

Weight Reduction with Plastic Foam for Structural Components of Vehicle

Yasushi TOSHIMITSU*

Akifumi SONODA**

ABSTRACT

Focusing on absorbing energy in the side frames of a vehicle as compressive deformation occurs during a frontal impact, increased energy absorptance and weight reduction of the structural components of a body do occur by filling them with urethane foam. It was found that it is possible to achieve approximately 30% weight reduction by filling urethane foam and modifying cross-section structures while insuring flexural rigidity and absorbed energy equal to that of body frames. At the same time efforts were also made to construct CAE technology that enables investigation into a lightweight body frame structure filled with plastic foam. The difference in absorbed energy between CAE simulations and tests with an actual hybrid frame unit consisting of aluminum piping (shell element) filled with urethane foam (solid element) was approximately 10% while under 50% compressive deformation or more.

1. Introduction

While automobile crash safety performance continues to get better, vehicle body weights are increasing. On the other hand, CAFE target values are being established and improvements in fuel economy mandated in order to reduce greenhouse gas emissions. Amidst these circumstances, demands are increasing for the conflicting goal of lighter vehicle body weights.

Thus far the main use of plastic foam in vehicle bodies has been for soundproofing. However, there is potential for enhancing crash performance through the use of foam in structural components. One example of this application focused on the increase in energy absorption and reduction in vehicle deformation distance during bending deformation of structural components of the vehicle that were filled with plastic foam.⁽¹⁾ This case mainly used epoxy foam.

This paper reports on research performed on vehicle structural components filled with plastic foam that enable reductions in weight while maintaining crash safety performance.

2. Concept of Weight Reduction

First, the concept of reducing weight using plastic foam is described below. When a metal pipe structure with the enclosed section in the lengthwise direction such as the side frame of a vehicle undergoes compressive deformation, it generally exhibits the deformed state shown in Fig. 1. Fig. 2-a shows the relationship between the force and the deformation distance at that time, and Fig. 3-a shows the relationship between energy absorption and the deformation distance at that time. On the other hand, when the same metal pipe is filled with plastic foam, the relationships between the deformation distance and the force and between the deformation distance and the energy absorption are as shown in Fig. 2-b and Fig. 3-b. When the main structural components (for example the side frame) of a vehicle undergo compressive deformation during a crash, they exhibit the performance shown in Fig. 2 and Fig. 3. Looking at the energy absorption (Fig. 3) which is particularly important, the plastic foam filled component shows a higher energy absorption even for the same deformation distance.

* Tochigi R&D Center

** PSG Inc.

This is an effect of filling with plastic foam. Conversely, when the energy absorption is the same, the radial thickness of the metal pipe can be reduced as shown in Fig. 4. At this time, the filled plastic foam increases the weight, but an even greater weight reduction is achieved by reducing the radial thickness of the metal pipe, which leads to an overall reduction in the weight.

