Application of Fiber Reinforced Composites as Energy Absorption Member in Vehicle

Yuqiu Yang[1], Xiaofeng Wu[2], Hiroyuki Hamada[1]

[1]*Kyoto Institute of Technology, Matsugasaki, Sakyo-ku, Kyoto, Japan, 606-8585*

[2]*Fudan University, Handan Road 220, Shanghai, China, 200433*

Email: xiaofengwu@fudan.edu.cn

Abstract: In this study, a new design concept of impact beam completely made in FRPs (Fiber Reinforced Polymer) is proposed, which combines the conventional square thin-wall tube with circular short tubes embedded. Such architecture can not only retains the assemble convenience from square cross-section of the outer tube but also utilize the high energy absorption from the inner circular tubes which face towards the external impact force. Quasi-static compression tests were performed to investigate the basic characteristics including energy absorption and strength of the new designed impact beam. Experimental results showed that compared to the conventional architecture of the composites impact beam, the new design was able to lead to both high energy absorption and high tension of the impact beam. The combination of square cross-sectional glass reinforced FRP tube with embedded circular cross-sectional carbon reinforced FRP tubes had the highest synergetic energy absorption capability.

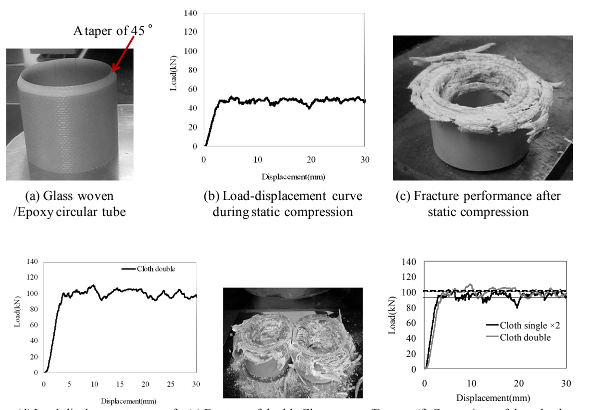
Keywords: impact beam; energy absorption; tension; fiber-reinforced composite; pultrusion tube

1. Introduction

As well known, the safety problem is always one of the most important issues during the growth of the automobile. Although injuries due to the traffic accidents are a serious problem, it is considerably controllable if adequate attention is paid to accident and injury prevention strategies. Therefore, nowadays, a wide range of passive safety equipments and features are incorporated into the automotives, such as airbags, energy-absorbing steering columns, bumpers, etc., to provide an energy-absorption barrier, while the safe cabin in high tension helps to divert forces away from the occupant to keep the survival space. Traditionally, most of above protections are made of metals. However, for metals, high tension and high energy absorption are usually conflict, i.e., less deformation owing to the high tension would decrease the energy absorption capability. Furthermore, conventional metallic structures are quite heavy to cause the high fuel consumptions which cannot be satisfied to the increasing concerns on the sustainability issues represented by the environment and resource protection. Therefore, novel light materials catch more and more attentions to reduce the structure weight without sacrificing the safety of the automotives.

In this field, fiber-reinforced polymer (FRP) composites are found so attractive. Up to now, there is a considerable amount of researches carried on the energy absorption characteristics of FRP composites and it can be summarized from the published data that FRP composites with proper design could achieve higher specific energy absorption than metals[1-11]. Furthermore, unlike metallic structures which undergo plastic deformation during impact and absorb energy by forming hinges, FRP composites absorb the impact energy by micro-fractures through progressive crushing. With this unique mechanism, FRP composites tubes exhibit a considerable flat load displacement curve, and with proper crush initiators such as a taper in some proper angle, the peak load can be controlled in the same level as the average load [12-18]. Thus, during an impact the FRP material will crush at a constant force instead and the passengers will not experience big acceleration. Although the energy absorption mechanisms of FRP tubes is complicated, it is considered that it is possible for the FRP tubes which fracture in a stable mode i.e. progressive crushing to get a summation absorbed energy of each ones. For example the load-displacement curve and the fractured performance of glass woven/Epoxy circular tube with a chamfer of 45º on one end (Figure 1a) during the static axial compression were shown in Figures 1(b & c) [19]. It is found that the compression load-displacement (Figure 1d) of two those tubes (Figure1e) is much similar with that obtained just multiply the loads of (Figure1b) by two (Figure 1f).

