

Impact Absorption Characteristics of a CFRP Member for the Front Part of an Automobile in the Axial Compressive Direction: Experimental Consideration on Protection for Structural Parts

by

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(Received on May. 11, 2020 and accepted on Jul. 24, 2020)

Abstract

The energy-absorption ability of the front part of vehicles should be improved to absorb more energy with less deformation of structural parts. This study investigated the use of carbon fiber reinforced plastic (CFRP) for only the crash box (CB) to absorb impact energy, with steel used for the front side member (FSM) of structural members. We focused on CFRP, which is a high-performance material for energy absorption, and experimentally examined the structure of a CB that can effectively be crushed and absorb energy while maintaining the original shape of the FSM. A test piece was fabricated by joining a cylindrical CFRP member as the CB with varying number of layers and a cylindrical steel member assumed as the FSM. A drop weight test was performed and the crushing characteristics of the CFRP and steel member were investigated. The results showed, that our proposed CFRP pipe, in which the number of laminations of the CFRP prepreg decreases the structural strength of the CB facing the impactor, reduce the peak load in the initial stage of crushing and maintained the shape of structural parts.

Keywords: Carbon fiber reinforced plastic, Crash box, Impact absorption, Front side member

1. Introduction

The collision safety standards for automobiles are becoming stricter year by year to increase the survival rate of pedestrians and cyclists in traffic accident. On the other hand, from the viewpoint of additional value for the customer, automobiles are required more large volume as possible in the cabin. 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. The front part of the vehicle should improve its energy-absorption ability to absorb greater energy with less deformation. Furthermore, it is required that the front part of vehicle be compact to increase the volume of the cabin. In generally, metals such as steel and aluminum are often used as energy absorbing members, but carbon fiber reinforced plastic (CFRP) has been focused as a new material for reducing the weight of vehicle bodies.

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Fig. 1 Racing car manufactured by CFRP.

It has been reported that CFRP which is easy to be formed any shape of member exhibits high energy absorption performance^{1, 2)}. In racing cars, many parts, such as CB and structural members including FSM, are manufactured by CFRP as shown in Fig. 1³⁻⁵⁾. However, in general passenger cars, the use of CFRP components is limited from the viewpoint of cost and productivity. Therefore, this study investigated in the case that CFRP is used for only CB to absorbing impact energy and steel is used for FSM of structure member.

CFRP can be installed in a small space in front of the car, since it has high formability and performance of energy absorption. Therefore, it is expected to absorb the collision energy with a small amount of crushing. We fabricated cylindrical CFRP specimens with a partially changed number of plies and evaluated the energy absorption performance of the specimens by a drop weight test. From the experimental results, it has been confirmed that the energy absorption performance of the test piece can be controlled by changing the number of plies⁶⁾.

On the other hand, if the structural strength of the CB is higher than the FSM, the FSM may buckle first than CB in collision. It would make damage the passenger's lower limbs⁷⁾. In order to prevent the FSM from buckling first, it is necessary to increase the structural strength of both the FSM and the CB, and to design the strength so that it crushed from the CB. Some researchers have reported that the energy absorption characteristics of members such as CBs and bumpers to protect passengers and pedestrians previously^{8,9)}. However, it has not reported that energy absorbing performance of the member which consist of the CB needed to crush for energy absorb and FSM needed to maintain the structure without crush.

Therefore, this study focuses on CFRP, which is a high-performance material of energy absorb, and experimentally examines the structure of CB that can effectively crush and absorb energy while maintaining the original shape of FSM. A test piece was fabricated by joining a cylindrical CFRP member assumed as CB with a partially different number of layers and a cylindrical steel member assumed as FSM. Furthermore, a drop weight test was performed and investigated the crushing characteristics of the CFRP and steel member.

