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A Basic Study of the Impact Absorption Performance of a CFRP Cylindrical Shell Member with Changes in Ply Number in Half of the Member

by

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Abstract

In conventional vehicles, a crash box (CB) for absorbing the impact energy is mounted at the tip of the front side member (FSM), which is the main frame of the vehicle. However, it is difficult to install a CB in an ultra-compact vehicle in terms of weight and space. In recent years, carbon fiber reinforced plastic (CFRP) has been extensively used as a material for impact-absorbing members subjected to compressive loads. The CFRP not only exhibits extremely high specific strength and specific rigidity, but also offers the advantage that the material strength and rigidity can be designed freely as the designer wishes. However, the impact-absorbing performance required for future ultra-small vehicles means that the CB collapses earlier than the FSM, and the impact energy is sufficiently absorbed by the CB. That is, the CB strength is lower than that of the FSM in frontal collisions, and so the goal is expected to be to provide the CB only with the necessary rigidity to resist the impact energy. To the best of the authors' knowledge, no research has been conducted on developing a member to obtain an arbitrary energy absorption form while exhibiting high energy-absorption performance using the CFRP. Therefore, in this study, we produced a member in which the ply number of the CFRP in the cylindrical shell was partly changed. We examined the impact-absorption performance of a CFRP cylindrical shell, in which the ply number did not change in one member, under an axial impact load. Furthermore, the impact-absorption performance in the case where the number of laminated CFRP plies was changed in the middle of the member was considered.

Keywords: Ultra-compact vehicle, Carbon fiber reinforced plastic, Crash box, Impact absorption

1. Introduction

Ultra-compact mobility, which is expected to create innovation in an aging and low-carbon society, has been actively proposed for use in car sharing and other applications in Japan. However, such a vehicle has not achieved remarkable demand expansion. One of the reasons is the significant lack of crash safety owing to the omission of airbags and the reduction in structural strengh[1)]. In conventional vehicles, a crash box (CB) for absorbing the impact energy is mounted at the tip of the front side member (FSM), which is the main frame of the vehicle, as illustrated in Fig. 1. However, in ultra-compact mobility, it is difficult to install the CB in terms of weight and space. In order to address the collision safety issue, the development of a CB

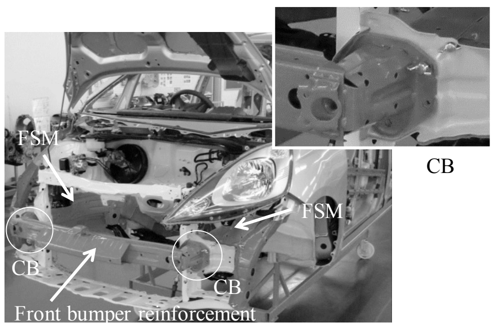

Fig. 1 Structure of front of vehicle, consisting of FSM and CB.

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with sufficient rigidity to ensure safety with a light weight and easy mounting on the mobility, is essential. Numerous studies have been conducted on the structural mechanics of impact-absorbing members in various fields, as well as automobiles. In metallic materials, it is preferable to use progressive buckling, which allows for continuous compressive buckling deformation over the entire member while overlapping the buckling wrinkles as finely as possible, instead of Euler buckling, the shape of which is bent halfway. For example, Zhao et al. proposed an energy-absorbing member utilizing folding paper engineering to obtain progressive buckling actively[2-4]. Yasui considered the dynamic impact crushing behavior of multi-layer honeycomb sandwich panels with different shapes to increase the impact load as the crushing progressed[5]. Furthermore, Ogasawara et al. considered the impact absorption characteristics of aluminum honeycomb material with cell walls in which the plate thickness was changed continuously[6]. Moreover, Furukoshi et al. considered the strength characteristics in the case of an FSM containing a bend[7]. As described above, various researchers have developed members that can obtain the energy absorption form intended by the designer, while securing higher energy absorption performance.