In short, FRP composites possess excellent crashworthiness properties for ideal crash structures. However, there are still some problems to prevent this kind of novel materials to formally substitute the traditional metallic structures. For an example, the FRP tubes only show their excellent energy absorption under axial compressions which are not the usual application cases for impact beams (for an example, the side-door impact beam) in traffic accidents which are suffered lateral compression. Therefore, in this study, new design of impact beam was carried out for such application in door of automobile shown in Figure 2. Unlike the general way to design a composite member from its geometric structure as a whole, in which it has been proved difficult to predict and control its energy absorption capability, the basic concept of this new design is quite simple: try to properly combine the elemental FRP units well-studied for application requirements. In this paper, the circular tubular components i.e. the ones with circular cross section were added into the impact beam with their axial direction towards the external impact force as possible so that they can efficiently absorb the impact energy. Therefore, in the new structure design circular FRP tubes were inserted into the cavity of the square cross-sectional FRP tube (square FRP tube) one by one, whereby the axial direction of circular tubes was parallel to the impact force direction. In order to study the synergetic energy absorption capability and the effects of various factors on this new structure design, the ubiquitous composites material combinations of circular and square tubes including glass fiber reinforcement polymer (GFRP) and carbon fiber reinforcement polymer (CFRP) and different taper angle on one end of the circular tubes were carried out and tested at quasi-static compressions.



(a) Glass woven /Epoxy circular tube (b) Load-displacement curve during static compression (c) Fracture performance after static compression

(d) Load-displacement curve of compression of double tubes (e) Fracture of double Glass woven /Epoxy circular tubes compressed together (f) Comparison of those load-displacement curves

Figure 1. Example from glass woven/Epoxy composite tubes to explain the possibility of energy absorption summation of each part [voted from reference 19]

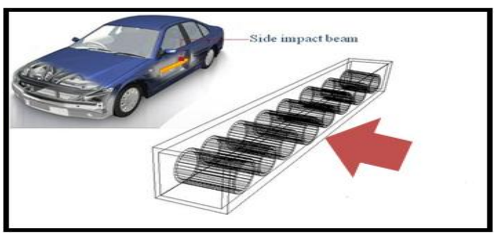


Figure 2. Schematic illustration of impact beam for a component installed within door

whereby the longitudinal direction of circular tube was parallel to the impact force direction

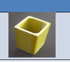
2. Materials and Experiments

Two kinds of representative FRPs, which are made in unidirectional glass fiber and carbon fiber respectively as the reinforcement and the unsaturated polyester resin as the matrix, were used to fabricate the impact beam or its components by pultrusion process (Fukui-fibertech Co. Ltd, Japan). The test samples can be categorized into two groups according to the geometry in the transversal cross section which are listed in Table 1. One group has all the square cross-sectional pultrusion tubes with the size of 50mm×50mm and the thickness of 4mm, which are used as the shell of the impact beam; while the other group has all the circular cross-sectional pultrusion tubes with the out-diameter of 30mm and the thickness of 3mm, which are used as the embedded components of the impact beam.