2. Energy absorbing performance of test piece connected with CFRP and steel member

2.1 Outline of drop weight test

To evaluate the energy absorbing performance of test pieces, drop weight test was carried out. A drop weight tester was shown in Fig. 1. The drop weight as impactor is lifted by the winch, and the drop weight falls at the start of the test, crushing the test piece placed under the drop weight. The test piece was placed on a steel plate processed with spot facing, as illustrated in Fig. 2, and fixed by filling it with molten metal U-alloy. A laser displacement sensor for measuring the displacement of the impactor and a load cell for measuring the load were installed under the test piece, and the measurement was performed at a sampling frequency of 500 kHz. In this section, the mass of the impactor was 17.9 kg and the height was 2.5 m. The test piece was manufactured by

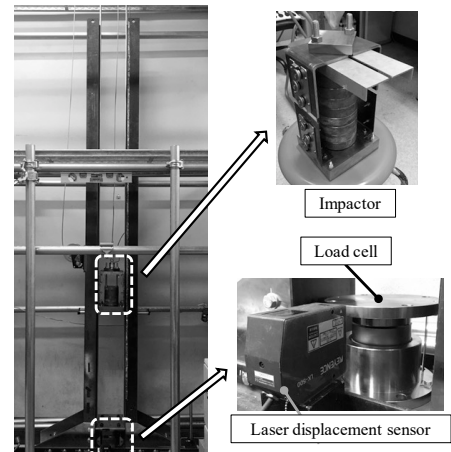


Fig. 2 Photograph of drop weight tester.

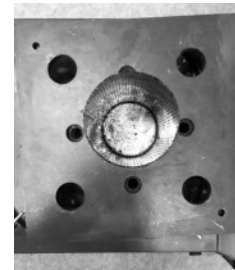


Fig. 3 Test piece fixed with fusible alloy.



(a) Steel + Steel (b) CFRP 3Ply + Steel

Fig. 4 Connected test piece.

connecting a CFRP pipe assumed CB and a steel can assumed FSM. The CFRP pipe with a height of 100 mm, an inner diameter of 50 mm was manufactured by 3 plied prepreg of plain weave which bundled of 3000 fibers. The CFRP pipe and the steel can were connected with adhesive of the metal lock manufactured by CEMEDINE co. Ltd. The height of the steel can was 104 mm, the inner diameter was 52 mm, and the thickness was 0.2 mm. To compare the connected test piece of CFRP and steel member, we fabricated 2 test pieces that is the test piece connected 2 steel cans (hereafter Steel + Steel) and the steel can and the CFRP pipe (hereafter CFRP 3Ply + Steel) as shown in Fig. 4. Figure 5 shows the equipment used for video recording.