In recent years, carbon fiber reinforced plastic (CFRP) has been extensively used as a material for impact-absorbing members subjected to compressive loads, in contrast to the above-mentioned researches on metallic materials[8-12]. In particular, CFRP has been used to ensure safety performance in racing cars in many cases[13-15]. The front part of the vehicle should improve its energy-absorption ability to absorb greater energy with less deformation. The CB in ultra-compact mobility needs to absorb greater collision energy with smaller deformation than conventional vehicles. Therefore, it is difficult for conventional metal materials to satisfy the required performance sufficiently. CFRP not only exhibits extremely high specific strength and specific rigidity, but also offers the advantage that the material strength and rigidity can be designed according to intentions. As noted, numerous studies have been carried out only from the viewpoint of achieving high energy-absorption performance under various load conditions. However, the impact-absorbing performance required for future ultra-small mobility means that the CB collapses earlier than the FSM, and the impact energy is sufficiently absorbed by the CB. That is, the CB strength is lower than that of the FSM in frontal collisions, and it is expected that the goal is to provide the CB with only the necessary rigidity against impact energy. To the best of the authors' knowledge, no research has yet been conducted from the viewpoint of developing a member that obtains an arbitrary energy absorption form while exhibiting high energy-absorption performance using CFRP.

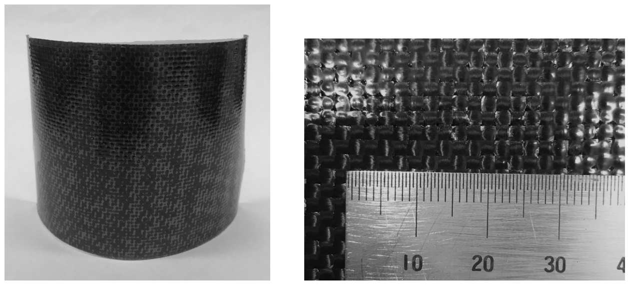


Fig. 2 Rectangular CFRP prepreg cut out for lamination.

Fig. 3 Metal jig for CFRP lamination.

Therefore, in this study, we produced a member in which the ply number of the CFRP in the cylindrical shell is partly changed, and investigated the impact-absorption performance of a member with a portion in which the strength intentionally decreases. Section 2 discusses the production method for the CFRP test piece. In section 3, we examine the impact-absorption performance of a CFRP cylindrical shell in which the number of plies, which forms the basic model, did not change in one member, under an axial impact load. Furthermore, in section 4, the impact-absorption performance in the case where the number of laminated CFRP plies was changed in the middle of the member is considered in comparison with the previous section.

2. Production Method for CFRP Test Piece

The CFRP test pieces were manufactured by resin film infusion, in which a member laminated with carbon fiber prepregs was packed, and then the inside of the pack was decompressed and heated. Figure 2 illustrates the rectangular prepreg cut out for lamination. In this study, plain weave prepreg CF/PPG/3KP/333G made by Lab-CAST Inc. was used. The specifications of this prepreg are as follows: the number of filaments bundled as one fiber is 3000, the thickness is 0.223 mm, the curing temperature is 130°C, and the curing time is 2 h or more. Figure 3 illustrates the metal jig used to produce the CFRP test pieces. The metal jig used

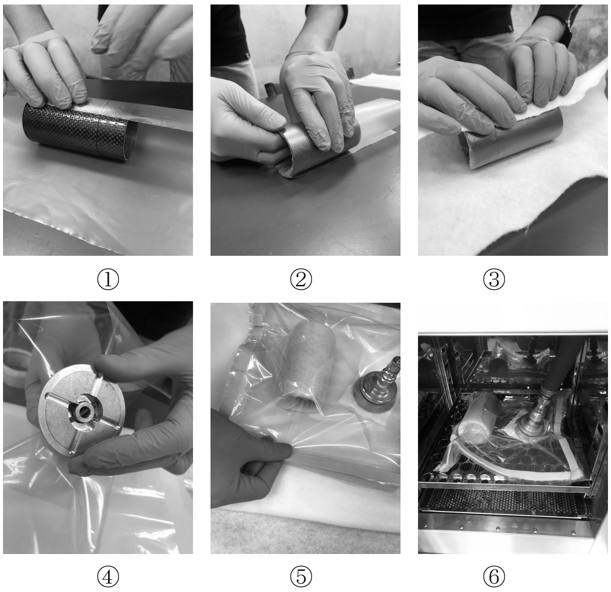


Fig. 4 Procedures for lamination and curing.

