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Mazda Motor Corp.

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Development of a Technique to Strengthen Body Frame with Structural Foam

**Kyoso Ishida, Mitsugi Fukahori, Katsunori Hanakawa,
Hideaki Tanaka and Kenji Matsuda**
Mazda Motor Corp.

ABSTRACT

A technique to strengthen body frame with a polymeric structural foam has been developed with benefits of reducing vehicle weight and improving drivability and fuel economy. The idea of this new technology was evolved from the concept that body frame strength will increase drastically if the body frames are prevented from folding on collision. The energy of a collision impact would be effectively absorbed if weak portions of body frames are reinforced by a high strength structural foam. The new technology composed of the high strength structural foam and a light-weight frame structure with partial foam filling is reported here.

INTRODUCTION

The objectives of achieving collision performance and light-weight body structure are co-existed with the advanced development of body structure, materials, and manufacturing (1). Up until now, steel bodies have been lightened mainly by applying high strength steel sheets, devising frame structures and applying new manufacturing technologies such as the tailored welded blank. However, the weight increase is sometime inevitable from the demand of further collision performance improvement. We have developed a body frame strengthening technology that uses a polymeric structural foam to enhance the collision performance with a minimum weight increase.

Deformation modes of body frames have both an axial collapse and a bending collapse during crash. The entire frame is distorted during the axial collapse. However, during the bending collapse, the deformation area does not extend and the energy absorption is relatively small because the frame is only partially distorted (2).

Our developed technology spreads the crash energy by preventing the bending collapse by filling a structural foam in the body frame which controls local buckling deformation of the frame. This newly developed structural foam which expands and cures at painting process with outstanding strength, and the partial filled frame structure with just a small amount of foam to improve the frame strength are reported in this paper.

REQUIREMENT OF STRUCTURAL FOAM

To increase the energy absorption during the frame bending deformation, it is essential to prevent the local buckling deformation and to broaden the deformation area.

To investigate the material properties of structural foam to prevent buckling deformation effectively, three-point bending tests were used to simulate the hat section frame with various structural foams. The test configurations and the relationship between the compression strength of the structural foam and the energy absorption of the frame are shown in Figure 1.

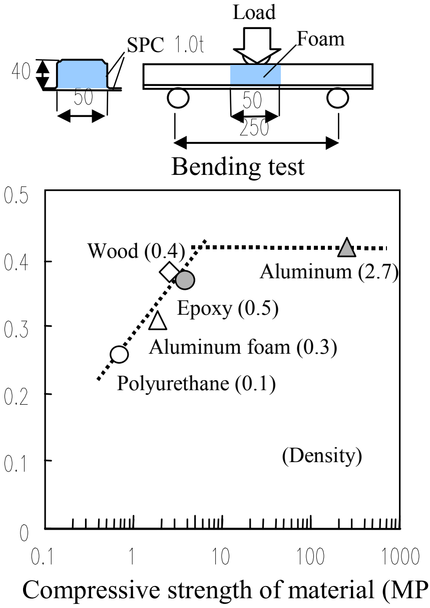


Figure 1. Results of three-point bending test

The energy absorption of the frame increases as the compressive strength increases regardless of the types of the foam, and levels off at about 7MPa. This is due to the fact that buckling deformation of central portion of the frame is prevented by the structural foam, and both ends support the final frame transformation.

Next, the effect of the adhesive strength between steel sheet and foam was studied which was thought to be an important material property for distributing the load to the frame.

The epoxy-based foam was filled in the frame, which has same cross-section geometry as the one shown in Figure 1, and bonded with different adhesives. The study was conducted by cantilever-bending test and the results are shown in Figure 2. The bending moment of the frame increases as the adhesive strength increases, and is roughly leveled off at 7MPa of the adhesive strength.