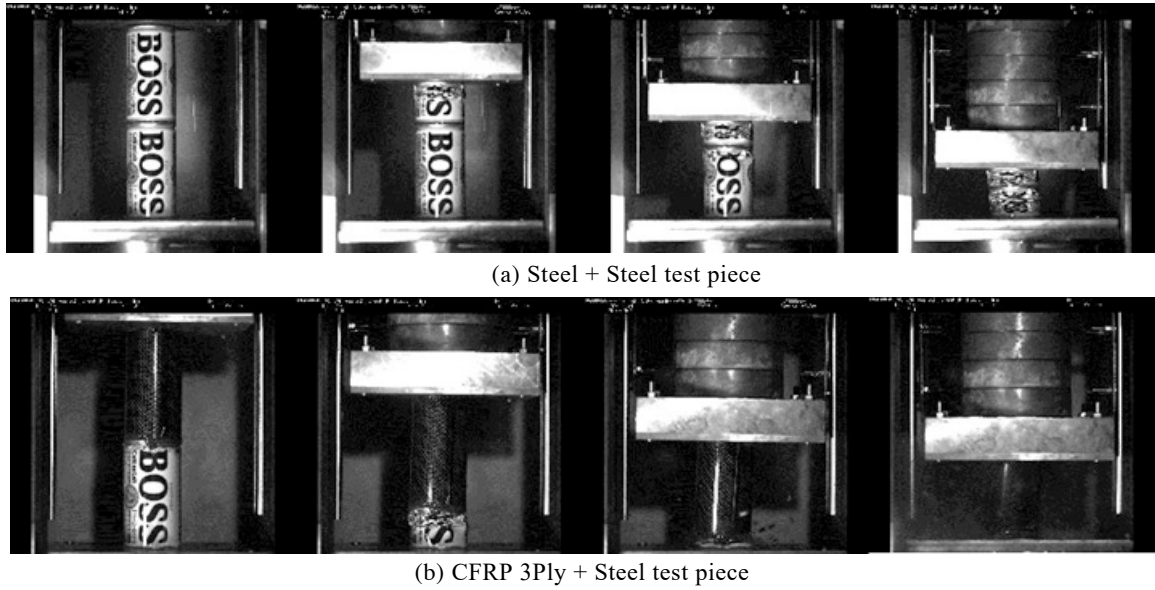


Fig. 7 Connected test piece was being crushed by impactor taken with the high-speed camera.



Fig. 5 High speed camera.



Fig. 6 Comparison of the test piece crushed in the drop weight test and the test pieces before the test.

2.2 Experimental result of drop weight test

Figure 6 shows the comparison of the test piece crushed in the drop weight test and the test pieces before the test. Although the Steel + Steel test piece was completely crushed, the CFRP 3Ply + Steel test piece was completely crushed at steel can part and remained its structure at CFRP part. Figure 7 shows how the test piece was being crushed by impactor taken with a high-speed camera. Figure 7 (a) shows that the steel can part which face to impactor was crushed at first in Steel + Steel test piece. On the other hand, the CFRP 3Ply + Steel test piece was crushed at the steel can part which did not face to impactor, as shown in Fig. 7 (b). Moreover, the crushing at CFRP part occurred at the side not to face to the impactor. In order to quantitatively evaluate the progress of crushing, the ratio of the amount of crushing δ to the length L of the entire test piece was defined as δ / L . Figure 8 shows comparison of these test pieces at approximately $\delta / L = 0.4$. In each test piece, it is confirmed that buckling occurred in the steel can part. From these results, it is considered that the

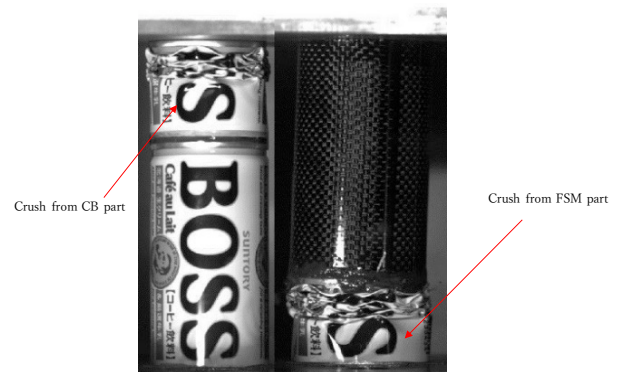
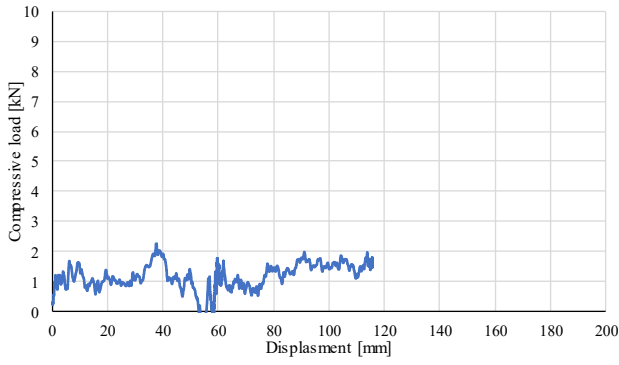


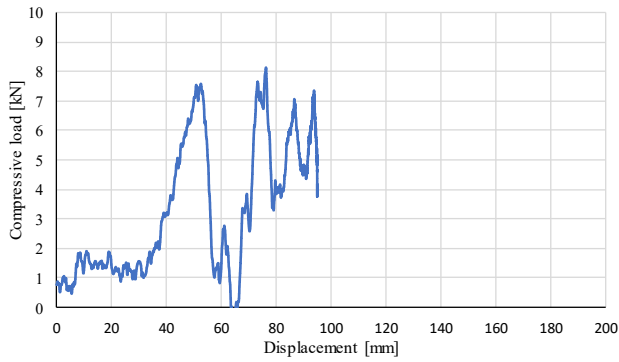
Fig. 8 Detail buckling of each test piece.

structural strength of CFRP part assumed as CB is extremely greater than steel can part assumed as FSM.