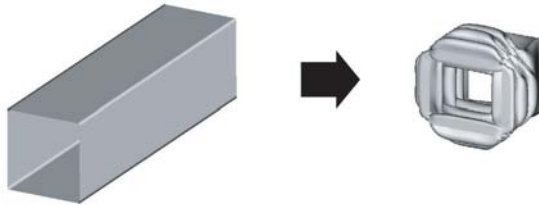


Fig. 1 Compressed deformation shape of metal frame

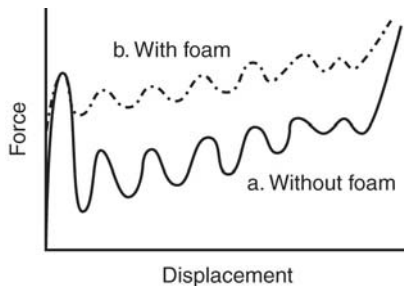


Fig. 2 Force vs. axial displacement

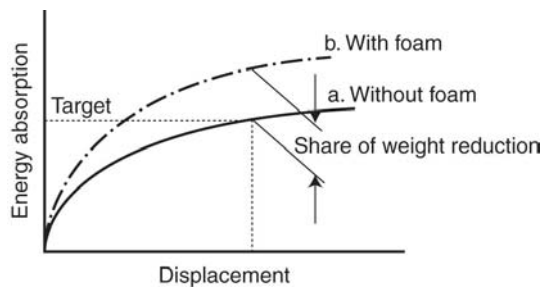


Fig. 3 Energy absorption

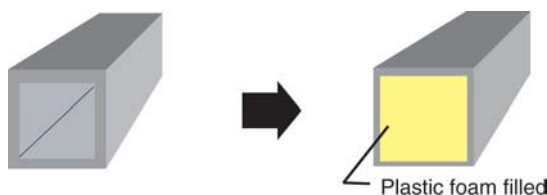


Fig. 4 Concept of weight reduction by means of plastic foam

3. Research Approach

This research was approached from the following three viewpoints.

3.1. Selection of Plastic Foam

There are various types of plastic foam including urethane, epoxy resin, rubber and PET. However, the aim was to select a type that allows for the large deformation of a compressibility of 50% or more, and which generates a large force during the compression process.

3.2. Verification of the Effects of Filling with Plastic Foam

The energy absorption and bending stiffness properties of plastic foam filled frames (hereafter “hybrid frames”) were investigated by varying the radial thickness, section size and structure, and comparing it to existing lightweight energy absorptive structures (for example, a “crash box” which is a type of frame structural component attached to the tip of the side frame).

3.3. Construction of CAE Technology for Investigating Lightweight Structures

In order to allow CAE-based prediction of performance for different hybrid frame structure, the initial theme was to construct performance prediction technology for the foam and metal portions. Following that, technology for predicting hybrid frame performance was constructed.

4. Setting Targets

This research took the following approaches toward setting targets.

- (1) The new structure should result in a larger reduction in weight compared to existing energy absorptive structures. And, the vehicle structural component properties (compressive energy absorption, bending stiffness) should be equivalent to crash boxes with a 30% reduction in weight.
- (2) Construction of CAE technology that predicts hybrid frame crash performance should be possible.

5. Course of the Investigations

5.1. Selection of Plastic Foam

Various types of plastic foam were molded into test pieces of the shape shown in Fig. 5, and compression tests were performed using Amsler’s universal testing machine. Fig. 6 shows the force and displacement measurements. The foaming rate was set at 3 times for all cases. The results showed that rigid urethane foam⁽²⁾ most satisfied the plastic foam selection aims, so rigid urethane was selected as the plastic foam. In addition, Fig. 7 shows that the relationship between energy absorption and weight is roughly linear, and that deformation of 50% or more, that is to say compression of 2 times or more is possible. Therefore, the foaming rate was set at 3 times due to demands for greater energy absorption.

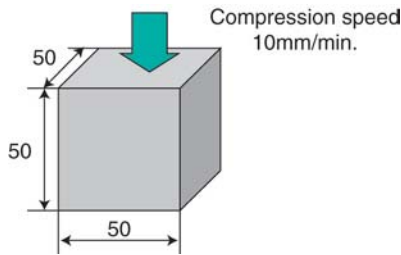
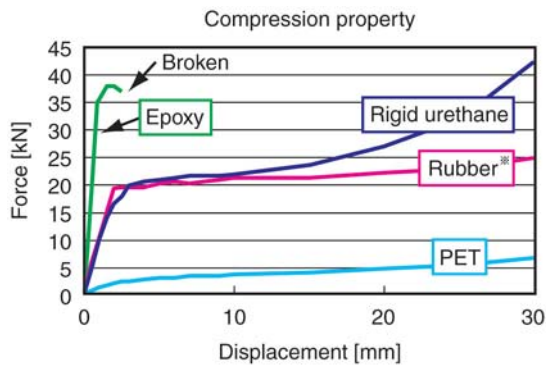