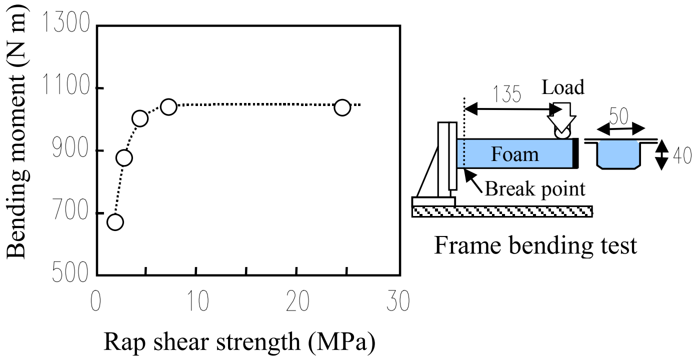
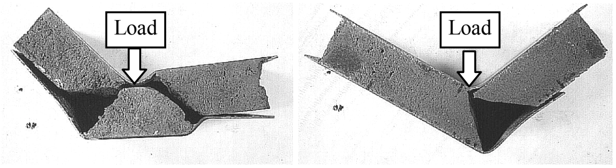


Figure 2. Results of bending test

The three-point bending test was then conducted with a sandwich test specimen to clarify the mechanism of which strength of the specimen would be improved by bonding. The sandwich test specimen is a structure with the structural foam placed between two steel sheets. The test specimens after test are shown in Figure 3. When the adhesive strength is low, the interface of the steel sheet and the structural foam separates at an initial stage of deformation. Because the structural foam breaks after the interface separates, the bending strength of sandwich test specimen is smaller. On the other hand, the steel sheet and the structural foam are kept bonded when the adhesive strength is high. Because the structural foam breaks cohesively from near the interface, the bending strength of the sandwich test specimen is higher.



High adhesive strength Low adhesive strength

Figure 3. The appearance of tested specimens

It is thought that the structural foam is broken by maximum principal stress because the structural foam is porous. The elastic stress distribution of the sandwich test specimen was calculated assuming a high adhesive strength. The result is shown in Figure 4. The principal stress of the structural foam is the same value as shear stress and the shear stress at the interface between steel sheet and structural foam is almost the same as the shear stress of the structural foam in addition. Therefore, the adhesive strength between steel sheet and structural foam needs to be higher than the shear strength of the structural foam. When the adhesive strength is secured, steel sheets and structural foam can transform together until the latter stage of the deformation.

To confirm the effect of the structural foam and adhesion on preventing a local strain concentration, the strain of the buckling part of the frame was measured by the cantilever-bending test shown in Figure 5. It was confirmed that a strain concentration was clearly prevented by the structural foam from this measurement.

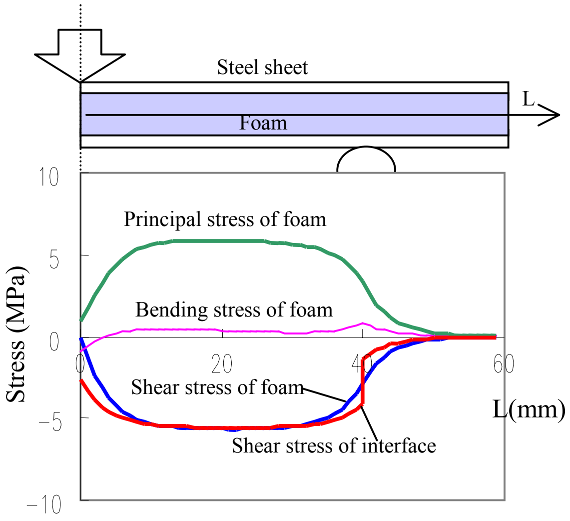


Figure 4. Stress distribution of sandwich test specimen

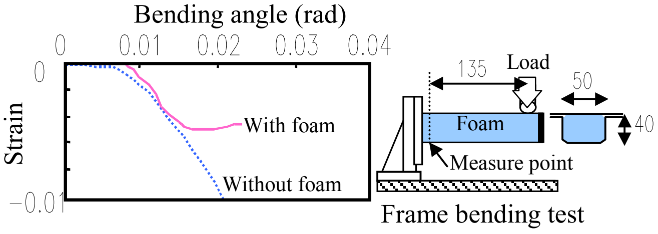


Figure 5. Results of strain measurement on the break point

IMPROVEMENT OF STRENGTH OF STRUCTURAL FOAM

To make the strength characteristics compatible with the manufacturing ability, epoxy resin was selected as the base material and the component with structural foam was studied.

In the subsequent development for the manufacturing, epoxy resin and accelerator were specifically optimized for the compression strength, bending strength, and adhesive strength. Moreover, blowing agent with unexpanded micro-balloon was introduced for the assurance of strength. The strength characteristics of the developed structural foam are shown in Figure 6.

The high-speed deformation characteristics are important in an actual crash. Because the dynamic characteristics of the development foam exceeded the static one, it is thought that the effect of the developed foam in the high-speed deformation is beyond the static effect (Figure 7).

