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COLLAPSE CHARACTERISTICS OF ALUMINUM EXTRUSIONS FILLED WITH STRUCTURAL FOAM FOR SPACE FRAME VEHICLES

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ABSTRACT–For improving high-safety, convenience, and ride comfort, the automotive design suffers from radical increase of the weight, the recycling-related rules, regulations on the waste gas, and environmental protection of the resources. Among them, it is well known that the weight increase is the most critical. Thus, in order to minimize the weight of the body-in-white that takes up 20-30% of the whole weight of the automobile, most automotive manufacturers have attempted to develop the aluminum intensive body-in-white using aluminum space frames. In this research, the crush test and simulation for aluminum extrusions are performed to evaluate the collapse characteristics of that light weighted material. Also, the same test and simulation was done for aluminum extrusions filled with structural foam. Then, these results are analyzed and compared. From these studies, the effectiveness of structural foam is evaluated in improving automotive crashworthiness. Finally, the design strategy and guideline of the structural form are suggested in order to improve the crashworthiness for aluminum space frame in the vehicle.

KEY WORDS : Aluminum space frame, Crashworthiness, Collapse mode, Structural foam

1. INTRODUCTION

It has become a norm that the general strategic mechanical development goal for automotive engineering of high-safety, convenience, and ride comfort is contrary to the environmental concerns, leading its focus towards an increase in the automobile weight. Recent strategic mechanical development goals have turned their direction to the application of high-quality aluminum for the vehicle structure design and manufacturing technology in aluminum space frame vehicles. The prior expectation of exploiting aluminum technology was the fuel efficiency. This did not meet the satisfactory improvement level. However, there are some possible approaches in utilizing the monocoque steel body manufacturing process to aluminum. This is now under the spotlight being defined as an aluminum space frame technology (Gitter, 1990; Kang *et al.*, 2000; Lakshminarayan *et al.*, 1995; Roger *et al.*, 1995). This paper evaluates the quasi-static test and simulation results for the crashworthiness issues via the structural foam material.

2. CRUSH TEST OF ALUMINUM EXTRUSION FILLED WITH STRUCTURAL FOAM

Structural foam is used for the purpose of improving both structural stiffness and strength of each part consisting the aluminum space frame. It is a kind of chemical material, which is composed of epoxy resin, hardener, filler, etc. Because it has a low density, it is very effective for mass reduction. In order to evaluate the realistic crashworthiness of this, there are two tests that are being done – axial collapse test and 3-point bending collapse test (Kim *et al.*, 2002).

2.1. Axial Collapse Test

In order to diagnose the energy absorption capacity of aluminum extrusion filled with structural foam, an axial collapse test was done. Figure 1 compares the deformed shape and force-displacement diagram between two extrusions without and with the application of structural foam. As seen in Figure 1(a), the rectangular cross-sectional aluminum extrusion filled with structural foam shows no sign of folding but only fractures (Maurice, 1992; Kim *et al.*, 2002) and irregular external crush flow of the foam leading to a collapse mode. Figure 1(b), on the other hand, the reinforced rectangular cross-sectional

