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ENERGY ABSORPTION CHARACTERISTICS IN SQUARE OR CIRCULAR SHAPED ALUMINUM/CFRP COMPOUND TUBES UNDER AXIAL COMPRESSION

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ABSTRACT−With the respective collapse characteristics of aluminum and CFRP (Carbon Fiber Reinforced Plastics) tubes in mind, axial collapse tests were performed for aluminum/CFRP compound tubes, which are composed of square or circular shaped aluminum tubes wrapped with CFRP outside. In this study, the collapse modes and the energy absorption characteristics were analyzed for aluminum/CFRP compound tubes which have different fiber orientation angle of CFRP. Fracture modes in the aluminum/CFRP compound tubes were rather stable than those in the CFRP tubes alone, probably due to the ductile nature of the inner aluminum tubes. The absorbed energy per unit volume of the aluminum or the aluminum/CFRP compound tubes was higher than that of CFRP tubes. Meanwhile, the absorbed energy per unit mass, for the light-weight design aspect was higher in the aluminum/CFRP compound tubes than in the aluminum tubes or the CFRP tubes. The energy absorption turned out to be higher in circular tubes than in square tubes. Beside the collapse modes and the energy absorption characteristics were influenced by the orientation angle, and the compound tubes took the most effective energy absorption when the fiber orientation angle of CFRP was 90 degrees.

KEY WORDS : Aluminum/CFRP compound tubes, Fiber orientation angle, Axial collapse test, Collapse modes, Energy absorption characteristics

1. INTRODUCTION

Side members of automobile front parts are structural members which absorb energy under axial load (Cha *et al.*, 2004; White *et al.*, 1999a, 1999b). The structural members absorb more energy in collision if they have higher strength and stiffness, and stable folding capacity (local buckling). Using the above characteristics on energy absorption, automobiles should be designed light-weight to improve fuel efficiency.

When the energy absorption members, such as an aluminum and a CFRP tube, are subjected to axial loading, the aluminum tube absorbs energy by stable plastic deformation (Avalle and Belingardi, 1997; Bardi and Yun, 2003; Kim and Heo, 2003; Li and Reid, 1990; Minoru *et al.*, 2003) but the CFRP tube absorbs most of the energy by unstable brittle failure (Kim *et al.*, 2001, 2002; Mamalis *et al.*, 2004; Minoru *et al.*, 2003).

In this study, the aluminum/CFRP compound tubes which are composed of square or circular shaped aluminum tubes wrapped with CFRP outside were manufactured in an attempt to get a synergy effect when the aluminum/CFRP tube is combined with the advantages of each member, such as energy absorption by the stable folding deformation of the aluminum tube and by the high specific strength and stiffness of the CFRP tube. Next, the axial collapse tests were performed for the aluminum/CFRP compound tubes. Because the CFRP is an anisotropic material whose mechanical properties, such as strength and elasticity, change with its fiber orientation angle, special attention was given to the effects of the fiber orientation on the collapse characteristics of the compound tubes.

The test results showed that the collapse of the aluminum/CFRP tubes complemented the unstable brittle failure of the CFRP tube alone with the influence of the aluminum tubes, regardless of their shapes, circular or square. The absorption energy per unit volume was

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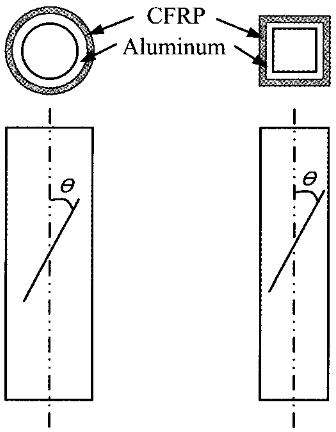
**Corresponding author.* e-mail: iyyang@chosun.ac.kr higher in the aluminum tubes or the aluminum/CFRP tubes than in the CFRP tubes. However, in the light-weight design aspect, the absorption energy per unit mass was the highest in the case of the aluminum/CFRP compound tubes. The energy absorption of the circular shaped tube was higher than that of the square shaped tube, and the aluminum/CFRP tubes showed the highest energy absorption when the fiber orientation angle of CFRP was 90 degrees.