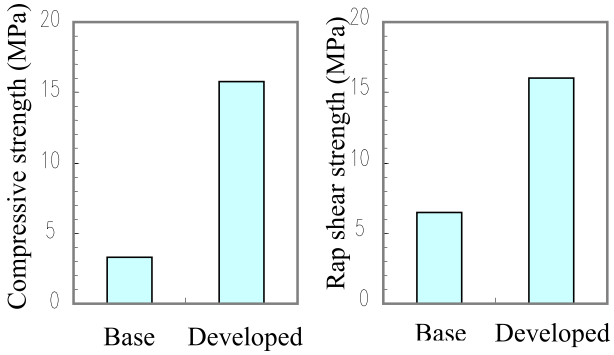


Figure 6. Strength of the developed foam

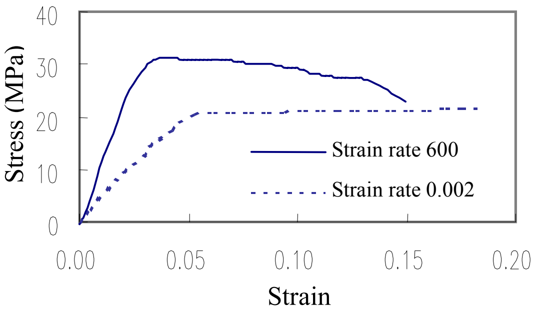


Figure 7. Dynamic and static compressive characteristics

PARTIAL FILLED FRAME STRUCTURE

To improve the frame strength effectively with a small amount of structural foam, the influence of the filled location, the thickness of foam was examined by using the frame with reinforcement.

EXAMINATION OF FILLING LOCATION

The cantilever-bending moment full filling were compared with the outer side partial filling (buckling side) and inner side partial filling.

The structural foam weight ratio and examination results are shown in Figure 8. And the cross-sections of the frame after test are shown in Figure 9. The frame strength, which is about equal to a full filling, can be obtained to fill only on the outer side with a small amount of structural foam to prevent buckling. Therefore, we believe that the partial filling to the outer side is a structure with the optimal balance between strength and weight.

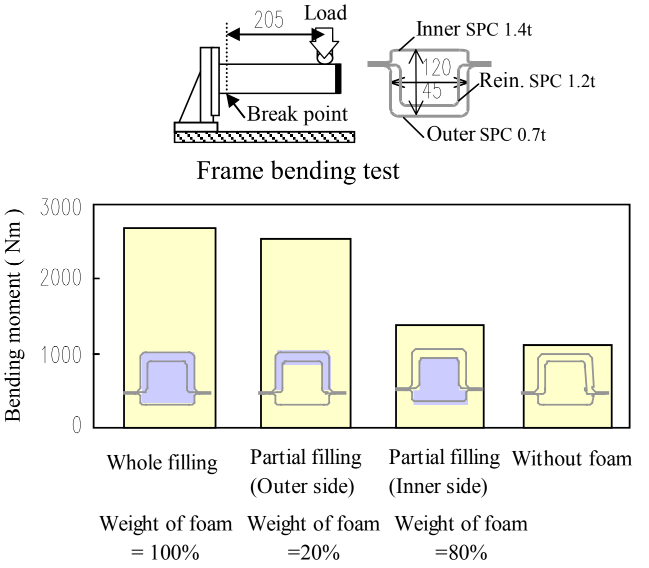
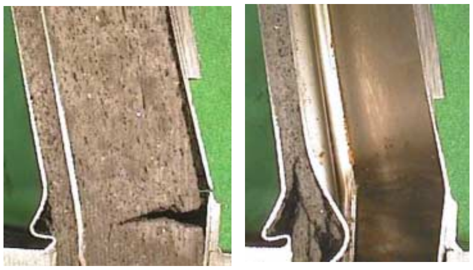


Figure 8. Comparison of bending moments for several samples with different filling ratio and structure of foam



Whole filling

Partial filling (Outer side)

Figure 9. Cross-section of frames

EFFECT OF FILLING THICKNESS OF FOAM

The effect of the filling thickness of the foam on the outer side partial filled structure was examined.

When the filling thickness increases, the bending strength of the structural foam improves. However, if there is no foam filling but with the increased gap distance, the bending strength decreases because the reinforcement is moved relatively toward internally.