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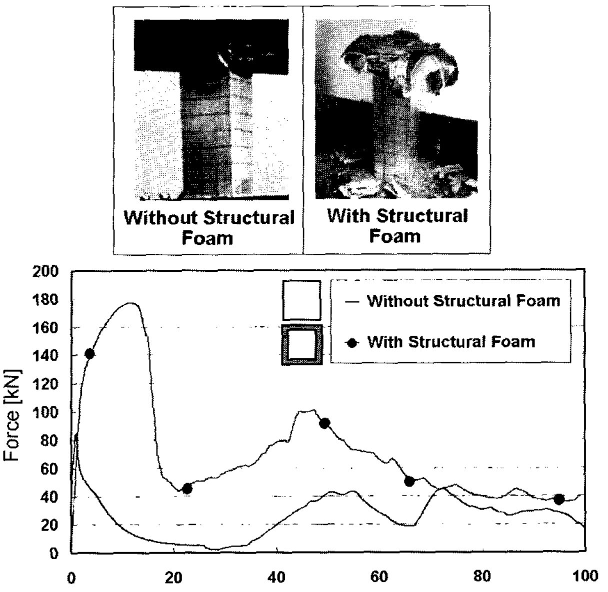
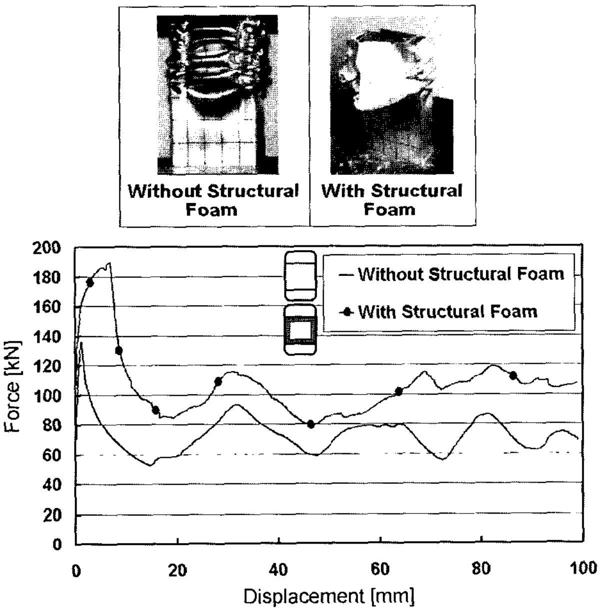


(a) Aluminum extrusion with rectangular cross-section



(b) Aluminum extrusion with reinforced rectangular cross-section

Figure 1. Typical axial collapse modes and force-displacement diagrams of aluminum extrusions with and without structural foam.

aluminum extrusion with structural foam shows folding and fractures. Also, it shows a leveled external crush in the contacting point between the structural foam and the aluminum extrusion in reference to the collapse mode. Force-displacement diagrams in Figure 1 confirm that the use of structural foam increases energy absorption.

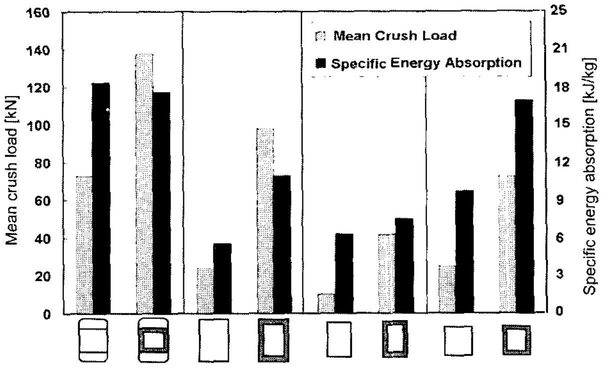


Figure 2. Comparison of energy absorption test results with and without applying structural foam to aluminum extrusions.

On the other hand, Figure 2 shows that the energy absorption capacity per weight cannot be improved drastically by applying the structural foam material to aluminum extrusions. Therefore, based on the results of the axial collapse test, the effectiveness of applying the structural foam to the frontal vehicle structures will be minimal.

2.2. Bending Collapse Test

3-point bending collapse test has been done in order to diagnose the bending collapse mode of aluminum extrusions filled with structural foam. Figure 3 demonstrates the 3-point bending collapse test result of an aluminum extrusion through bending collapse modes and force-

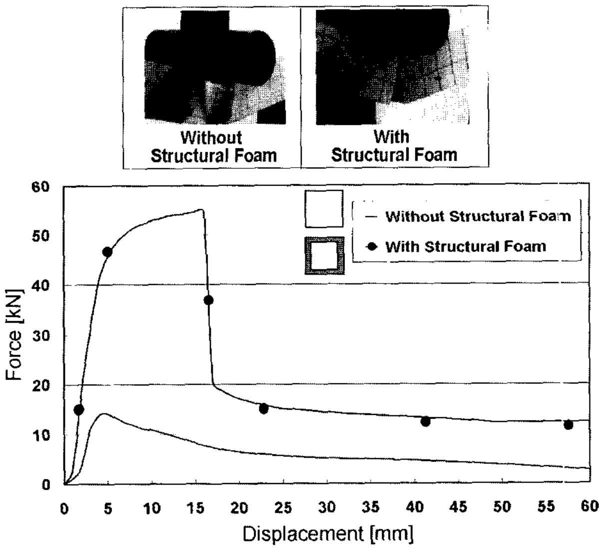


Figure 3. Typical bending collapse modes and force–displacement diagrams of aluminum extrusions without and with structural foam.

