COMPARISON OF EXPERIMENTAL RESULTS WITH FEM ONES OF RECTANGULAR CFRP TUBES FOR FRONT SIDE MEMBERS OF AUTOMOBILES

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Abstract

The objective of this study is to establish the simulation technology for impact response behaviors of rectangular CFRP tubes under full-lap collision. We adopted drop weight impact tests to investigate impact response behaviors and impact energy absorption characteristics of the rectangular CFRP tubes. The impact test was carried out by dropping the impactor from height of 12 m. Impact speed was approximately 55 km/h just before the impact. The weight of the impactor was 105 kg. It was observed that the five specimens show the same tendency of the impact response behaviors in the impact test. A finite element (FE) model was also developed by using a nonlinear, explicit dynamic code LS-DYNA to simulate the progressive failure behavior and to calculate the absorbed energy of the rectangular CFRP tubes under impact load. The comparison of experimental results with that of FEM for the load-displacement curves was favorable. The maximum load, absorbed energy and final displacement calculated by FEM model were in good agreement with the average values of the impact test results.

1 Introduction

It is well known that CO_2 emissions, which are one of the greenhouse gases emitted from passenger vehicles such as automobile and aircraft, are major cause of global warming. In the automotive industry, to reduce CO_2 emissions, we have found that the most effective method is to make the most fuel efficient automobile. To increase the fuel efficiency of the automobile, the most effective approach is to reduce the automobile weight using lightweight materials such as fiber reinforced composite materials.

As Carbon fiber reinforced plastics (CFRPs) possess the merits of fabrication convenience, crushing stability and high energy absorption performance, they have been widely used in aerospace and passenger vehicles. With an increasing interest in the lightening of the automobile and the safety to the passenger, many researches have been performed. Many experimental researches have been reported that the main factors affecting the energy absorption performance of fiber reinforced plastic (FRP) tubes such as circular and square tubes are mechanical properties, fabrication conditions, tube shapes (including crush initiators) and testing speeds (i.e. static and impact loading) [1-10]. Also, a few finite element analyses to simulate the progressive failure behaviors and absorbed energy of the FRP tubes have been performed [10-12].

In this study, we develop rectangular CFRP tubes with two ribs in order to design impact energy absorption members under full-lap collision. A drop weight impact test is carried out to investigate the impact response behavior and the impact energy absorption characteristic of the rectangular CFRP tube. A finite element (FE) model is also developed by using a nonlinear, explicit dynamic code LS-DYNA [13] to simulate the progressive failure behavior and the absorbed energy of the rectangular CFRP tube with ribs under impact loading.

2 Experiment

2.1 Specimen Fabrication

The rectangular CFRP tubes with a rib were manufactured from unidirectional prepregs (P3052s-20, Toray Industries, Inc.) by using the sheet winding method. Configuration of the rectangular CFRP tube is shown in Fig. 1. Stacking sequences of the main and rib parts in the rectangular CFRP tubes were $[(0/90)_6/0]_S$ and [0], respectively. An initial imperfection with an external bevel type was introduced in order to get a stable progressive failure behavior.

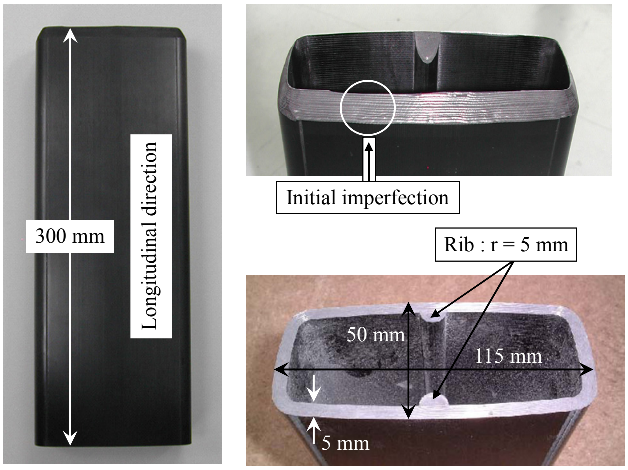
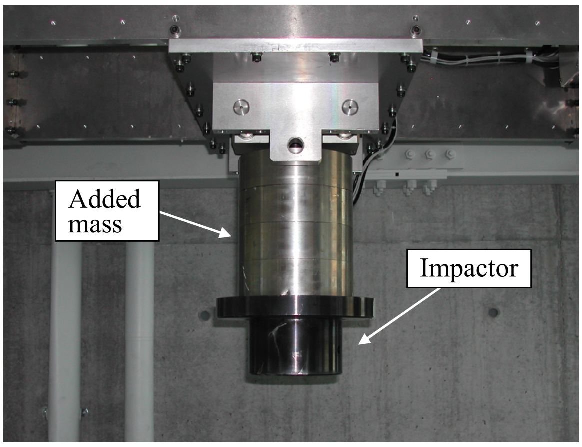