To manufacture the impact beams with new architecture design, all the circular tubes to be embedded into the cavity of a traditional long square beam were chamfered with 15, 45 or 75 degrees taper on one end respectively if required. Afterward, the circle tubular components were cooled quickly by liquid nitrogen to be inserted into the long hollow square tube easily. In the specimen of experimental impact beam, there were three circular tubes placed into one segment of square tube whereby both ends of the circular tube could touch the square tube walls well. Because the inner length is about 41.6 mm (50-2x4.2) in square tube, the circular tubes were cut in a length of about 42mm

In order to study the efficiency of new architecture design, the quasi-static lateral compression tests of the impact beams were performed on an AUTOGRAPH (AG-250kN, SHIMADZA, Japan) testing machine at a constant cross-head speed of 5mm/min. Different material combinations for the components of impact beam were tested individually to find out the optimal composite materials usage. The quasi-static lateral compression tests with the same conditions were also performed for the impact beams in traditional architecture design, e.g., the hollow square cross-sectional tube without embedded circular tubes, as the reference. Additionally, similar quasi-static compression tests were performed for the embedded circle cross-sectional tubes with different taper in one end, which are 15, 45, 75 and 90 (that is no taper) degrees respectively, to clarify the energy absorption contribution from this kind of components in the new architecture design of impact beam.

Table 1. FRP tubes fabricated by pultrusion

Geometry of the cross section	Material	Photograph	Dimension (mm)	Thickness (mm)
(Square)	GFRP		50X50 (length:100)	4.2
	CFRP		50X50 (length:100)	4.2
(Circular)	GFRP		Φ 30 (length:42)	3.0
	CFRP		Φ 30 (length:42)	3.0

3. Results and Discussions

3.1. Efficiency of New Architecture for Side Impact

As an example, general square cross-sectional beam made of GFRP and the new designed beam (combination of GFRP square tube and inner GFRP circular tubes with 45º taper) are compared by their load-displacement curves and performances during the quasi-static lateral compression tests in Figure 3. In the load-displacement curve, the load increased rapidly to peak during the initial compression stage for both beams. However the new designed beam got a peak value at about 100kN while the general beam had the maximum load of only 40kN. Additionally, the loads of general beam decreased to almost zero soon after arrival of the peak value. From the sequence of photographs taken in the crushing procedure, it could be easily seen that the square tube was broken at the corner, which is considered to be related to the loss of the load. On the other hand, although the load of new designed beam decreased gradually, it still supported approximate 70kN load. Unlike the former general one, for the new designed beam, even the square tube was broken, the circular tubes inside were crushed in the typical progressive crushing mode and sustain the load without serious dropping. The total absorbed energy during the displacement from 0 to 20mm was only 218J in general beam while 2067J in the new designed one. Owing to the 2.5 times in peak load and 10 times in total absorbed energy, new design beam could be said much better than the general one because it realized the unit of both high tension and high energy absorption.

The similar results were also observed in the other experiments in which the general beam was made of CFRP and the new designed beams are made of various FRP composites combinations. Therefore, the basic objective of new structure design for the impact beam is achieved – the high side impact energy absorption capability.

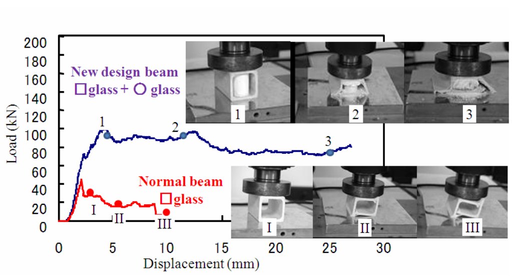


Figure 3. Comparison between normal beam and new designed beam

3.2. Effect of Taper Angle of the Circular Tubes on the Energy Management of Impact Beam

According to results of existing researches on axial circular FRP tubes, initiators such as tapers hardly affected the load during the stable crushing stage but significantly affected the load variation during the initial stage. In order to clarify the effect of taper angle in the new structure design of the impact beam, here, a set of new designed beams which compose of CFRP square tube and GFRP circular tubes with different taper angles was used as examples to discuss the effect of the taper on the energy absorption capability. The illustration of 15, 45, 75 and 90 degrees taper on one end of the circular tubes and the load-displacement curves of the beams during lateral compression were compared in Figure 4. It is found that the taper angle of circular tubes influences the crushing load of the beam at the initial stage significantly, in particular the peak load. The peak load values became small with the decrease of the angle. In details the beam with 90º taper circular tubes, i.e. the tubes without any modification on any ends had maximum load of over 200kN while that one with a 15°taper had less than 50kN in the initial compression stage. However, no matter which the angle of the taper is, the mean load after 10mm of all of the beams were getting closed. As mentioned before, this phenomenon provides a good way to control the force that passengers sustain during the initial stage of the side impact.