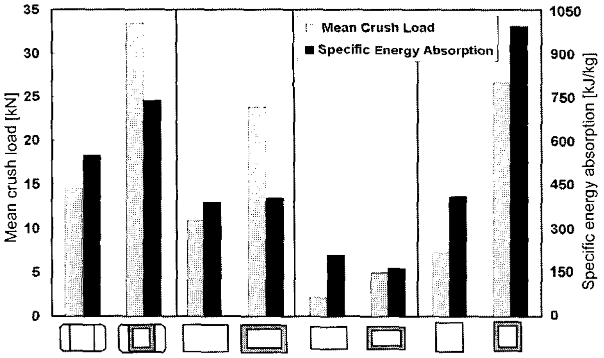


Figure 4. Comparison of energy absorption test results with and without applying structural foam to aluminum extrusions.

displacement diagram. When the structural foam was not applied, there was one folding and no fracture.

On the other hand, with the structural foam, there was a transformation at the length of 16mm along with a relative fracture increase. As it can be seen in Figure 3, the maximum load right before the plastic deformation domain is about three times more severe when the structural foam is applied in comparison to when the structural foam is not applied. Furthermore, considering the energy absorption capacity per overall weight in Figure 4, it can be presumed that the structural foam is highly effective when applied to the A-pillar, B-pillar, and side sill for the reinforcement of the frame and side impact safety.

3. CRUSH ANALYSIS OF ALUMINUM EXTRUSION FILLED WITH STRUCTURAL FOAM

3.1. Finite Element Model of Aluminum Extrusion Filled with Structural Foam

Finite element analysis was performed on the aluminum extrusion filled with structural foam to complete crush analysis and to design an effective cross-sectional shape for the real application of structural foam using PAM-CRASH commercial code.

For comparison, the actual aluminum extrusions filled with structural foam and the finite element models of the same material are shown in Figure 5. This finite element model was composed of the computer generated solid elements simulating the structural foam itself, the shell-type aluminum extrusion material and the carrier steel that holds the structural foam in place. The 'tied contact model' feature was selected to eliminate the contact consistency problem while combining the aluminum extrusion and the structural foam for the purpose of the finite element analysis.

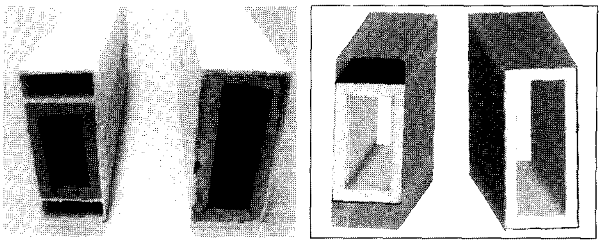
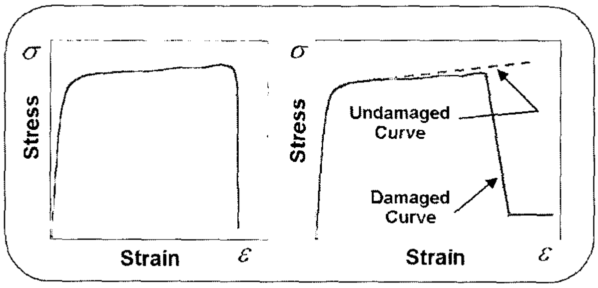

(a) Real specimens (b) Finite element model

Figure 5. Aluminum extrusions with structural foam.



(a) Real test result (b) Damaged curve for the simulation

Figure 6. Material characteristic curves.

In addition, to incarnate analytically the fractures and tears that occurred in real crush test, the damaged curve was utilized using modified material characteristic curve as shown in Figure 6 (Kim *et al.*, 2001) and then it was applied both for aluminum extrusion and structural foam model.

3.2. Axial Collapse Analysis

As for the detailed analysis of the axial collapse test on the aluminum extrusion filled with structural foam, the velocity of axial load and the all the other boundary conditions were applied to simulate an actual axial collapse test. Figure 7 illustrates the axial collapse test and analysis results of aluminum extrusion filled with the structural foam.