2. SPECIMENS

The circular or the square aluminum tubes were manufactured using a sheet metal of 6063-T5 type with thickness of 1.0 mm by SEOUL Metal Co.. The outside diameter of the circular tube was 38 mm, and the width of one side of the square tube was 30 mm. The materials of the circular or square aluminum tubes had identical mechanical properties. The CFRP tubes were made of 8 Plies (about 1.0 mm) of uni-directional prepreg sheets of carbon fiber/epoxy (HANKUK Fiber Co., CU125NS). The circular or square aluminum/CFRP tubes were manufactured by wrapping CFRP prepreg sheets outside the circular or square aluminum tubes in the autoclave, as shown in Figure 1. To investigate the influence of the fiber orientation angle, the orientation angles of the circular or square compound tubes were stacked to $[+\Theta_2/-\Theta_2]_S$ of 8 plies, where Θ is 15°, 30°, 45°, 60°, 75°, and 90°. During manufacturing by the autoclave, the hardening conditions were set up as the hardening temperature of 130°C, the hardening time of 90 minutes, and the vacuum pressure of 10^{-1} Pa. It was also compressed up to 3×10^5 Pa from the outside of the vacuum bag. All the specimens were cut to have the specimen length of 120 mm using a diamond cutter. Table 1 shows the material properties of the aluminum tubes, and Table 2 shows the material properties of the CFRP prepreg sheet.



(a) Circular tube (b) Square tube

Figure 1. Configuration of aluminum/CFRP tube.

Table 1. Material properties of the aluminum tube.

Density [Kg/m^3]	Poisson's ratio	Young's modulus [GPa]	Yield stress [MPa]	Tensile stress [MPa]
2.68	0.31	67.2	165	192

Table 2. Material properties of the CFRP prepreg sheet.

	Fiber (Carbon)	Resin (Epoxy #2500)	Prepreg sheet
Density [Kg/m^3]	1.83×10^3	1.24×10^3	
Poisson's ratio			0.3
Young's modulus [GPa]	240	3.60	132.7
Tensile stress [GPa]	4.89	0.08	1.85
Breaking elongation [%]	2.1	3.0	1.3
Resin content [% Wt]			33

3. COLLAPSE TEST

A quasi-static axial collapse test was performed by using a universal testing machine (Instron 4206-001, 15 Ton). Two compressed zigs were set up in parallel between the load cell and the actuator. All specimens were compressed to 58.3% (70 mm) of the whole length (120 mm) in the axial direction at a rate of 10 mm/min.

Five to seven collapse tests were performed for each specimen to access the reliability of the data. The variation of the data from several tests fell within 3%. Figures 2 and 3 show the load-displacement curves

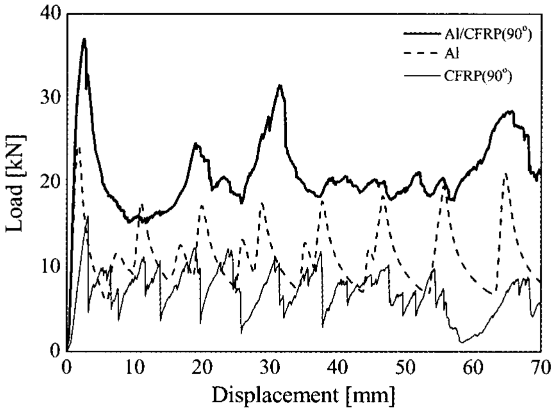


Figure 2. Load-displacement curve of the circular tubes.

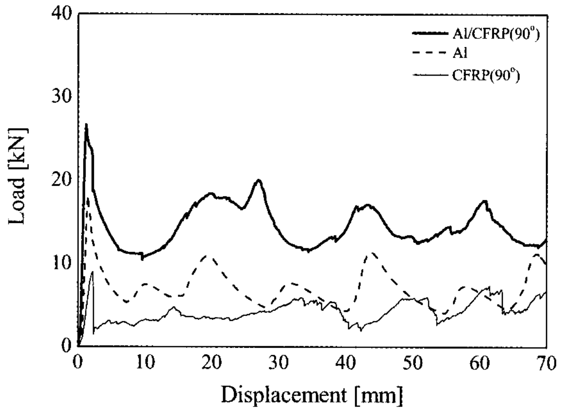


Figure 3. Load-displacement curve of the square tubes.

which were randomly chosen from the data. Figure 2 shows the load-displacement curves of the circular aluminum tube, the circular CFRP tube with fiber orientation angle of 90°, and the circular aluminum/ CFRP tube with fiber orientation angle of 90°. Figure 3 shows the load-displacement curves of the square aluminum tube, the square CFRP tube with fiber orientation angle of 90°, and the square aluminum/CFRP tube with fiber orientation angle of 90°. In Figures 2 and 3, the bold solid lines, the thin solid lines, the dotted lines indicate for the aluminum/CFRP tube, the CFRP tube, and the aluminum tube, respectively.