Figure 9 shows the load-displacement diagrams of the drop weight test in each test piece plotted by displacement measured by the laser sensor and load detected by the load



(a) Steel + Steel test piece



(b) CFRP 3Ply + Steel test piece

Fig. 9 Load-displacement diagrams in drop weight test.

cell. In this study, the point at which the load 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. At first, the tendency of both test piece was same when the steel can part was crushed. Then, at the crush amount $\delta = 37$ mm, the load of CFRP 3Ply + Steel test piece increased drastically when the crushing occurred at the CFRP part. Finally, the total crushing amount was 116 mm at Steel + Steel test piece and 95 mm at CFRP 3Ply + Steel test piece.

Assuming that the impact load at a minute crushing amount ds [mm] of the test piece is $f(s)$ [kN], the absorption energy U when the impactor is displaced by x [mm] can be expressed by the following equation⁶⁾:

$$U = \int_0^x f(s) ds. \quad (1)$$

By using eq. (1), the absorption energy at the crushing rate $\delta/L = 0.1, 0.3, 0.5$ and crushing completed were summarize to Table 1. From these experimental results, Steel + Steel test piece could not completely absorb the energy of the impactor. Although CFRP 3Ply + Steel test piece was able to completely absorb energy, the steel can which assumed as FSM was completely crushed. Therefore, it is necessary to study the structural strength of CB that can absorb energy while maintaining the structure of FSM.

Table 1 Absorption energy of each test piece.

	Steel+Steel [J]	CFRP3 Ply+Steel [J]
$\delta/L = 0.1$	7.8	16.2
$\delta/L = 0.3$	50.6	68.8
$\delta/L = 0.5$	60.2	158.6
Crushing completed	134.6	305.2

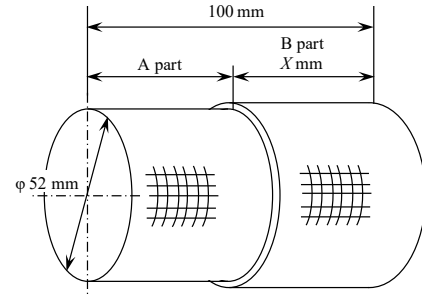


Fig. 10 Schematic diagram of CFRP test piece with different ply numbers.

3. Consideration to maintain the FSM structure by using CFRP test piece which the number of plies partly changed

3.1 CFRP test piece which the number of plies partly changed

Experimental results in previous section shows that it is important to control the strength of the CFRP part to maintain the structure of the FSM. In our previous study, we have confirmed that partial change of the ply number of prepreg in cylindrical CFRP test piece can control the energy absorption performance⁶⁾. In this section, it is investigated that the CFRP test piece partly changed the ply number was applied in CB to maintain the structure of the FSM made of the steel can. Moreover, we aim to clarify the condition so that the CB is firstly crushed.

The CFRP pipe was manufactured by laminating CFRP prepreg of CF / PPG / 3KP / 33G manufactured by CAST co. ltd. and forming to the cylindrical test piece. Figure 10 shows a schematic diagram of the manufactured test piece with a total height of 100 mm, an inner diameter of 52 mm. Part A is the side that contacts the impactor, and part B is the side that is fixed to the steel can assumed as FSM. To decrease the structural strength comparing to the test piece in previous section, the number of plies was 1 ply in part A and 2 plies in part B. To change the structural strength of the CFRP part, 3 CFRP pipes with the height of part B $X = 50$ mm, 75 mm, and 100 mm were manufactured.