Fig. 5 Plastic foam test piece and compression test



※ Rigid plastic foam using rubber principal-based material

Fig. 6 Compression test result of plastic foam

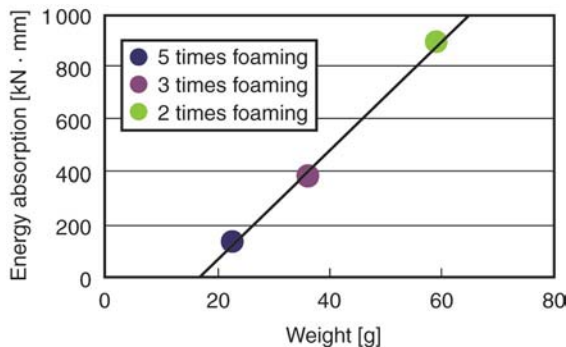


Fig. 7 Axial compression test result

5.2. Verification of the Weight Reduction Effects of Hybrid Foam

Test parts were manufactured, and compression and bending tests were performed to quantitatively clarify the weight reduction effects. Test pieces having various sectional sizes and radial thickness were manufactured as shown in Table 1. The metal pipes corresponding to the side frame used the same aluminum materials as those used for crash boxes. The compression test parts were all 240 mm long, and the bending test parts were all 800 mm long. The test method used Amsler's universal testing machine to measure the force and the deformation distance. Fig. 8 shows an outline of the compression test apparatus, and Fig. 9 shows an outline of the bending test apparatus.

Fig. 10 shows the compression test results for the parts illustrated in Table 1 in terms of weight and energy absorption. The arrows in the figure indicate the change when urethane foam is added. This indicates that the type (4)-a specifications in Table 1 provided energy absorption equal or greater than the crash box while allowing a 30%

Table 1 Section form for supplied test pipes

1. Aluminum pipe

(1)-a	(1)-b	(2)-a	(2)-b	(3)-a	(3)-b
φ 60-t2 Foam filled	φ 60-t2	φ 50-t2 Foam filled	φ 50-t2	φ 50-t3 Foam filled	φ 50-t3

2. Aluminum dual pipe

(4)-a	(4)-b	(5)-a	(5)-b
φ 60-t2/φ 40-t1 Foam filled	φ 60-t2/φ 40-t1	φ 55-t2/φ 40-t2 Foam filled	φ 55-t2/φ 40-t2

3. Aluminum hexagon pipe

(6)-a	(6)-b	(7)
Width50 All holes filled	Width50	Width90 (Crash box)

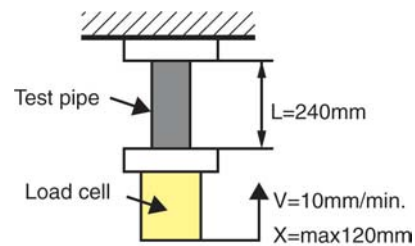


Fig. 8 Axial compression test setup

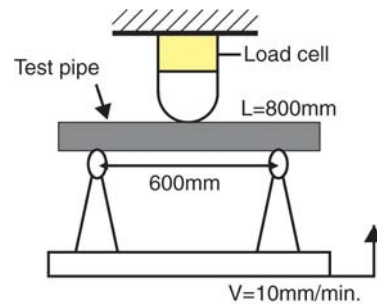


Fig. 9 Bending test setup

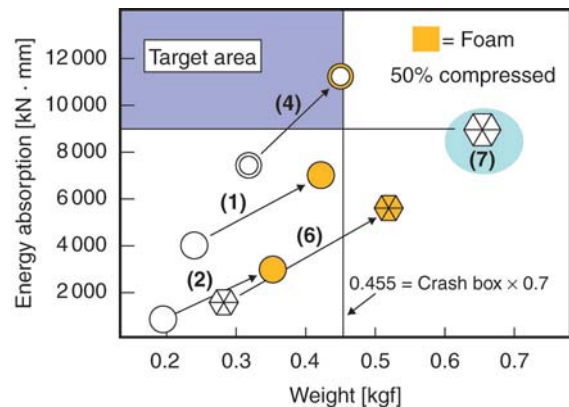


Fig. 10 Axial compression test result

weight reduction. Furthermore, Fig. 11 compares the compressive properties, energy absorption and bending stiffness of this specification, with the crash box, and shows that even the bending stiffness of this specification is equal or greater than the crash box. This clarified that of the aforementioned test parts, the hybrid frame that provided results most satisfying the targets was the aluminum dual pipe filled with urethane foam (specification (4)-a) shown in Table 1.

5.3. Construction of CAE Technology for Investigating Lightweight Structures

Among the few cases that have simulated large deformation of a hybrid frame using plastic foam⁽³⁾, it cannot be said that the CAE results have always accurately reproduced the actual test results. This study aimed to reproduce the force waveform and energy absorption amount relative to the displacement distance. The investigation used the explicit method software RADIOSS.