The absorbed energy is represented by the area of the load-displacement curve shown in Figure 2 and 3. So, it can be obtained by integrating the curve, as shown in Equation (1).

$$E_a = \int_0^S P dS \qquad (1)$$

where, E_a, P and S indicate the absorbed energy, the collapse load, and the collapsed length of the specimen, respectively.

The absorbed energy per unit volume can be calculated by dividing it by the volume of collapsed part, as in shown Equation (2). The absorbed energy per unit mass can be calculated similarly by dividing it by the mass of collapsed part, as shown in Equation (3).

$$E_V = \frac{E_a}{(A_{Al} + A_{CFRP})S} \qquad (2)$$

$$E_S = \frac{E_a}{(\rho_{Al} A_{Al} + \rho_{CFRP} A_{CFRP})S} \qquad (3)$$

where, E_v and E_s are the absorbed energy per unit volume, and unit mass, respectively. A_{Al} and A_{CFRP} are the sectional area of the aluminum tube, and the CFRP tube, respectively. ρ_{Al} and ρ_{CFRP} are the density of the aluminum tube, and the CFRP tube, respectively.

4. RESULTS AND DISCUSSION

4.1. Collapse Modes

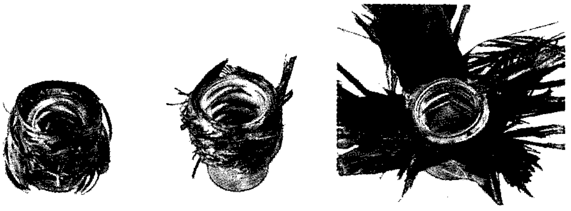
The collapse modes of the circular aluminum tube are categorized into axisymmetric mode, non-axisymmetric mode, and the combination of these two modes. As in the circular aluminum tube, the square aluminum tube is collapsed stably and in a regular sequence with axisymmetric and non-axisymmetric modes (Avalle and Belingardi, 1997; Bardi and Yun, 2003; Kim and Heo, 2003; Li and Reid, 1990; Minoru *et al.*, 2003). However, the collapse mode of the CFRP tube is mainly determined by change of fiber orientation angle, and characterized by unstable brittle failure, such as a wedge collapse mode and a splaying collapse mode (Kim *et al.*, 2001, 2002; Mamalis *et al.*, 2004; Minoru *et al.*, 2003).

The collapse modes of circular or square aluminum/ CFRP tube are categorized into three modes which are composed of the mixed collapse modes of the aluminum and the CFRP tube, respectively. The collapse mode is mainly determined by the fiber orientation angle of CFRP. Figures 4 and 5 show the collapse modes of the circular and the square aluminum/CFRP tubes, respectively.

The collapse mode of the circular aluminum/CFRP tubes are classified into three types; (a) compound fragmentation mode, (b) folding mode and (c) compound splaying mode, as shown in Figure 4.

The compound fragmentation mode is defined as a mode that when the inner aluminum tube is folded, most of the circumferential fibers of the CFRP tube are broken, and some of the fibers are held between folding of the aluminum tubes. This type frequently appear in a circular tube with fiber orientation angle of 90°. The larger fiber orientation angle the circular CFRP tube has, the larger circumferential stress occurs. It is believed that as the regular collapse of the inner aluminum tube is disturbed, the circumferential fibers of the external CFRP tube fail owing to the occurred high load.

The folding mode of the circular aluminum/CFRP tube is defined as a mode that CFRP tube is held between the aluminum tube foldings. It was frequently found when



(a) (b) (c)

Figure 4. Typical collapse modes of the aluminum/CFRP circular tubes: (a) Compound fragmentation mode (b) Folding mode (c) Compound splaying mode.