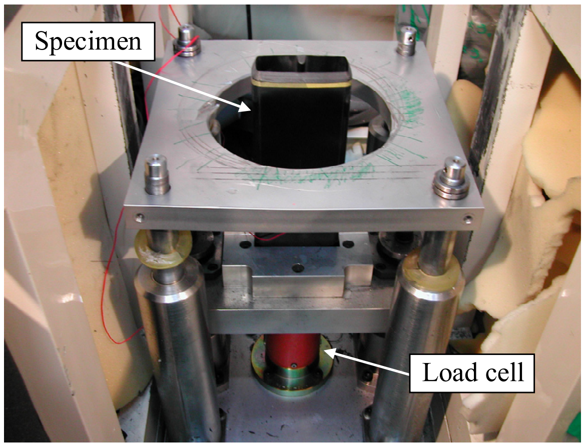
Fig. 1. Configuration of the rectangular CFRP tube with two ribs

2.2 Impact Tests

We adopted drop weight impact tests to investigate impact response behaviors and impact energy absorption characteristics of the rectangular CFRP tubes as shown in Fig. 2. The impact tests were carried out by dropping the impactor from height of 12 m. The weight of the impactor was 105 kg. Also, the impactor speed was approximately 55 km/h just before the impact. The impact load was measured from a load cell under the specimen which was mounted by metallic base (see Fig. 2(b)). In order to investigate the progressive failure mechanism of the rectangular CFRP tubes, a high speed camera was employed.



(a) impactor



(b) mounted specimen

Fig. 2. Tower drop impact test setup

3 FEM Analysis

3.1 Details of FEM Model

In our previous study [14], to simulate the progressive failure behaviors and absorbed energy of the rectangular CFRP tubes with a rib under impact loading, a finite element (FE) model was developed by using the nonlinear, explicit dynamic code LS-DYNA. In our previous FEM model (designated as Model 1), the rectangular CFRP tube with a rib was modeled by 24 and 44 layers, respectively. Stacking sequences of the main and rib parts were $[(0/90)_6/0]_S$ and $[0_{10}/(0/90)_6/0]_S$, respectively. There were 8125 elements and 8316 nodes in the Model 1.

In this study, in order to actually model the rectangular CFRP tube with ribs, a T-shape rib part is modeled as shown in Fig. 3 (designated as Model 2). Furthermore, the FEM model improved the Model 2 is revised as shown in Fig. 4 (designated as Model 3). The stacking sequences of the main and rib parts in the Model 2 and Model 3 were $[(0/90)_6/0]_S$ and [0], respectively. The elements and nodes of the Model 2 and Model 3 were 9656 and 9784, respectively. The impactor and rectangular CFRP tube with two ribs were modeled by solid and shell elements, respectively.

In the all FEM models, the imperfection part was introduced to reduce a maximum load and to get the stable progressive failure behaviors from the top edge of the FEM model to a length of 10 mm below (see Fig. 5). The FEM models with and without the imperfection parts, were designated as thickness-changed and thickness-constant models, respectively.

The comparison between thickness-constant and thickness-changed models is shown in Fig. 6.