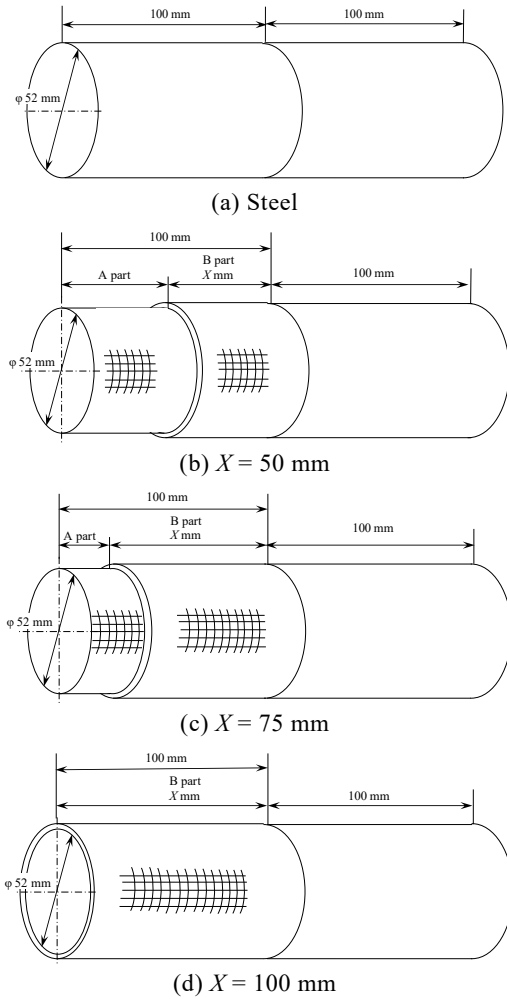


Fig. 11 Schematic diagrams of constructed test piece.

3.2 Experimental condition of drop weight test

The drop weight test was performed to investigate crush characteristics of the test piece connected the steel can assumed FSM to the manufactured CFRP pipe assumed CB as the same to previous section. In this section, the mass of the impactor was 17.9 kg and the height of the impactor was 1.5 m. We constructed 4 types of test piece which changes CB part connected to the FSM of the steel can as follows; (a) steel can (hereafter Steel, which is same to Steel + Steel test piece in previous section), (B) CFRP pipe with $X = 50$ mm, (c) $X = 75$ mm, and (d) $X = 100$ mm. Figure 11 shows schematic diagrams of these test pieces.

3.3 Experimental result of drop weight test

Figures 12 shows photographs of the crushed test pieces. The measured crush amount of FSM part, which is red line shown in Fig. 12, is shown in Fig. 13. Although the FSM part could almost be remained in test pieces of (a) Steel and (c) $X = 75$ mm, the FSM part was completely crushed before crushing CB part in the test piece of (d) $X = 100$ mm. Figure 14 shows the load-displacement diagrams in each test piece. In two types of test pieces shown in Figs. 14 (b) and (c), the



(a) Steel (b) $X = 50$ mm (c) $X = 75$ mm (d) $X = 100$ mm

Fig. 12 Photograph of the crushed test pieces.

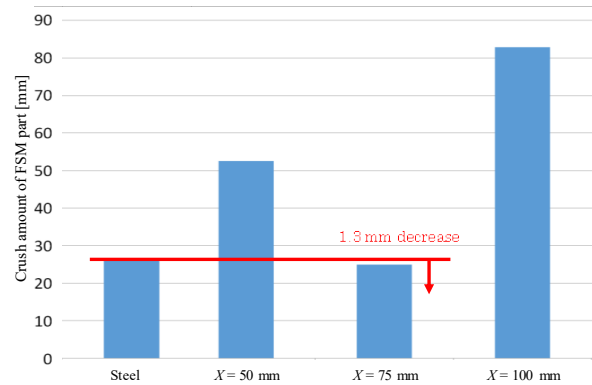


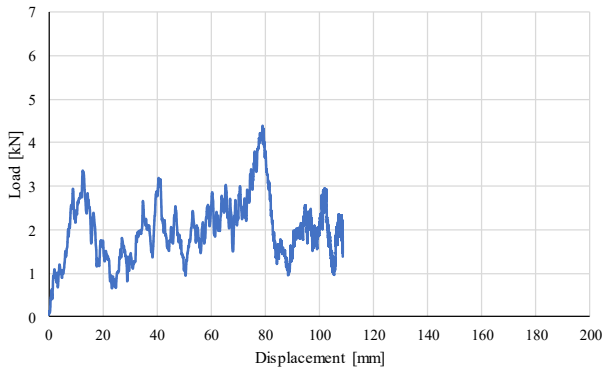
Fig. 13 Measured crush amount of FSM part.