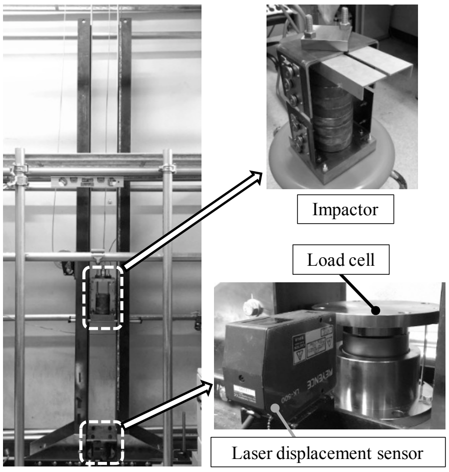


Fig. 5 Constructed drop weight tester.

for lamination was a steel cylinder with a length of 100 mm and an outer diameter of 52 mm, and the surface was mirror-finished. Prior to laminating the CFRP prepreg, the jig surface was washed with acetone and sprayed with a release agent.

Figure 4 illustrates the procedures for lamination and curing. During the lamination process, powder-free gloves were used to prevent sebum and other materials from adhering to the jig. During the lamination process of the second ply, the each edge of the prepreg joints was offset by approximately 5 mm from the joint of the previous layer to prevent uneven strength and thickness, as shown later in Fig. 6. Following the lamination work, it was necessary to wrap the members in breather fabric to prevent resin leakage from the prepreg. To prevent the breather fabric and CFRP prepreg from adhering during curing, the laminate was wrapped in release film, as illustrated in ① and ②, and then wrapped in breather fabric, as illustrated in ③. A bagging film with

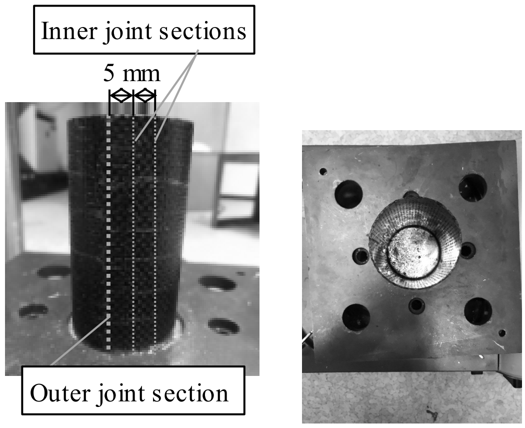


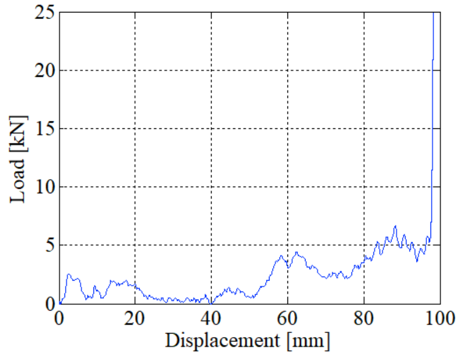
Fig. 6 Test piece fixed with fusible alloy.

heat resistance and strength was used to evacuate the laminated members. A vacuum valve was attached to the bagging film, as indicated in ④, and the bagging film was turned into a vacuum bag by using sealant tape to create a sealed space, as indicated in ⑤. This bag was heating using a DY300 curing oven manufactured by Yamato Scientific Co., Ltd., as illustrated in ⑥. The vacuum pump used was a TA150RB model, manufactured by Ichinen Tasco Co., Ltd. (ultimate vacuum: 2.0 Pa). The curing temperature remained consistent at 80°C for 60 min, and was then increased to 135°C at a heating rate of 3°C/min, following which it remained consistent for 105 min.

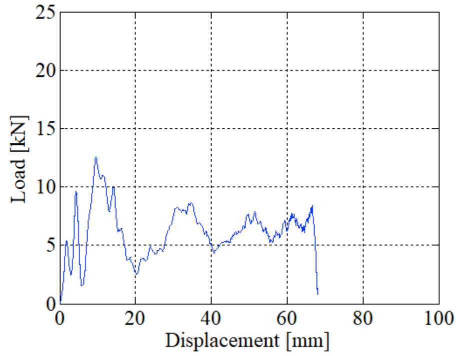
3. Impact-Absorption Performance of Uniform Laminated CFRP Member