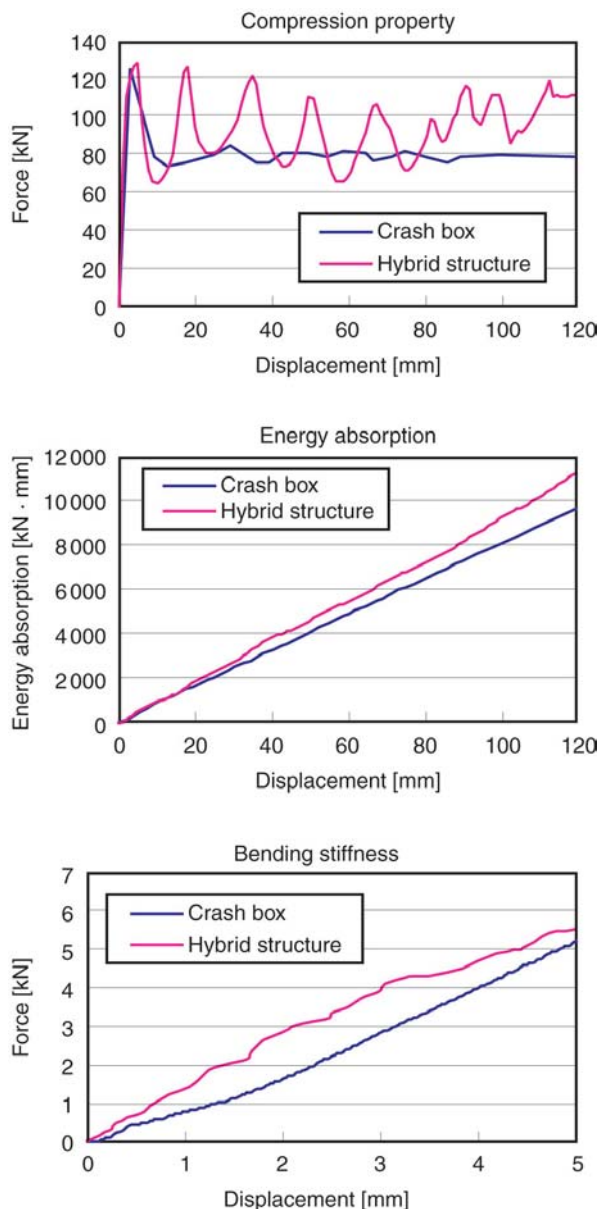


Fig. 11 Test result of compression and bending test

5.3.1. Simulation of the foam portion

The material model that provides the simulation results closest to the urethane foam curve was selected from among the plastic foam relationships between the compression force and deformation distance shown in Fig. 6. Like the tests, the simulation model was comprised of cubes having 50 mm per side, and was modeled with solid elements as shown in Fig. 12.

Fig. 13 shows the compressed deformation shapes obtained from actual tests and a simulation using the material model selected above. The simulation fairly reproduces the test results with compressive deformation appearing as barrel-shaped bulging. In addition, Fig. 14 shows the force and energy absorption curves relative to the deformation distance, and accuracy was excellent with a difference of only 2 to 3% from the test results in both cases.