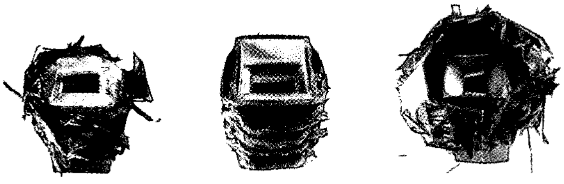

(a) (b) (c)

Figure 5. Typical collapse modes of the aluminum/CFRP square tubes: (a) Compound fragmentation mode (b) Folding mode (c) Compound splitting mode.

the fiber orientation angle of CFRP is more than 45°. Compared to the compound fragmentation mode, failure of CFRP fibers is less frequent probably due to less circumferential stress. Most of the fibers are held between folding parts of the inner aluminum tube.

The compound splaying mode of the circular aluminum/CFRP tube is defined as a mode that axial fibers of the external CFRP tube are splayed outward. This collapse mode occurs in case of small fiber orientation angle, where axial fibers of the CFRP tube were separated from the aluminum tube, and splayed outward.

Similarly, three types of the collapse mode in case of the square aluminum/CFRP tubes are the compound fragmentation, the folding mode and the compound splitting mode, as shown in Figure 5. The compound fragmentation mode of the square aluminum/CFRP tube, which is different from that of the circular tube, some of the fibers were held between foldings of the aluminum tube in case of the 45° fiber orientation angle of the CFRP tube. Most of the circumferential fibers of the CFRP tube were broken, but very few fibers were held in the folded aluminum tube.

The folding mode of the square aluminum/CFRP tube was observed when the fiber orientation angle of CFRP is above 60°. The folding length (length between adjacent hinges) of the square tube was larger than that of the circular tube, and fibers of the square CFRP tube were rarely broken, and easily held between square aluminum tube foldings.

The compound fragmentation mode of the square aluminum/CFRP tube is defined as a mode that the inner aluminum tube is collapsed in an axisymmetric mode, while fibers of the CFRP tube break, and split of the lamina at the edges of the square CFRP tube occurs. Thus the CFRP tube can not be held between aluminum tube foldings and separated from the aluminum tube. This mode was frequently observed when the fiber orientation angle of CFRP was small.

In the case of circular or square aluminum/CFRP tubes, the unstable brittle failure of the outer CFRP tube was complemented by the stable collapse of the inner aluminum tube. The absorbed energy of the aluminum/CFRP compound tube was higher than summation of respective energy of the aluminum and the CFRP tube, which will be shown in the subsequent section in this paper. In particular, the compound structures absorbed plenty of energy through folding modes or compound fragmentation modes.

4.2. Energy Absorption

Figure 6 shows the absorbed energy per unit volume for the aluminum tube, the CFRP tube with fiber orientation angle of 90°, and the aluminum/CFRP compound tube with fiber orientation angle of 90°. All the structures were deformed up to the identical strain, and two kinds of cross sectional shapes, circular or square, were drawn at the same time in order to compare absorbed energy during collapse. Figure 7 shows the absorbed energy per unit mass to reflect the light-weight design aspect. In Figure 6, the aluminum tubes and the aluminum/CFRP tubes have similar absorbed energy per unit volume, while the CFRP tube has the smallest value. Aluminum

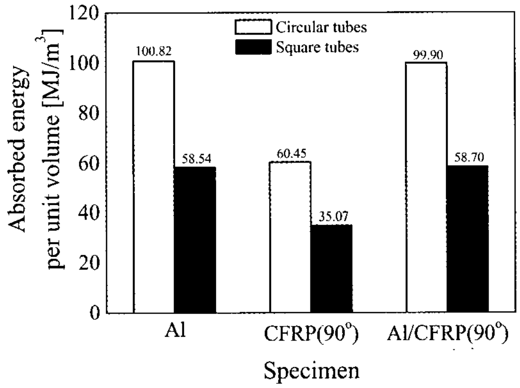


Figure 6. Absorbed energy per unit volume in the square and the circular tubes.