A realistic presumption of aluminum extrusion with axial collapse test and external crush flow of the foam were not easy to incarnate analytically. Since the imperfection factors were not under consideration, there might have been a slight difference between the actual test and the simulation results with respect to the force-displacement diagram and collapse mode. Nonetheless, the simulation shows little difference with the mean values of crush load obtained from the test results.

3.3. Bending Collapse Analysis

To simulate an actual bending collapse test of the aluminum extrusions filled with structural foam, the velocity of

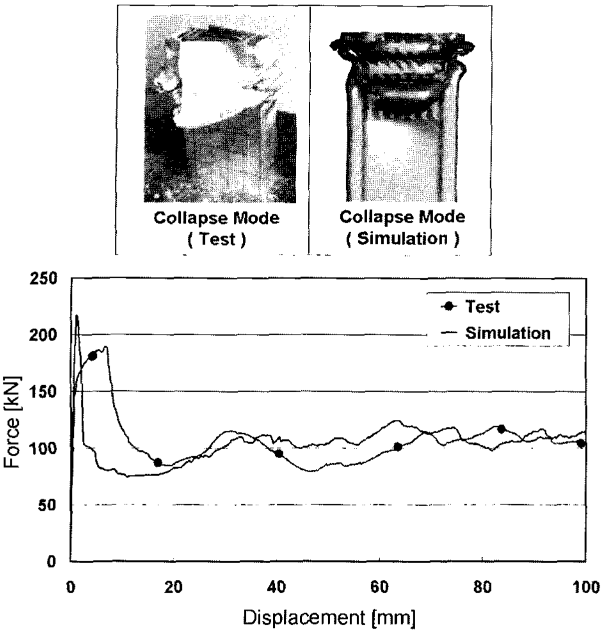


Figure 7. Comparison between axial collapse test and simulation results of aluminum extrusion filled with structural foam.

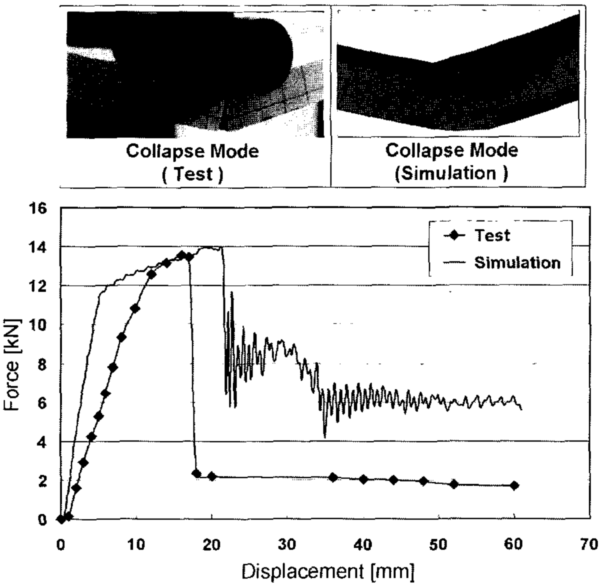


Figure 8. Comparison between bending collapse test and simulation results of aluminum extrusion filled with structural foam.

axial load and the other boundary conditions were configured and a complete analysis was performed. Figure 8 explains the 3-point bending collapse test result and analysis of aluminum extrusions with structural foam. It was not easy to plot a sudden depreciation of a load after structural foam destruction. However, there is an approximate analysis of the transition progress of load variation.

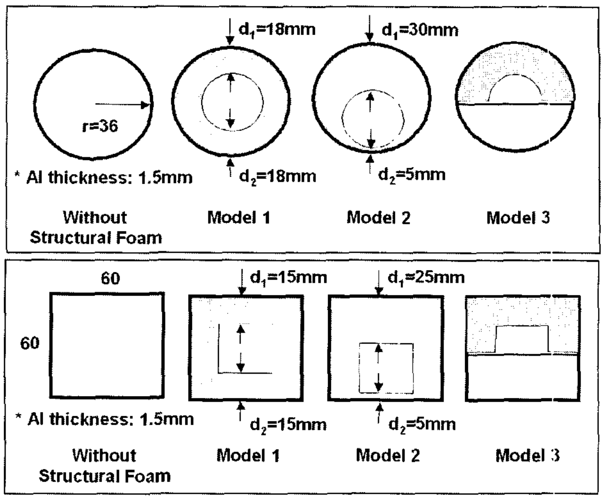


Figure 9. Cross-sectional profile design concepts of aluminum extrusion filled with structural foam.