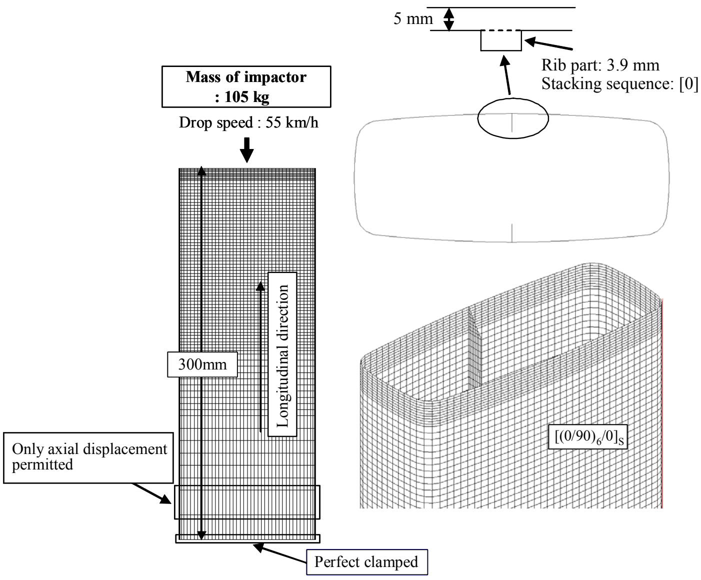
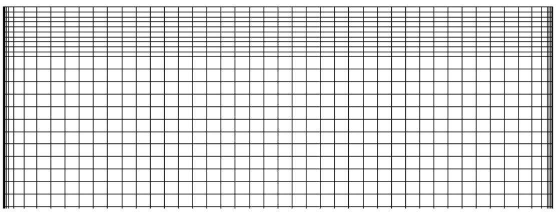
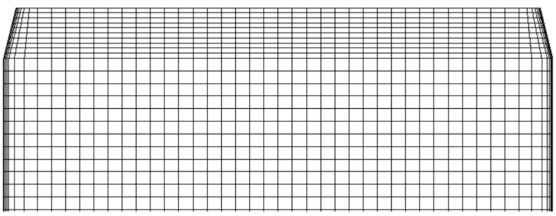


Fig. 3. Details of the finite element model (Model 2)

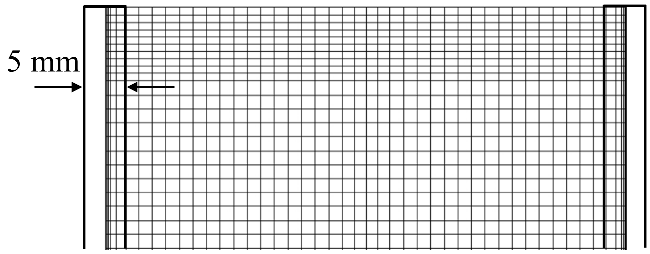


(a) Model 2

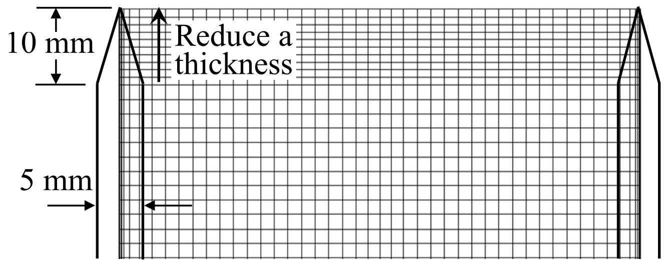


(b) Model 3

Fig. 4. Details of Model 2 and 3



(a) thickness-constant model



(b) thickness-changed model

Fig. 5. Details of the thickness-constant and thickness-changed models

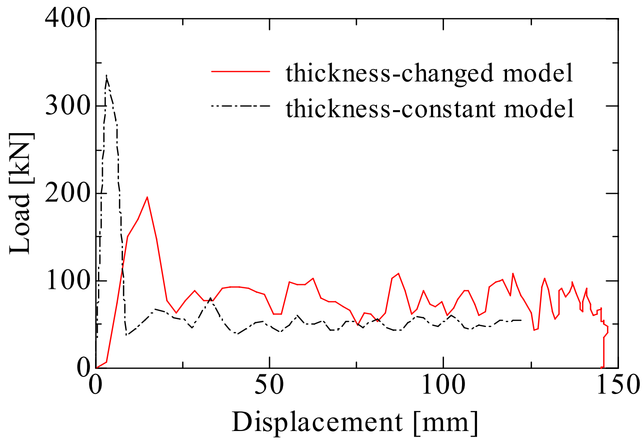


Fig. 6. Comparison of the thickness-constant and thickness-changed models for the load-displacement curve

The model without an imperfection part may produce a high initial maximum load. After that, the impact load drops rapidly. The initial maximum load of the thickness-constant model is approximately two times that of the thickness-changed model. On the other hand, impact load in the propagation region is seen that the thickness-changed model is higher than that of the thickness-constant model. Therefore, the thickness-changed method in the imperfection part is chosen. As a result, the tendency of the impact response behaviors in the FEM analysis is in good agreement with the impact tests.