3.3. Effect of Different Material Combination for Components

Table 2 lists the total absorbed energy of various FRP materials combination for the components of the impact beam from 0 to 30mm displacement. It is found that the embedded circular carbon tubes can contribute more to the energy absorption than the embedded glass circular carbon tubes during the lateral compression. In particular, the square glass tube which embedded with circular carbon tubes was the best combination of the total absorbed energy value.

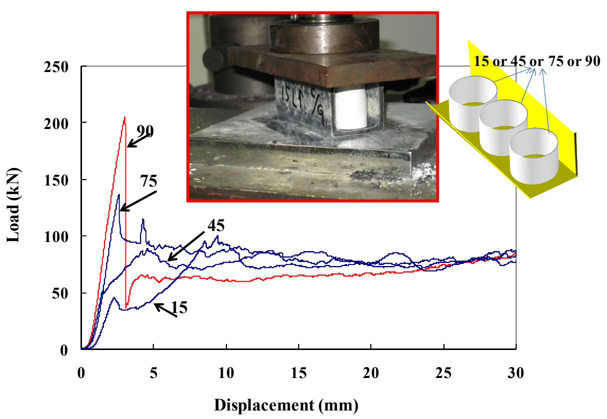


Figure 4. Load-displacement curves of the new designed beam which compose carbon square tube and inserted three glass circular tubes with different angles on one end

In order to thoroughly investigate the individual contributions to the total energy absorption for outer square tube and inner circular tubes under various material combinations, the square tubes were compressed laterally as well as the embedded circular tubes are compressed axially which are the same condition for side impact of new designed impact beam. The results are summarized in Figures 5 and 6.

Although they have similar crushing performance, the absorbed energies are different. Compared to CFRP square tubes, GFRP square tubes had higher energy absorption values. This might be explained that the lateral compression properties of square cross-sectional beam depend more on the interfacial properties between the reinforced fiber and resin, as it is well known that the interface between glass fiber and unsaturated polyester resin is better than that between carbon fiber and unsaturated polyester resin. Referring to the circular tubes compressed axially, both CFRP and GFRP tubes with 45º taper are compared in Figure 6 as an instance. During the compression process, the taper part of both tubes were firstly bent towards the inside of the tube and fractured. Then, the tube walls split into internal and external fronds like the spreading out of a flower. The observation result on the crush zone of CFRP circular tube was given in Figure 7 as an example. From the cross-sectional observation of crush zone, it is found that micro-fractures such as central crack, delaminations and fiber fractures were observed. All the above fractures, especially the absorbed energy by the fiber fractures, contribute greatly to the total absorbed energy. Therefore, compared to GFRP circular tubes, CFRP circular ones had better energy management because that carbon fiber has high strength and more energy can be consume through broke carbon fibers.

Furthermore, in quantities, the absorbed energy summation of square tubes and embedded circular tubes compressed individually was compared to the absorbed energy measured directly from the new designed beam to investigate whether such simple combination influence the energy absorption process. Here, the former absorbed energy summation value is defined as the prediction of the energy absorption capability of the new designed beam, which is expressed by the formula (1) as following:

$$E'_{\text{(Impact beam)}} = E_{squaretube} + 3E_{circulartube} \qquad (1)$$

Where $E'_{\text{(Impact beam)}}$ is the predictive absorbed energy value of the new designed beam, and $E_{squaretube}$, $E_{circulartube}$ are the experimental results of the square part and embedded circular parts compressed respectively in the same condition as the new designed beam.