3.4. Cross-sectional Profile Design of Aluminum Extrusion filled with Structural Foam for the Bending Collapse Improvement

According to the results of previous studies, aluminum extrusion filled with structural foam appears to have a superior advantage on absorbing the side impact energy on automotive frames that indicate dominant bending collapse. Thus, the automotive applications of the aluminum extrusions filled with structural foam were mainly focused on the cross-sectional profile design of the structural foam material.

In this paper, two kinds of cross-sectional profile design are considered and shown in Figure 9. The first design has a circular cross-sectional profile and the other design features a square cross-sectional profile. Each cross-sectional profile was then further categorized by structural foam filling methods. The bending collapse analysis results of the circular shaped aluminum extrusion filled with structural foam are shown in Figure 10 and Figure 11.

Figure 10 demonstrates the typical bending collapse modes and force-displacement diagrams. The Model 3, half filled circular cross-sectional profile design itself showed the most stable curve among the other models without a sudden depreciation of a load. Variations in circular cross-sectional profile designs yielded various bending collapse testing results, especially the effect of the structural foam indicates significant increase in

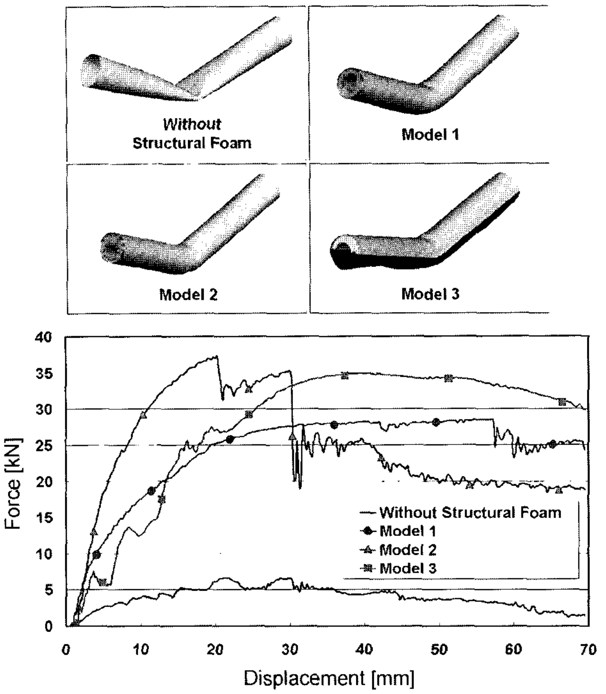


Figure 10. Typical bending collapse modes and force–displacement diagrams of circular cross-sectional shape aluminum extrusions filled with structural foam.

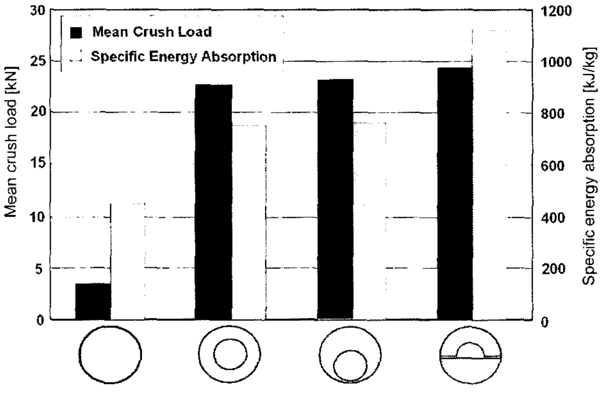


Figure 11. Comparison of energy absorption according to the circular cross-sectional shape aluminum extrusions filled with structural foam.

bending crush energy absorption as shown in Figure 11.

As for the overall energy absorption capacity per weight, a maximum increase of 147% was observed by the application of structural foam. Even for the half filled circular cross-sectional profile design, there was a 49% increase in energy absorption per weight compared with the other models filled with structural foam.