3.1 *Experimental conditions*

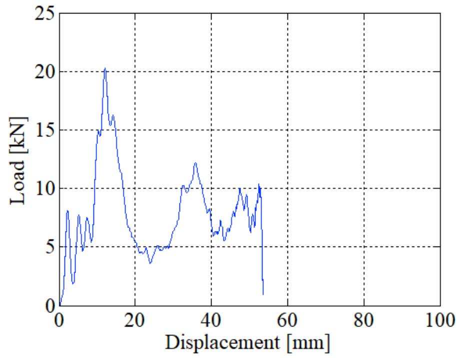
To evaluate the impact-absorption characteristics of CFRP members with a uniform ply number, we constructed a drop weight tester, as illustrated in Fig. 5, and carried out impact tests. At the start of the test, the impactor was pulled up by the winch and dropped, and the test piece placed at the bottom of the impactor was crushed. The CFRP test piece manufactured by the procedure explained in the previous section was placed on a steel plate processed with spot facing, as illustrated in Fig. 6, filled with the fusible alloy U-alloy, and fixed. A laser displacement sensor for measuring the displacement of the falling impactor and a load cell for measuring the impact load were installed at the bottom of the test piece. The sampling frequency of these measurement devices was 500 kHz. In this study, the impactor weight was 17.9 kg and the drop height was 2.5 m. The test pieces were made with an inner diameter of 52 mm and a height of 100 mm, and the numbers of laminated plies were 2, 3, and 4. Each thickness of test piece with 2, 3 and 4 Ply is 0.45, 0.67 and 0.89 mm. In this study, the point at which the load



(a) 2 ply



(b) 3 ply



(c) 4 ply

Fig. 7 Load–displacement diagrams of CFRP test piece.

detected by the load cell started to increase after the impactor falling was defined as the contact between the impactor and test piece, and crushing began; the displacement at this time was defined as 0 mm. Then, the point at which the distance between the impactor and test piece was closest was defined as the end of crushing.

3.2 *Experimental results*

Figure 7 presents the load–displacement diagram from the start to the end of crushing obtained in the drop weight test. Figure 7 (a) provides the results for the test piece of 2 ply, (b) is 3 ply, and (c) is 4 ply. In the case of 2 ply, almost no load was generated, even when the crushing started, and the load increased rapidly near a displacement of 100 mm. This is because the test piece of 2 ply could not absorb the impactor energy even if the test piece was completely

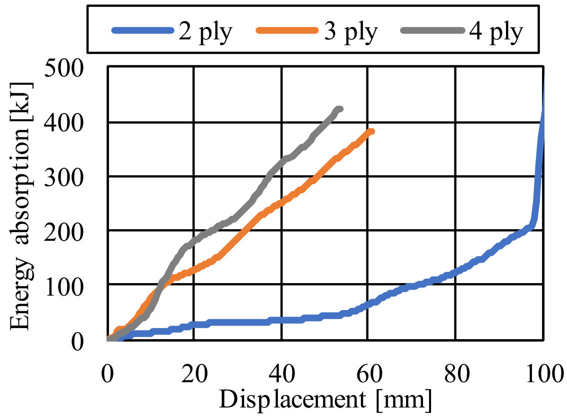


Fig. 8 Relationship between energy absorption and displacement.

Table 1 Energy absorption performance of each test piece.

Ply number	Energy absorption performance [J/mm]
2 ply	1.824
3 ply	6.190
4 ply	8.269

crushed, and an impact load was applied to the load cell directly. In the case of 3 ply, the crushing ended when the test piece was crushed at approximately 70 mm. This is because the test piece of 3 ply, in which the structural strength was increased, could absorb all of the impactor energy, as the load increased overall from the initial crushing stage compared to the 2 ply. Furthermore, in the case of 4 ply with a greater number of plies, crushing was completed at approximately 55 mm, and the impactor energy could be absorbed with less crushing. The CB is required to absorb large amounts of energy with a small amount of crushing. Assuming that the impact load at a minute crushing amount ds [mm] of the test piece is f [kN], the absorption energy U when the impactor is displaced by x [mm] can be expressed by the following equation:

$$U = \int_0^x f ds . \tag{1}$$

Figure 8 illustrates the relationship between the displacement of the impactor and absorption energy U in the three test piece types. Large gradients of the plot indicate the test piece absorbed the impactor energy with a smaller crushing amount, and it can be stated that the energy-absorption characteristics of the test piece are superior. Table 1 presents the gradients when the results of each test piece in the figure are linearly approximated. The gradient increased as the number of plies of the test pieces increased, and the energy-absorption performance was improved.

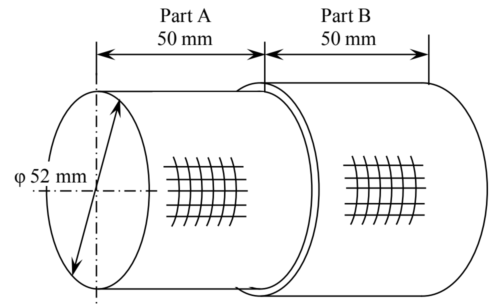


Fig. 9 Schematic of CFRP test piece with different ply numbers.