measured load was less than the Steel test piece in the initial stage of crushing. Then, the load increased after the crushing of part A was completed, and the amount of the load was almost the same as the result of the (a) Steel test piece. On the other hand, in the result of (d) $X = 100$ mm as shown in Fig. 14 (d), a large load was measured after the impactor immediately contacted to the CB part.

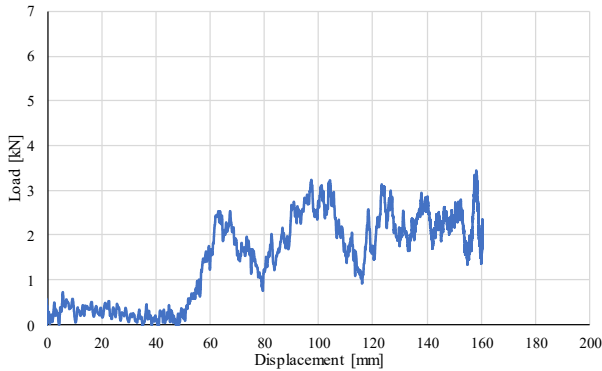
The amount of energy absorbed by the CB part is clarified, and the relationship between the amount of energy absorbed by the CB and the fracture size of the FMS part is quantitatively explained. For the purpose of this study, we compare (a) CFRP [$X = 50$ mm] and (c) CFRP [$X = 75$ mm] for steel materials, and link the knowledge obtained from this comparison with the establishment of design guidelines for high-efficiency CB that can effectively crush and absorb energy while maintaining the original shape of FSM. Figure 15 shows the maximum load peak in Fig. 14 of each test piece in the initial stage of crushing which we defined in the range of $\delta / L = 0 \sim 0.25$. The CB with $X = 50$ mm had the lowest load peak at the initial stage of crushing. However, the CB with $X = 50$ mm crushed completely and the FSM also crushed. As the height of 2 Ply part X increases, the initial load peak also increases. The initial peak at $X = 75$ mm was almost equal to Steel test piece, and the result at $X = 100$ mm was larger than the result of the Steel. However, the absorption energy as shown in Fig. 16 was minimum at $X =$

100 mm. It was shown that the CB with $X = 100$ mm could not absorb the impact energy.

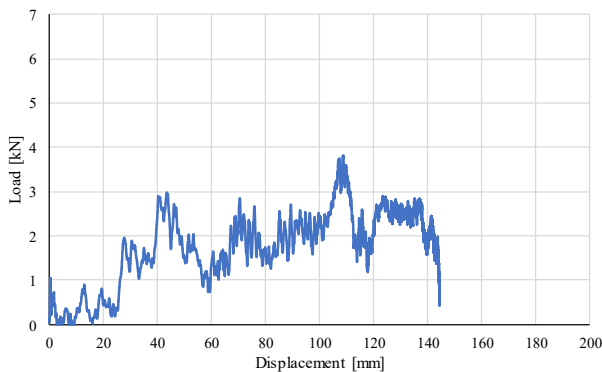
From these results, it is considered as follows. In the case of $X = 50$ mm and 75 mm, the load increased smoothly by intentionally reducing the structural strength of the CB facing the impactor. It is considered that the load in the initial stage of crushing was lower than the structural strength of the FSM, thereby preventing the buckling of the FSM. It is probable that the impact energy could not be completely absorbed by CB alone because CB with $X = 50$ mm had too weak a structural strength. In the case of $X = 100$ mm, the load in the initial stage of crushing increased drastically, and the maximum load was greater than the structural strength of the FSM. Therefore, the buckling of the FSM could not prevent.