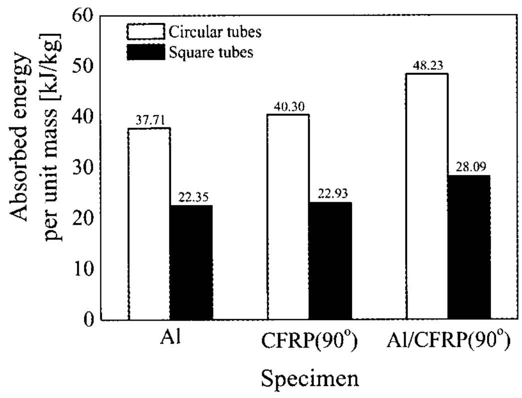


Figure 7. Absorbed energy per unit mass in the square and the circular tubes.

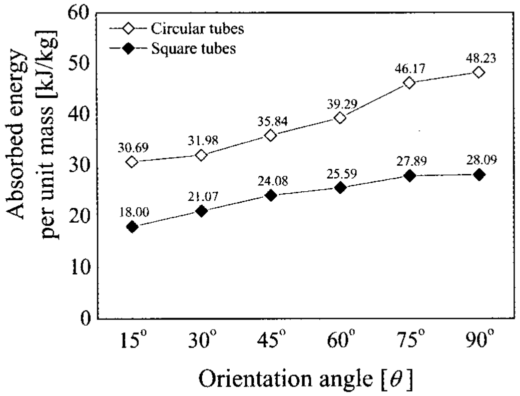


Figure 8. Absorbed energy per unit mass of the aluminum/CFRP compound tubes with the different fiber orientation angle.

tubes and aluminum/CFRP tubes absorbed more energy than CFRP tubes for identical strain, which implies the use of CFRP alone should be avoided. Considering that the aluminum tube has higher density than the CFRP tube, the absorbed energy per unit mass of the CFRP tube is slightly larger than that of the aluminum tube, as shown in Figure 7. It is worth noticing that the absorbed energy per unit mass of the aluminum/CFRP tube was larger than those of the aluminum tube and the CFRP tube. Therefore, in light-weight design aspect, the aluminum/CFRP tubes are quite recommendable as for structural members under axial loads, such as the side members in a vehicle. For all the investigated cases, circular tubes had more capability in absorbing energy than square tubes.

Figure 8 shows the variations of the absorbed energy per unit mass with change of the fiber orientation angle for the circular or the square aluminum/CFRP tubes. In the figure, the absorbed energy per unit mass increases with increase of fiber orientation angle in the aluminum/CFRP tubes. As the fiber orientation angle of the aluminum/CFRP tube increases, the CFRP tube supports more load in the form of hoop stress, which disturbs the folding of the aluminum tube. The folding with hoop stress occurs at higher load than without one. As the fibers of the CFRP tubes are broken, they are held between the aluminum tube foldings which are generated by a stable and effective collapse mode. The absorbed energy per unit mass of the circular aluminum/CFRP tube was about 60% higher than that of the square aluminum/CFRP tube. When structural members are subjected to axial loadings, stress is concentrated on their edges in case of square tubes, thus assuming that the circular tubes have unlimited edges, it sustain higher load and absorb more energy (Minoru *et al.*, 2003).

5. CONCLUSIONS

With the respective collapse characteristics of aluminum and CFRP tubes in mind, the axial collapse tests were performed for aluminum/CFRP compound tubes which are composed of square or circular shaped aluminum tubes wrapped with CFRP on their outside. The results are as follows:

(1) Aluminum/CFRP compound tubes had a stable collapse mode by complementing unstable brittle failure of CFRP tubes due to the ductile nature of their inner aluminum tubes. The collapse modes of circular aluminum/CFRP tubes were compound fragmentation mode, folding mode and compound splaying mode. The collapse modes of square aluminum/CFRP tubes are compound fragmentation mode, folding mode and compound splitting mode. In the compound fragmentation mode and the folding mode, the collapse occurred in stable and effective ways.

(2) The absorbed energy per unit volume in both the aluminum and aluminum/CFRP compound tubes was higher than in CFRP tubes. Meanwhile the absorbed energy per unit mass, which is in the light-weight design aspect, was higher in aluminum/CFRP compound tubes than in aluminum tubes or CFRP tubes. The energy absorption in circular tubes turned out to be higher than in square tubes.

(3) The energy absorption in both the circular and the square aluminum/CFRP tube increased with increase of fiber orientation angle. The most effective energy absorption was shown when it was 90°.

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