3.2 Boundary and Contact Conditions

The mass and initial velocity of the impactor modeled as a rigid body were 105 kg and 15.27 m/s (55 km/h), respectively. For the boundary conditions of impactor, the displacements along the global axes *x* and *y*, and the rotations for the three global axes were constrained in the FE analysis. The displacement of impactor along the *z* axis downwards was only permitted. On the other hand, in the case of the rectangular CFRP tube with a rib, the bottom side of the model was perfectly fixed.

In this FE analysis, the rectangular CFRP tube was modeled by using a shell element (MAT_54, mat_enhanced_composite_damage) and the Chang-Chang failure criterion [13,15,16] was used to determine the failure of element.

The mechanical properties used for MAT_54 in LS-DYNA are listed in Table 1. Also, we adopted a removing element method base on a time-step failure parameter (Tfail). These analyses were conducted with Tfail parameter equal to 0.3. Two different contact algorithms were used throughout FE analysis. The "contact_automatic_surface_to_surface" contact interface type was used for the boundary between the impactor and the top part of rectangular CFRP tube. In case of the CFRP tube, the "contact_automatic_single_surface" contact interface type was adopted.

Table 1. Material properties of rectangular CFRP tube used in the FE analysis

Material property	Symbol	Values
Longitudinal Young's modulus	E_a	140.0 GPa
Transverse Young's modulus	E_b	9.0 GPa
Minor Poisson's ratio	ν_{ba}	0.0219
Shear Modulus in plane (*ab*)	G_{ab}	4.0 GPa
Shear Modulus in plane (*bc*)	G_{bc}	2.0 GPa
Longitudinal tensile strength	X_T	2.6 GPa
Longitudinal compressive strength	X_C	1.5 GPa
Transverse tensile strength	Y_T	0.07 GPa
Transverse compressive strength	Y_C	0.05 GPa
Shear strength in plane (*ab*)	S_C	0.09 GPa

4 Results and Discussions

4.1 Impact Test Results

Fig. 7 shows the load-displacement curves of the rectangular CFRP tube with ribs under impact loading. The load in the figure shows the value of the load cell. And the displacement in the figure shows the displacement of the impactor. It is seen that the same tendency of the impact response behaviors is obtained in the all test specimens.

In Table 2, the maximum load, the maximum displacement and the absorbed energy obtained from the experimental tests are listed. Here, the absorbed energy was obtained from load-displacement curves.

Fig. 8 shows the photographs of impact tested rectangular CFRP tube with a rib. It is seen that the crush zone spread out towards inside and outside of

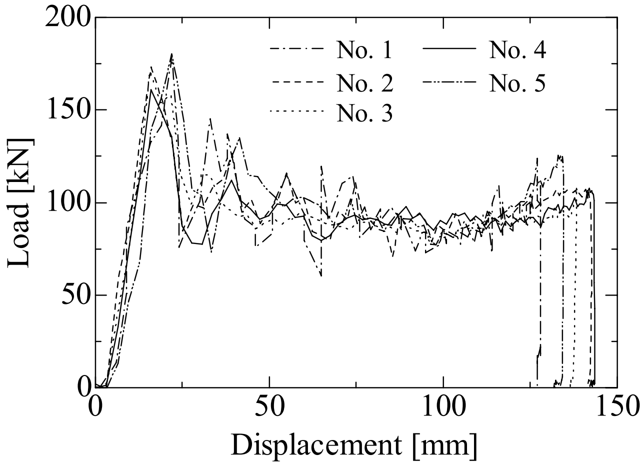
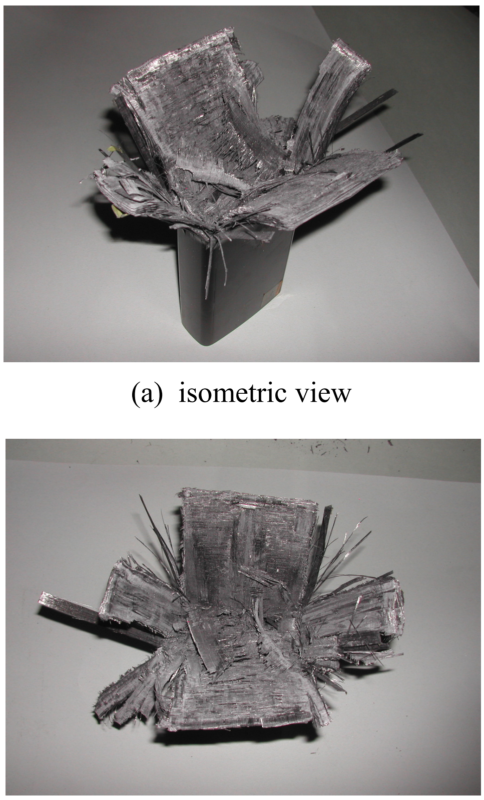