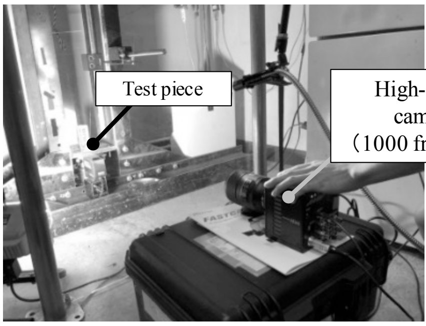


Fig. 10 High-speed camera

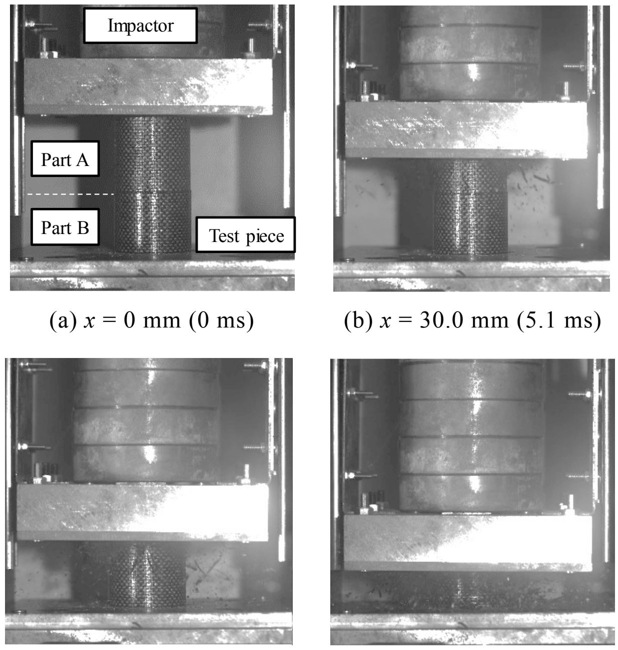
4. Impact Absorption Performance of CFRP Member in which Ply Number Changes

4.1 *CFRP member in which ply number changed*

In the previous section, the impact-absorption characteristics of the uniform lamination model were examined. In this section, we investigate the number of laminated CFRP plies changing in the middle of one cylindrical shell. We studied the impact-absorption performance of a CFRP member with a portion in which the strength was intentionally decreased. The test pieces were manufactured based on the procedure described section 2, but the number of laminations was changed, as illustrated in Fig. 9. Part A indicates the side in contact with the impactor, while part B is the side on which the test piece is fixed and connected to the load cell. The height of the test piece was 100 mm, as in the previous section, and the length of parts A and B was 50 mm. In each test piece, the ply number in part B was 4 ply, while the number of laminations in part A was changed from 1 to 3 ply.

4.2 *Drop weight test of CFRP test piece with different lamination numbers*

As in the previous section, we performed a falling weight test to evaluate the impact-absorption characteristics of the CFRP test pieces, and photographed the crushing state with a high-speed camera, as indicated in Fig 10. Figure 11 illustrates the crushing states in the drop weight test of a test piece with 2 ply in part A and 4 ply in part B (hereafter referred to as the 2P-4P test piece), captured with the high-speed camera. Figure 11 depicts (a) the situation in which the impactor contacted the test piece (x = 0 mm), (b) x = 30 mm, (c) x = 50 mm, and (d) the end of crushing. Firstly, it can be confirmed that crushing occurred from part A, where the ply number was small. Then, after part A was completely crushed, crushing of part B began, and finally, the crushing was completed at x = 76.3 mm.



(a) x = 0 mm (0 ms) (b) x = 30.0 mm (5.1 ms)

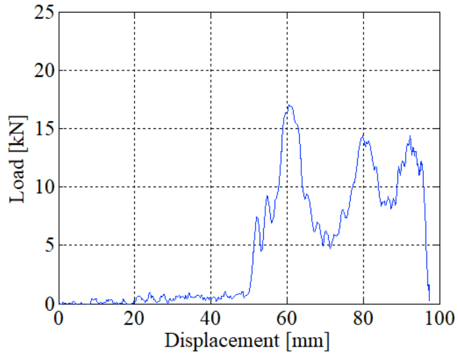
(c) x = 50.0 mm (8.4 ms) (d) x = 76.3 mm (20.1 ms)

Fig. 11 Crushing of CFRP test piece.