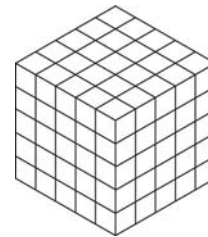


Fig. 12 CAE model for plastic foam

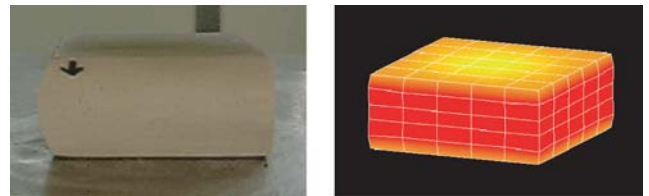


Fig. 13 Compressed deformation shape of plastic foam

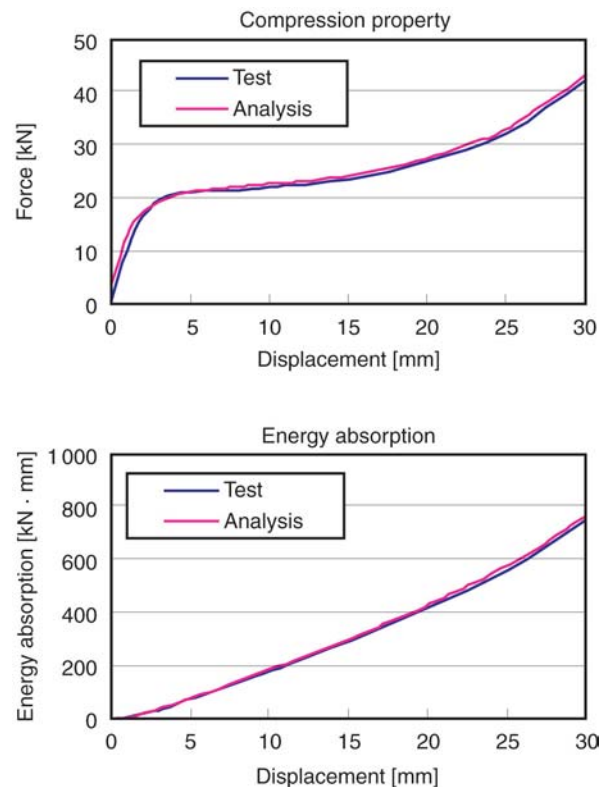


Fig. 14 Comparison of compression quality for plastic foam

5.3.2. Simulation of the metal portion

The metal portion was investigated by creating a model of the aluminum pipe (1)-b in Table 1 with a length of 240 mm and 1/4 the section in the diameter direction as shown in Fig. 15 as the simulation model. The mesh pitch was created in consideration of achieving a balance between accurately reproducing portions with bellows-shaped deformation and the calculation time. At this time material property data corresponding to the crash box was used.

Fig. 16 shows the test and simulated compressive deformation states of the aluminum pipe, and shows that the bellows-shaped deformation was also fairly accurately reproduced. In addition, although the test results for the components of force movement were not accurately reproduced as shown in Fig. 17, the energy absorption was reproduced with a difference of approximately 10%.



Fig. 15 CAE model for metal pipe

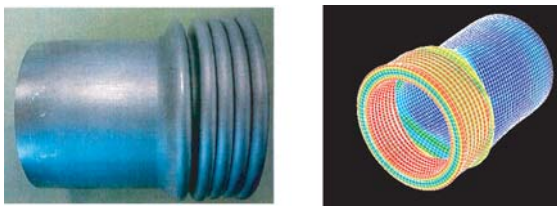


Fig. 16 Compressed deformation shape of aluminum pipe

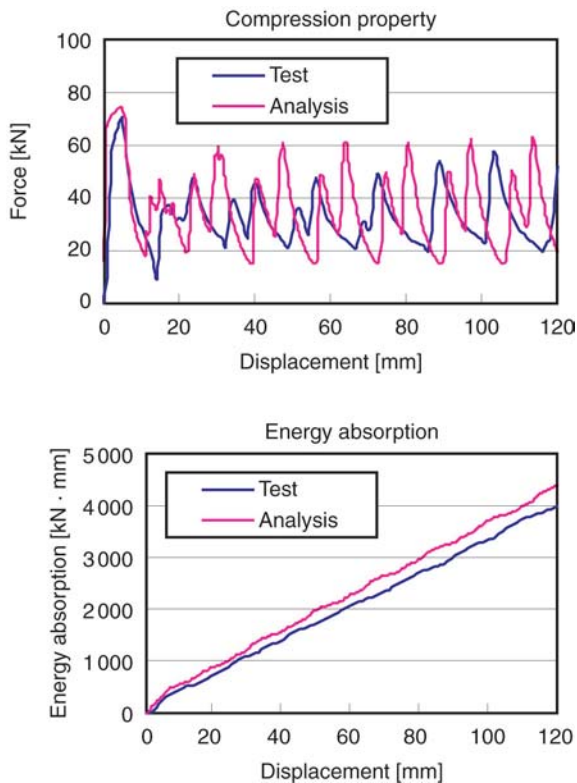


Fig. 17 Comparison of compression quality for aluminum pipe

5.3.3. Simulation of hybrid frame

A hybrid frame model was created that reflected the simulated foam and metal portion contents. A 240 mm long 1/4 section model of the urethane foam filled aluminum pipe specifications (1)-a in Table 1 was created as shown in Fig. 18. The calculation time was reduced by using a detailed solid element mesh pitch for portions experiencing complex deformation, and a rough solid element mesh pitch for other portions.