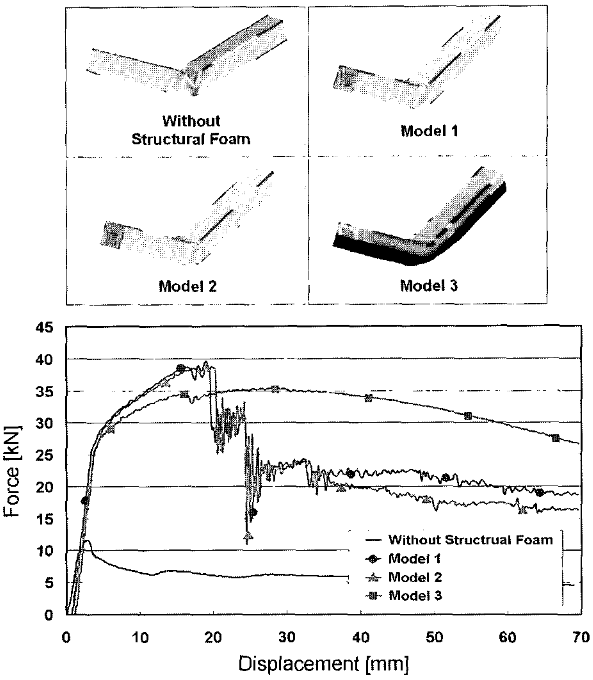


Figure 12. Typical bending collapse modes and force–displacement diagrams of square cross-sectional shape aluminum extrusions filled with structural foam.

The bending collapse analysis results of the square shaped aluminum extrusion filled with structural foam are shown in Figure 12 and Figure 13. Figure 12 showed a similar result from that of circular shaped aluminum extrusion filled with structural foam. It implies that the Model 3, half filled square cross-sectional profile design itself showed the most stable curve among the other models without a sudden depreciation of a load. For the half filled square cross-sectional profile design, even

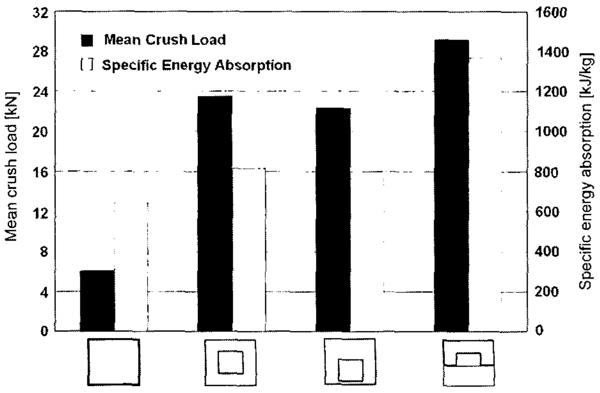


Figure 13. Comparison of energy absorption according to the square cross-sectional shape aluminum extrusions filled with structural foam.

greater rate of energy absorption was observed compared to the half filled circular design as shown in Figure 11 and Figure 13.

Furthermore, as seen in Figure 13, the use of the structural foam on the square cross-sectional profile design resulted in drastic improvement on energy absorption capacity per weight up to maximum 112%. The half filled square cross-sectional profile design yielded an increase of 79% in energy absorption per weight compared with the other models filled with structural foam.

4. DESIGN APPLICATION OF ALUMINUM EXTRUSION FILLED WITH STRUCTURAL FOAM

As discussed in previous sections 2 and 3, the advantage of the aluminum extrusions filled with struc-tural foam is clear and very effective absorbing impact energy relating to bending collapse. Especially, in case of applying the half filled cross-sectional profile design there was a dominant improvement in energy absorption from the results of simulation. Therefore, based on the test and analysis results of the aluminum extrusions filled with structural foam, the half filled structural foam was applied when manufacturing a real aluminum space frame considering the cross-sectional shape of A, B-pillar. Figure 14 exemplifies an aluminum space frame analysis model with structural foam in order to apprehend the side impact characteristics. The side impact boundary conditions of B-pillar were taken into account as shown in Figure 15. The deformed shape and force-displacement diagram as shown in Figure 16 and Figure 17 compared the side impact analysis result of B-pillar with