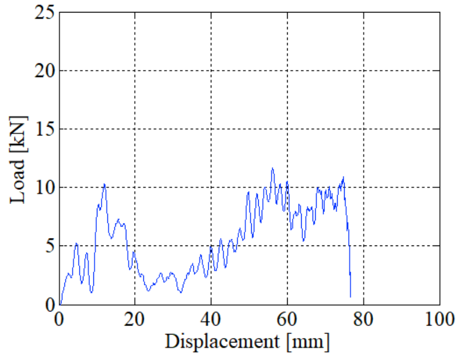
The load–displacement diagrams for each test piece are presented in Fig. 12, and the displacements of the impactor when the specimen was completely crushed are displayed in Table 2. Figure 12 illustrates the results of the test pieces of (a) 1P-4P, (b) 2P-4P, and (3) 3P-4P. The amount of crushing decreased as the ply number in part A increased, and it was confirmed that the result of 4 ply was approached. Furthermore, Fig. 13 illustrates the relationship between the impactor displacement and absorbed energy. In the case of the test piece in which the number of laminations was changed in the middle of the member, the gradient changed when it was crushed more than 50 mm, which was the length of part A. Furthermore, all the gradients of part B were in agreement with the results of the 4 ply test pieces. From the above results, it was possible to confirm experimentally that, even when the number of laminations was changed in the middle, the same crush characteristics as in the uniform case were exhibited.

5. Conclusion

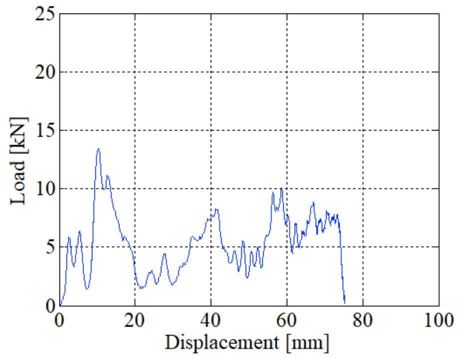
In this study, a cylindrical shell-shaped CFRP member



(a) 1P-4P



(b) 2P-4P



(c) 3P-4P

Fig. 12 Load–displacement diagrams of CFRP test pieces.

was manufactured, and its impact-absorption performance was examined by means of a drop weight test when changing the number of plies with the same shape. Firstly, a drop weight test was conducted on uniform members, and it was confirmed that energy can be absorbed with a small amount of crushing by increasing the number of plies; the impact-absorption performance was also improved. Next, the number of laminations was changed midway, and members having locations at which the strength was intentionally decreased were investigated. As a result, when the number of laminations was changed in the middle, crushing began from the portion with low strength at which the number of laminations changed, and the impact-absorption performance was varied. Furthermore, it was found that the crush characteristics obtained for each part where the number of

Table 2 Energy-absorption performance of each test piece.

Ply number	Muximum impactor displacement [mm]
1P-4P	80.4
2P-4P	76.3
3P-4P	74.9
4P	53.6

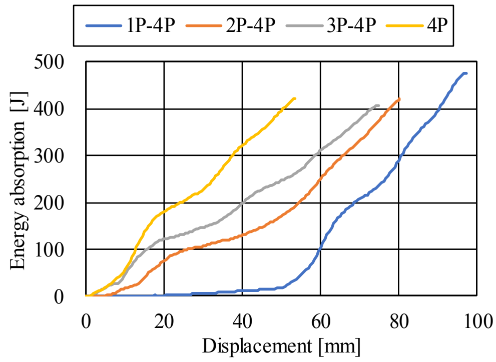


Fig. 13 Relationship between energy absorption and displacement.

plies differed exhibited the same tendency as the uniform case.

According to these results, it was experimentally demonstrated that the impact-absorption characteristics can be arbitrarily controlled by changing the number of laminated plies in a part, even if the members have the same shape. In future, we will conduct experiments to change the ply number and length in a wider range, and to control the impact-absorption characteristics of the members. Secondly, we will consider the impact absorption performance of the CFRP laminated with prepregs in which fiber orientation is changed. Moreover, we will conduct experiments when the CFRP CB is connected to structural material (such as the FSM), and investigate the impact-absorption characteristics of the CB under conditions closer to actual situations.

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