Then, the cantilever bending was examined by the method illustrated in the diagrams of Figure 8 with three levels of thickness of foam. The results are shown in Figure 10. The frame strength did not change because an increase in the bending strength of the structural foam was counterbalanced by a decrease in the cross sectional moment of inertia of the frame when the thickness of foam is changed. Therefore, the thickness of foam may be determined by the requirements in production such as expand rate and stick construction.

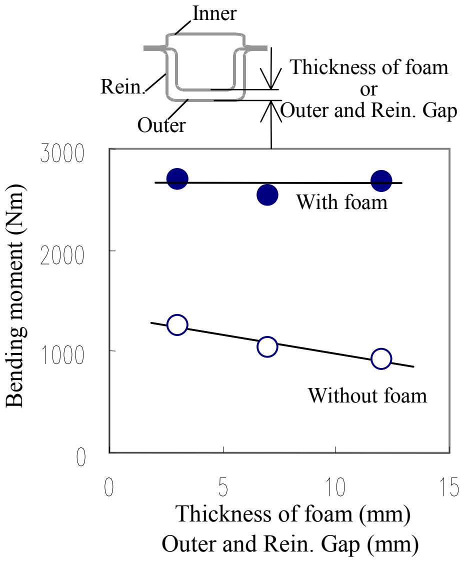


Figure 10. Bending moment as a function of thickness of foam

APPLICATION TO CENTER PILLAR

EFFECT ON CENTER PILLAR

The bending deformation is observed in some frames during the crash of vehicles.

Especially, the control of bending collapse of the center pillar is important in the side impact crash that the amount of the frame intrusion to the passenger compartment is very critical. Therefore, the effect of this technology applied to the center pillar was investigated.

The filling foam to the center pillar was processed as following: the resin molded like the seat was stuck on reinforcement, which is assembled to outer panel of the center pillar. The pillar is then spot welded, and the assembly is expanded and cured with heating(Figure 11). The heating condition was 150C for 30minutes plus 140C for 20minutes then finally 140C for 20minutes to simulate the painting process. The cross section of the center pillar is shown in Figure 12.

The results of the cantilever-bending test of the pillar are shown in Figure 13. The pillars before and after the test are shown in Figure 14. Local buckling deformation was prevented by the partial filling structure, and the bending moment of the pillar increased drastically.

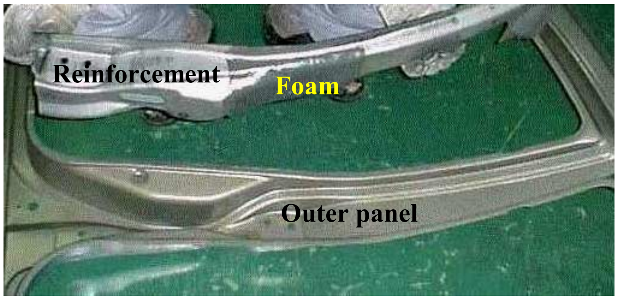


Figure 11. Assembly of the center pillar

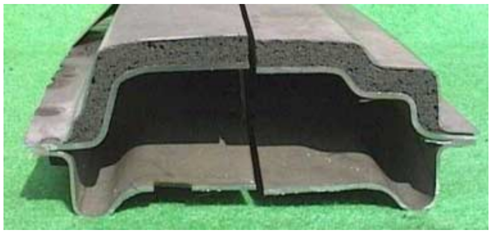


Figure 12. Cross-section of the center pillar

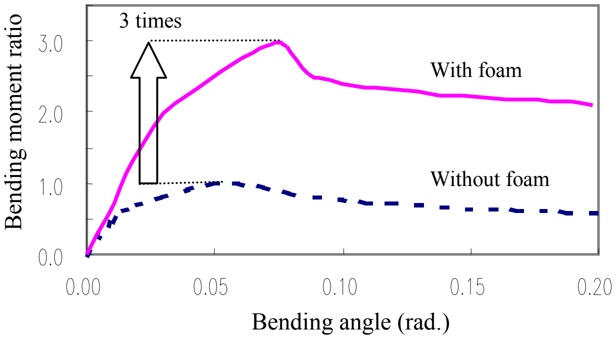
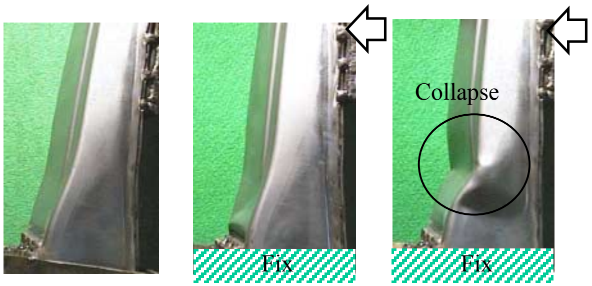


Figure 13. Results of the center pillar bending test



Before test
With foam (0.10 rad.)
Without foam (0.10 rad.)