As the comparison results i.e. prediction value vs. experimental value illustrated in Figure 8, a conclusion may be drawn that the total amount of energy absorption of the new designed impact beam approximately equals to the summation of energy absorption from each parts including square cross-sectional outer tube and embedded circular tubes. This result implies a pretty good property of the new design for impact beams that the energy absorption capability of such impact beams can be predicted from the well-studied FRP tubes with simple geometry in fundamental researches if they are in simple combination.

Table 2. Energy absorption of various materials combination of the new designed impact beams

Combination	Total absorbed energy (J)
□glass + ○ carbon (15º)	3052
□glass + ○ carbon (45º)	2537
□glass + ○ carbon (75º)	2752
□carbon + ○ glass (15º)	2281
□carbon + ○ glass (45º)	2250
□carbon + ○ glass (75º)	2470
□carbon + ○ carbon (15º)	2859
□carbon + ○ carbon (45º)	2348
□carbon + ○ carbon (75º)	2056

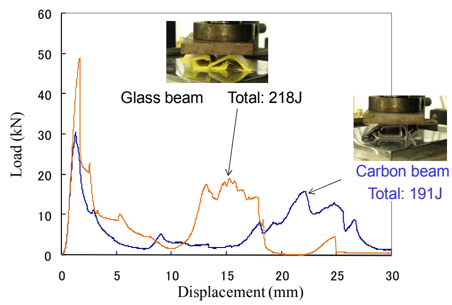
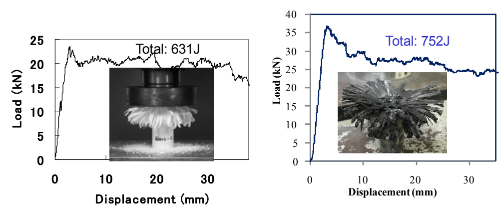


Figure 5. GFRP / CFRP square tube during lateral compression tests



(a) Glass circular tube (b) Carbon circular tube

Figure 6. GFRP / CFRP circular tube during axial compression tests

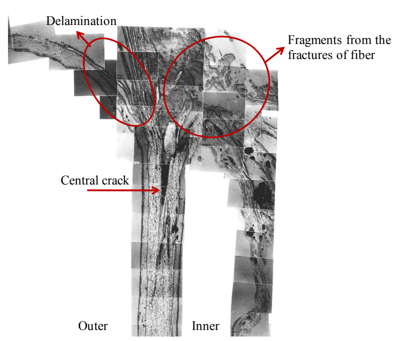


Figure 7. Observation results on the crush zone of the carbon FRP circular tube

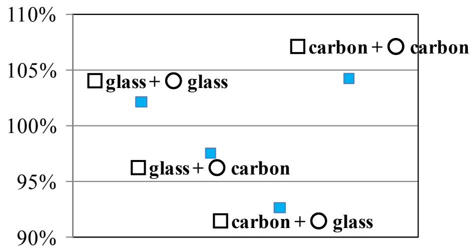


Figure 8. Prediction value vs. experimental value

4. Conclusions

In this study, a new design concept for impact beams was carried out to greatly improve the impact energy absorption for automobile safety. A conventional square cross-sectional FRP impact beam with several circular cross-sectional tubes embedded towards the external impact force axially was tested in lateral compression to investigate the absorbed energy. It was found that the impact beam with new architecture design had much better energy absorption capability and enough strength compared to the conventional one, i.e. only square tube without circular tube inside. Various popular FRP composites combinations for the circular and square tube components from glass or carbon fiber reinforcement and different taper angle on one end of the circular tubes were investigated further more. The experimental results show that the combination of GFRP square cross-sectional tube with embedded CFRP circular cross-sectional tubes had the highest synergetic energy absorption capability and the 45º taper on the circular tubes can help to obtain the flattest load-displacement curve without obviously losing energy absorption capability.

