3.58, 10.11), (3.41, 9.91), (3.43, 10.11), and the average was (3.51, 10.10). The second peaks were (3.81, 14.83), (4.03, 15.12), (3.52, 12.98), (3.79, 14.96), and the average was (3.79, 14.47). The continued residual load was observed in all of the specimens after the second load drop.

3.4. SH9

Figure 6 shows the load-displacement curves of SH9. The maximum load and corresponding displacement were (2.85, 9.46), (3.25, 9.38), (3.24, 9.28), (2.96, 9.36) for each specimen, and the average was (3.07, 9.37). The load drop after the maximum load was small, and the continued residual load after the peak was clearly observed.

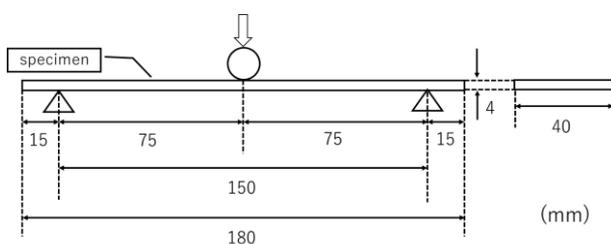


Fig. 11. Loading conditions (three-point bending).

4 Comparison with three-point bending behaviours

Figures 7 to 10 show the load-displacement curves of the same four laminates obtained under three-point bending load in the past research [6]. Although there is a difference in the load condition (Figure 11) and in the prepreg which will be described later, almost the same tendency is seen for each of the same laminate structures.

The properties of the prepreg are shown in Table 3. The fibre content of the prepreg is 70.3%, which is larger than the one used in the 4-point bending loading (Table 1).

4.1. CP

As shown in Figure 7, the maximum load and corresponding displacement of four specimens were (3.66, 12.15), (3.13, 10.74), (3.45, 12.31), and the average was (3.42, 11.73). After the maximum load, almost no load was retained, and the load quickly declined by repeating large load drops.

4.2. SH36

As shown in Figure 8, the maximum load and corresponding displacement of four specimens were (3.06, 15.46), (2.76, 12.14), (2.69, 12.70), and the average was (2.92, 13.47). The stepwise declination of the load drops after the maximum load is mitigated when compared to that of CP.

4.3. SH18

As shown in Figure 9, the maximum load and corresponding displacement of four specimens were (2.18, 13.78), (2.02, 13.71), (2.46, 16.85), and the average was (2.26, 13.55). In this laminate structure, there was a load increase once again after reaching the first peak of the load, and the maximum loads were recorded at the second peak. Therefore, the peak before the occurrence of a large load drop was taken as the maximum load. It was observed that about 50% of the maximum load was retained at the residual stage.

Table 3. Material properties of UD carbon fibre prepreg (for three-point loading).

	Unit	Measured value
Unit area weight of prepreg	g/m ²	178.3
Unit area weight of fibre	g/m ²	125.3
Fibre content	wt%	70.3

4.4. SH9

As shown in Figure. 10, the maximum load and corresponding displacement of four specimens were (2.02, 8.49), (2.23, 9.22), (2.05, 9.39), and the average was (2.11, 8.82). The load drop after the maximum load was small, and the residual load was also observed.

5 Discussions

5.1. Four-point bending case

It is observed that the average maximum load of CP is 5.31 kN, that of SH36 is 4.12 kN, the average of the first peak load of SH18 is 3.51 kN, the average of the second peak load is 3.79 kN, and the average maximum load of SH9 is 3.07 kN. It turned out that the maximum load tended to decrease as the orientation angle difference of the fibre sheets decreased. This is because the number of the 0-degree layers that coincides with the long axis direction of the specimen and contributes the most to the strength development is 20 layers in CP, 8 in SH36, 4 in SH18, and 2 in SH9.

Moreover, it was confirmed that, as the orientation angle difference of helicoidal laminate structures decreased, the load drop after the maximum load also decreased in the load-displacement curves, while the residual load continues for a longer time. This is thought to be, since the layer with an orientation angle of 90 degrees, which is considered to be weak in compression, decreases as the orientation angle difference decreases, and the number of broken layers at the time of the load drop after the maximum load decreases.

For the details of the above mechanisms and mechanisms why two peak loads are seen only in SH18, further investigation is necessary through theoretical analysis and video observation.

5.2 Comparison with three-point bending case

The difference between the four-point bending load and the three-point bending load is that shearing stress does not occur in the centre flexural span under the four-point bending load. Focusing on this difference, we compare and examine the above two experimental results based on the load-displacement curves at the three points of maximum load, displacement at maximum load, and behaviour after maximum load.

The maximum load and the displacement at the maximum load are compared based on the average value. (a, b), (c, d) is the maximum load and the maximum load displacement of the 4-point bending load and the 3-point bending load, respectively, and the differences are expressed as (a-c, b-d). The differences for CP are (1.89, 0.61), SH36 (1.20, -1.33), SH18 (1.52, 0.92), and SH9 (0.96, 0.55). It was found that the maximum load difference tends to increase as the fibre orientation angle difference of the helicoidal laminates increases.

Focusing on the difference of the prepregs, the fibre content of the prepreg used in the three-point bending case was 70.3 wt% and that used in the four-point bending case was 66.4 wt%. When comparing the strength under the same condition, the strength of prepreg used for three-point bending becomes larger.

However, in reality, the maximum load of the four-point bending experiment increased. This is because the layer contributing to the strength property is the layer with the orientation angle of 0 degrees, and the layer damaged by the shear force in the three-point bending is not damaged by the four-point bending test. Moreover, it is considered that the larger the orientation angle difference, the more the layer with the orientation angle of 0-degree increases. Factors affecting the displacement at maximum load need to be studied in future.

6 Conclusions

In this study, we investigated the possibility of improving the brittle behaviour of CFRP under four-point bending by helicoidally laminating fibre sheets in CFRP. We investigated the total of four types of laminate structures including one orthogonal stacking and three helicoidal stackings. In addition, we compared the results of the current study to those of three-point bending load case obtained in the past research. By decreasing the fibre orientation angle difference, it was confirmed that the brittle behaviour was improved with the helicoidal laminate structure. Namely, the load drop after the maximum load became smaller, and the residual load was maintained for a longer period.

On the other hand, when decreasing the fibre orientation angle difference, the maximum load decreased and the corresponding displacement decreased. By comparison with the three-point bending case, the maximum load exceeded even though the strength of the prepreg used in the four-point bending case was smaller. No shear stress occurred in the flexural span, but the effect of this will need to be verified in future by theoretical analysis and video observation.

References

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