Fig. 19 shows the test and simulated compressive deformation states of the hybrid frame, and Fig. 20 shows the relationship between the force and displacement distance and the energy absorption curve. Although the bellows-shaped crushing on both ends was reproduced, the movement

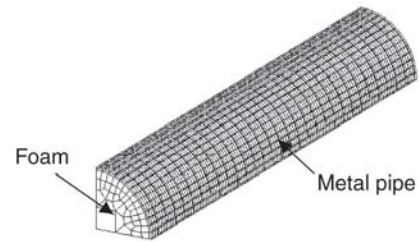


Fig. 18 CAE model for hybrid structure



Fig. 19 Compressed deformation shape of hybrid structure

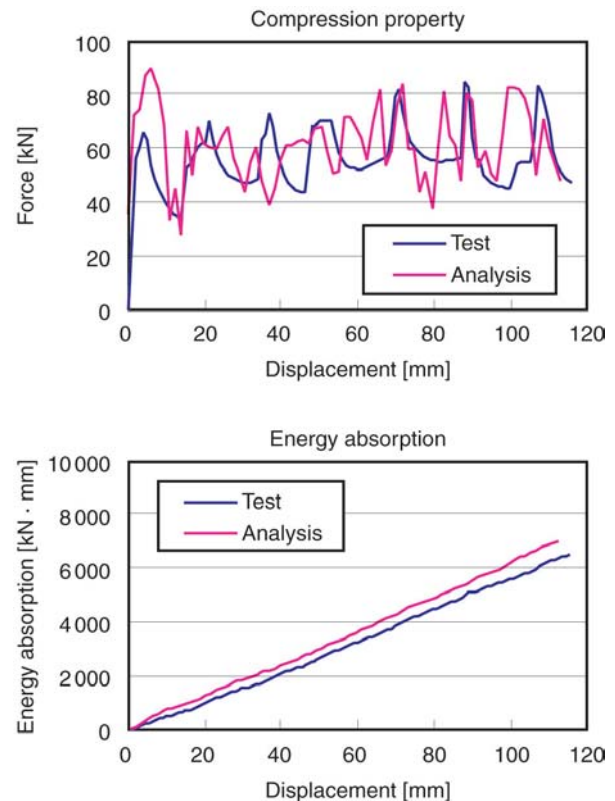


Fig. 20 Comparison of compression quality for hybrid structure

of force was not accurately reproduced. However, the energy absorption was reproduced with a difference of approximately 10%.

6. Conclusion

- (1) The foam filled aluminum dual pipe structure (4)-a was proven to allow weight reduction while maintaining compressive energy absorption and bending stiffness properties compared to the crash box (7) shown in Table 1.
- (2) The hybrid frame (1)-a shown in Table 1 was investigated using RADIOSS. The results showed that while energy absorption could be predicted within a difference of approximately 10% compared to the test results, the waveforms including the movement of force component relative to the deformation distance showed insufficient correlation, so this remains a future issue.

Acknowledgements

The authors wish to express their deepest thanks to related parties in the Antivibration Rubber Development Division and R&D Division of Tokai Rubber Industries, Ltd. for their enormous cooperation in promoting this research.

References

- (1) Ishida, K., Fukahori, M., Hanakawa, K., Tanaka, H., Matsuda, K.: Development of a Technique to Strengthen Body Frame with Structural Foam, Society of Automotive Engineers of Japan, Inc., Proceedings of the Spring Convention, No. 7, p. 21–24 (2000)
- (2) Imai, Y.: Polyurethane Foam, Chapter 8 Rigid Polyurethane Foam, Kyoto, Koubunshikankoukai Corp, p. 79–91 (1987)
- (3) Jamil M.Alwan, Chi-Chin Wu, Clifford C.Chou: Effect of Polyurethane Foam on the Energy Management of Structural Components, SAE Paper 2000-01-0052

■ Authors ■



Yasushi TOSHIMITSU



Akifumi SONODA