References

[1] Farley, G.L., (1983). "Energy Absorption of Composite Materials", Journal of Composite Materials, Vol. 17, pp. 267-279.
[2] Hull, D., (1991). "A Unified Approach to Progressive Crushing of Fibre-Reinforced Composite Tubes", Composites Science & Technology, Vol. 40, pp. 377-421.
[3] Hamada, H., Coppola, J.C., Hull, D., Maekawa, Z, & Sato, H., (1992). "Comparison of Energy Absorption of Carbon / Epoxy and Carbon / PEEK Composite Tubes", Composites, Vol. 23, No. 4, pp. 245-252.
[4] Hamada, H., Ramakrishna, S. & Sato, H., (1996). "Effect of Fiber Orientation on the Energy Absorption Capability of Carbon Fiber / PEEK Composite Tubes", Journal of Composite Materials, Vol. 30, No. 8, pp. 947-963.
[5] Mamalis, A.G., Manolakos, D.E., Viegelahn, G.L., Yap, S.M. & Demosthenous, G.A., (1991). "On the Axial Crumpling of Fibre-Reinforced Composite Thin-Walled Conical Shells", International Journal of Vehicle Design, Vol. 12, No. 4, pp. 450-467.
[6] Fairfull, A.H. and Hull, D., (1988). Energy Absorption of Polymer Matrix Composite Structures: Frictional Effects, Structural Failure, Ed.s WIERZBICKI,T. and JONES,N., pp.255-279.
[7] P.H. Thornton, (1979). 'Energy Absorption in Composite Structures', Journal of Composite Materials, 13 247-263.
[8] P.H. Thornton, 1990. 'The Crush of Fiber-Reinforced Plastics', in Handbook of Ceramics and Composites Volume 1: Synthesis and Properties, Cheremisinoff, N. P. ed., Marcel Dekker Inc., New York, pp. 307-337.
[9] D. Hull, (1982). 'Energy Absorption of Composite Materials under Crash Conditions', Proceedings of the Fourth International Conference on Composite Materials (ICCM IV), 1 861-870.
[10] D. Hull & T.W. Clyne, (1996.) An Introduction to Composite Materials, Second Edition, Cambridge, University Press, Cambridge.
[11] A.G. Mamalis, D.E. Manolakos, M.B. Ioannidis and D.P. Papapostolou, (2005). 'On the response of thin-walled CFRP composite tubular components subjected to static and dynamic axial compressive loading: experimental', Composite Structures, Vol.69 pp.407-420.
[12] D. Hull, (1983). 'Axial crushing of fiber reinforced composite tubes', in N. Jones and T. Wierzbicki, Eds, Structural Crashworthiness, Butterworth, London.
[13] G.L. Farley, (1983). 'Energy absorption of composite materials', J. Compos. Mater, 17 267-279.
[14] I.Sigalas, M. Kumosa, and D. Hull, (1991) 'Trigger mechanisms in energy-absorbing glass cloth/epoxy tubes, Composite science and technology, 40 265-287.
[15] J.C. Michael and E.R. Richard, (1991). 'Comparison of Bevel and Tulip Triggered Pultruded Tubes for Energy Absorption', Composite Science and Technology, 40 31-46.
[16] H. Saito, R Inai, and H. Hamada, (2002). 'Crushing properties of pultruded glass reinforced square tubes', International Journal of Crashworthiness, 7 (1) 21-33.
[17] Yuqiu Yang, Tadashi Uozumi, Asami Nakai, Hiroyuki Hamada, (2006). 'A study of applicability of fiber reinforced plastics as energy absorption member', Review of Automotive Engineering, 27 3.
[18] Y. Yang, A Nakai and H Hamada, (2009). A method to improve the energy absorption capability of fiber reinforced composite tubes, International Journal of Crashworthiness, Vol.14, pp.315-322.
[19] Unpublished works in Hamada Laboratory, Kyoto Institute of Technology.