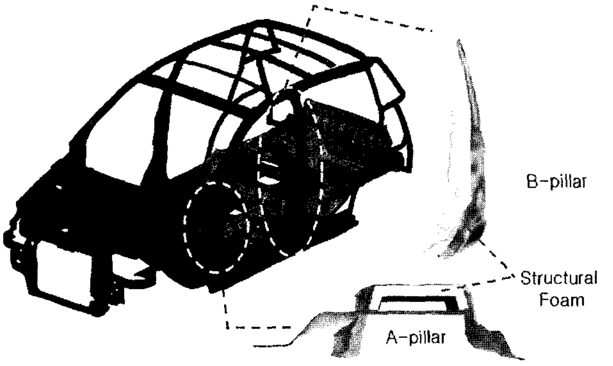


Figure 14. Analysis model of aluminum space frame with structural foam.

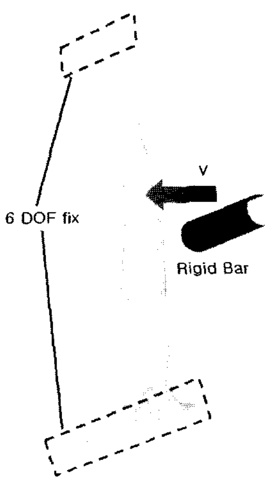


Figure 15. Side impact boundary condition of the B-pillar.

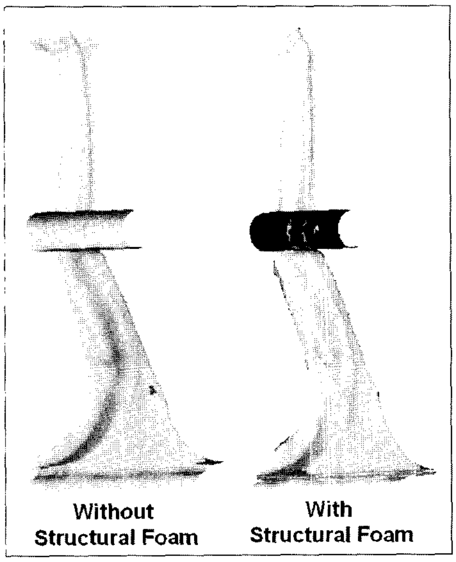


Figure 16. Comparison of the deformed shape between B-pillar without and with application of structural foam.

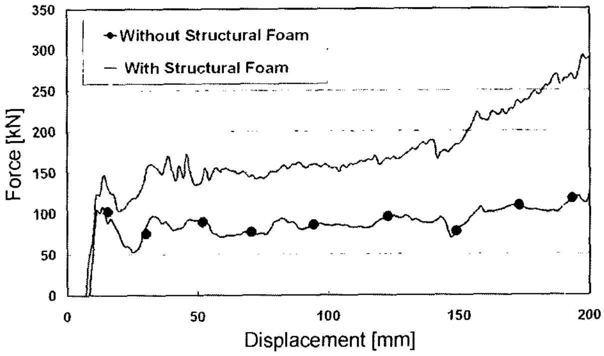


Figure 17. Comparison of force–displacement diagram between B-pillar without and with application of structural foam.

and without structural foam. There was little difference in the deformed shapes of the both cases as seen in Figure 16. On the other hand, by the application of structural foam, Figure 17 implies that the force-displacement load curve was going up and there was a 50% increase in energy absorption per weight. Hence, under a realistic circumstance of an aluminum space frame, there seems to be an improvement in the side impact performance and the bending rigidity of the aluminum space frame when the structural foam was applied.

5. CONCLUSIONS

This research tested and analyzed the application feasibility of the structural foam to aluminum extrusion in its crashworthiness aspect. There are four fundamental points achieved from this research.

(1) Considering the frontal crash feature, the application of structural foam to aluminum extrusion has shown little improvement in energy absorption and collapse mode.
(2) Considering the bending rigidity of the frame and side impact features, the application of structural foam to aluminum extrusion has shown significant improvement.
(3) Considering the filling methods of structural foam, the half filled cross-sectional profile design has shown higher energy absorption capacity per weight than completely filled cross-sectional profile designs.
(4) Based on the test and analysis results, it can be presumed that the half filled with structural foam is highly effective when applied to the A, B-pillar, and side sill with respect to the reinforcement of the frame and side impact safety.

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