Fig. 7. Load-displacement curves for all test specimens

Table 2. Summary of the experimental results

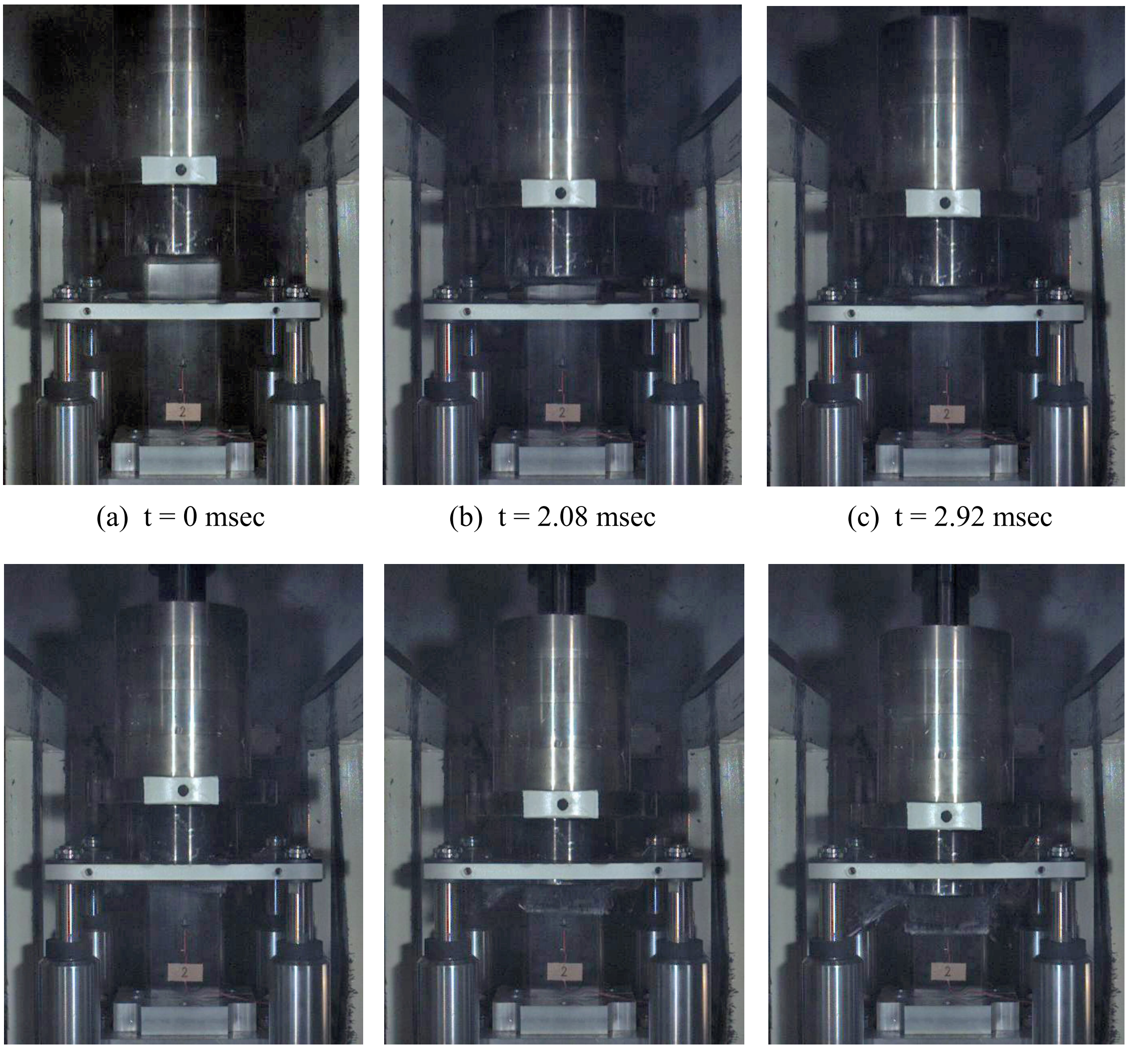
	No. 1	No. 2	No. 3	No. 4	No. 5	Ave.
Maximum load [kN]	179.0	173.1	170.9	160.8	180.3	172.8
Absorbed energy [kJ]	11.7	13.7	12.7	13.1	12.9	12.8
Maximum displacement [mm]	128.0	142.6	138.3	146.8	134.6	138.1