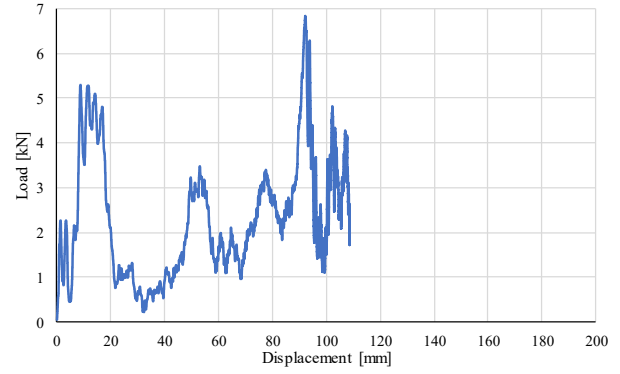
(a) Steel



(b) $X = 50$ mm



(c) $X = 75$ mm



(d) $X = 100$ mm

Fig. 14 Load-displacement diagrams in each test piece.

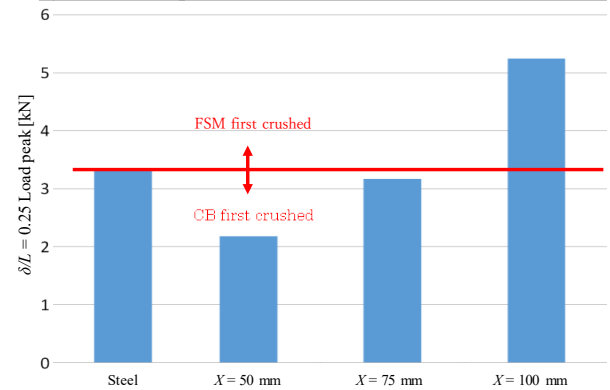


Fig. 15 Maximum load peak in the initial stage of crushing ($\delta / L = 0 \sim 0.25$).

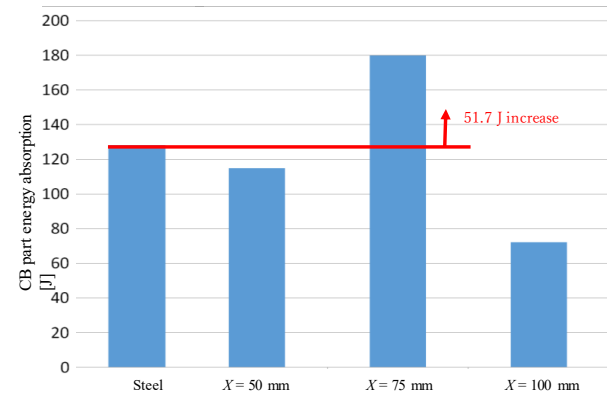


Fig. 16 Absorption energy in the initial stage of crushing ($\delta / L = 0 \sim 0.25$).

4. Conclusion

In order to establish a design guideline for a highly efficient CB that can effectively crush and absorb energy while maintaining the original shape of FSM, the crushing characteristics of the test piece, which consist of the CFRP pipe assumed as CB and the steel can assumed as FSM, was investigated by the drop weight test. From experimental results, the CB which has excessive structural strength could not absorb the impact energy and maintain the structure of

the FSM part. In especially, it was found that the FSM tend to crush firstly due to the large load peak occurred in the initial stage of crushing in the case of the excess structural strength of the CB. Therefore, the our proposed CFRP pipe which the laminate number of CFRP prepreg was partly changed was applied to CB connected with the FSM. The proposed CFRP member intendedly decrease the structural strength of the CB facing to impactor, and the load peak in the initial stage of crushing was able to be reduced. This reduction of the initial stage peak allowed the FSM structure to be maintained. From this result, in order to design a CB that can maintain the structure of FSM, it is necessary to have sufficient strength to absorb impact energy and reduce the initial stage peak of load. In the future, we would investigate the energy absorbing characteristics of the CFRP member in more detail when the number of plies, laminate direction and shape of the member is changed.

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