Figure 14. Deformation of center pillar through bending test

The weight of the structural-foam partial filled pillar is 3Kg lighter than the pillar reinforced by upper gauging with equal strength.

To further investigate the factor of this strength improvement quantitatively, the cantilever-bending of the filled pillar and the unfilled pillar was analyzed by FEM. The energy absorption of each parts of the pillar is shown in Figure 15. The energy absorption of the structural foam is extremely small. However, the structural foam broadens the deformation areas of the steel sheet parts, and energy absorption of the steel sheet parts increases significantly. Especially, the contribution from the reinforcement is remarkable.

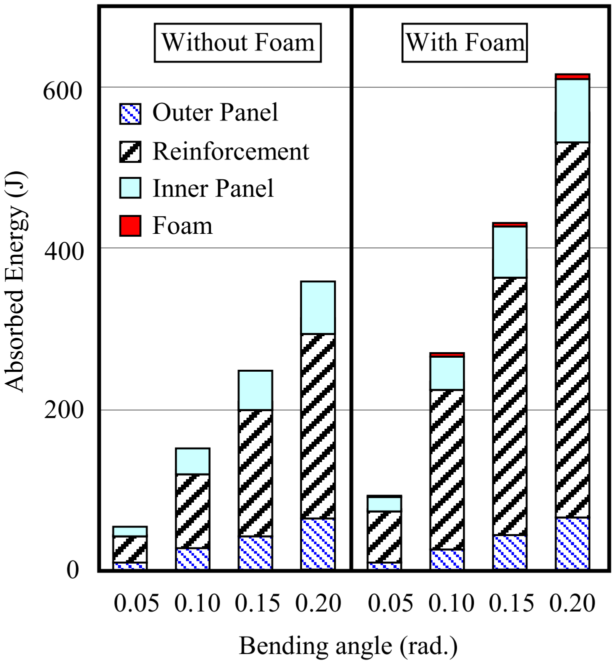


Figure 15. Energy absorption of each part of center pillar as a function of bending angle obtained by FEM analysis

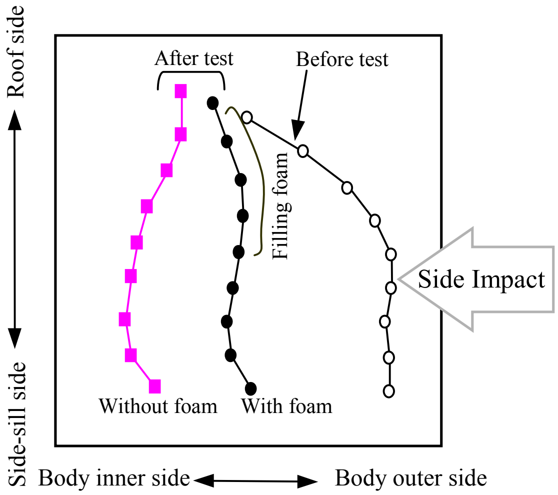


Figure 16. Deformation of center pillar through actual collision test

VELIDATION OF THE CRASH PERFORMANCE BY VEHICLE TEST

The body with the partial filled center pillar was examined on side crash test of a vehicle. The center pillar profiles (car inner side) intrusions before and after the crash test are compared with the unfilled pillar and show in Figure 16. In the vehicle test where the body is traveled at a high speed, it is found to absorb the crash energy sufficiently enough by installing the partial filled pillar with a small amount of deformation.

CONCLUSION

1. It is very effective to enhance the frame strength with improvement to the structural foam's strength and the adhesive strength between steel sheet and structural foam in the bending deformation of the body frame.
2. We have developed epoxy-based structural foam, which is excellent in both compressive strength and adhesive strength, and is expanded and cured by heating of paint process.
3. It is demonstrated the partial filled frame structure of high frame strength with only a small amount of structural foam.
4. It was confirmed to be able to reduce about 6Kg/car weight compared with the steel sheet reinforcement pillar with equal crash strength when this technology was applied to the center pillar.

We have applied this technology to the center pillar of a vehicle model which has been in production since June 2000.

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