(a) isometric view

(b) top view

Fig. 8. Photographs of impact tested rectangular CFRP tube with two ribs



(a) t = 0 msec (b) t = 2.08 msec (c) t = 2.92 msec

(d) t = 6.25 msec (e) t = 8.33 msec (f) t = 10.42 msec

Fig. 9. Photographs recorded with a high speed camera system (specimen No. 2)

the rectangular CFRP tube wall. Tearing failure mode was also seen in all of the rectangular CFRP tubes in the corners. Photographs recorded with a high speed camera system under impact tests are shown in Fig. 9. From the images, the stable progressive failure behaviors are observed.

4.2 Comparison between Impact Test Results and FEM Results

Fig. 10 shows the impact load-displacement curves of FEM results, for Model 1, Model 2 and Model 3. It is seen that their tendency of the impact response behaviors was relatively the same in the all FEM models.

Fig. 11 shows the comparison of experimental results with that of Model 3 for the load-displacement curves. It is seen that the comparison

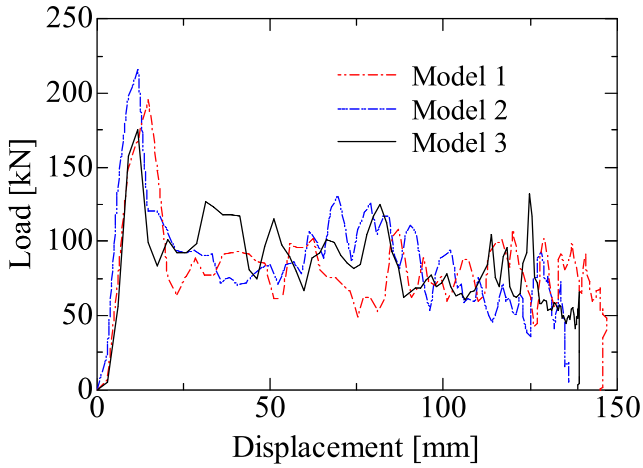


Fig. 10. Load-displacement curves obtained From the FEM analysis

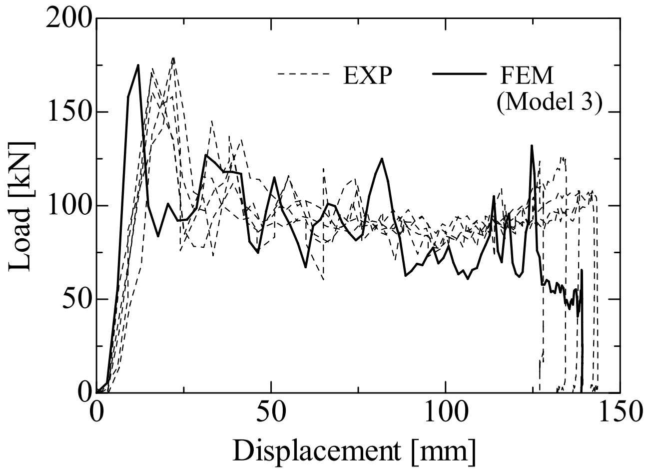


Fig. 11. Comparison of experimental and FEM (Model 3) load-displacement curves

Table 3. Comparison between the experimental and FEM results of the rectangular CFRP tube

	Model 1	Model 2	Model 3	Experiment (ave. values)
Maximum load [kN]	196.0	215.0	174.0	172.8
Absorbed energy [kJ]	11.8	11.9	12.1	12.8
Maximum displacement [mm]	146.0	136.0	140.0	138.1

of the impact response behavior was favorable.

In Table 3, the maximum load, the maximum displacement and the absorbed energy obtained by the FE analyses and average values of the experimental results are listed. The results of the Model 3 were in good agreement with the average values of the impact test results.

5 Conclusions

In this study, we develop rectangular CFRP tubes with two ribs in order to design impact energy absorption members under full-lap collision. The drop weight impact tests were carried out to investigate the impact response behavior and the impact energy absorption characteristic of the rectangular CFRP tube. Also, the FE model was also developed by using the nonlinear, explicit dynamic code LS-DYNA to simulate the progressive failure behavior and the absorbed energy of the rectangular CFRP tube with ribs under impact loading. Based on this study, the following conclusions can be drawn:

(1) It was proven that the rectangular CFRP tubes with two ribs were effective as an impact absorption member under full-lap collision.

(2) The comparisons of experimental results with FEM ones for the load-displacement curves were favorable. Especially, the maximum load, the maximum displacement and the absorbed energy calculated by Model 3 were in good agreement with the average values of the impact test results.

Acknowledgement

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References

[1] Farley G.L. and Jones R.M. “Crushing Characteristics of Continuous Fiber-Reinforced Composite Tubes”. *Journal of Composite Materials*, Vol. 26, No. 1, pp 37-50, 1992.

[2] Thornton P.H. “Energy Absorption in Composite Structures”. *Journal of Composite Materials*, Vol. 13, pp 247-263, 1979.

[3] Farley G.L. “Energy Absorption of Composite Materials”. *Journal of Composite Materials*, Vol. 17, pp 267-279, 1983.

[4] Farley G.L. “Effect of Specimen Geometry on the Energy Absorption Capability of Composite Materials”. *Journal of Composite Materials*, Vol. 20, pp 390-400, 1986.

[5] Farley G.L. and Jones R.M. “Crushing Characteristics of Composite Tubes with ‘Near-Elliptical’ Cross Section”. *Journal of Composite Materials*, Vol. 26, No. 12, pp 1741-1751, 1992.

[6] Thuis H.G.S.J. and Metz V.H. “The Influence of Trigger Configurations and Laminate Lay-Up on The Failure Mode of Composite Crush Cylinders”. *Composite Structures*, Vol. 25, pp 37-43, 1993.

[7] Sigalas I., Kumosa M. and Hull D. “Trigger Mechanisms in Energy-Absorbing Glass Cloth/Epoxy Tubes”. *Composite Science and Technology*, Vol. 40, pp 265-287, 1991.

[8] Song H.W., Du X.W. and Zhao G.F. “Energy Absorption Behavior of Double-Chamfer Triggered Glass/Epoxy Circular Tubes”. *Journal of Composite Materials*, Vol. 36, No. 18, pp 2183-2198, 2002.

[9] Ramakrishna S. and Hamada H. “Energy Absorption Characteristics of Crash Worthy Structural Composite Materials”. *Key Engineering Materials*, Vols. 141-143, pp 585-620, 1998.

[10] Bisagni C., Pietro G.D., Fraschini L. and Terletti D. "Progressive Crushing of Fiber-Reinforced Composite Structural Components of a Formula One Racing Car". *Composite Structures*, Vol. 68, pp 491-503, 2005.

[11] Mamalis A.G., Manolakos D.E., Ioannidis M.B., Kostazos P.K. and Papapostolou D.P. "Axial Collapse of Hybrid Square Sandwich Composite Tubular Components with Corrugated Core: Numerical Modeling". *Composite Structures*, Vol. 58, pp 571-582, 2002.

[12] Mamalis A.G., Manolakos D.E., Ioannidis M.B. and Kostazos P.K. "Crushing of Hybrid Square Sandwich Composite Vehicle Hollow Bodyshells with Reinforced Core Subjected to Axial Loading: Numerical Simulation". *Composite Structures*, Vol. 61, pp 175-186, 2003.

[13] LS-DYNA 970, LSTC Co. (2003).

[14] Kim H.S., Ben G., Aoki Y. and Shikada A. "Comparison of FEM Results with Experimental Ones for CFRP Tubes in Automobiles under Impact Loading". *The 5th Japan-Korea Joint Symposium on Composite Materials*, pp 95-96, 2005.

[15] Chang F.K. and Chang K.Y. "A Progressive Damage Model for Laminated Composites Containing Stress Concentration". *Journal of Composite Materials*, Vol. 21, pp 809-833, 1987.

[16] Kim H.S., Ben G. and Aoki Y. "Impact Response Behaviors of Rectangular CFRP Tubes for Front Side Members of Automobiles". *Proceedings of the 12th US-Japan conference on Composites Materials*, pp 367-378, 2006.