EVALUATING STRUCTURAL FOAM AS AN ALTERNATIVE TO STEEL IN A FRONT OFFSET CAE ANALYSIS

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ABSTRACT

This study compares a lightweight structural foam design to a steel design while meeting the same level of performance. Static crush analysis using LS-DYNA was conducted for this evaluation. Partial structures of the white body were crushed to determine their performance in two areas: (1) the front frame rail near the lower dash and (2) the front A-Pillar area to check intrusion numbers. Structural foam designs were compared to the base steel designs and modifications were made to improve performance. The new structural foam designs were considered having met their target if their performance was similar to the base model. The final iteration of the structural foam design met the performance target set by the base model. The simulation showed that structural foam would be a good replacement for selected steel parts and would improve performance according to the criteria described above. It would also reduce weight and cost while maintaining similar body performance in crash tests.

INTRODUCTION

The structure of a vehicle is designed to absorb energy and protect its occupants in various types of crashes that occur on the road each year. Most of these are frontal crashes. In the 40 mph offset test, 40 percent of the total width of the vehicle strikes a barrier on the driver side. The results of the crash test are based on structural performance, restraints/dummy kinematics and injury measurements. The front offset crash has therefore been an important factor in purchasing a vehicle.

This simulation study was based on maintaining the current vehicle performance in an offset collision while reducing weight and cost through the use of structural foam. The following two areas were chosen for evaluation: the Lower Dashboard intrusion and the A-Pillar intrusion. Models were made up of parts from the full vehicle and statically crushed to determine their energy absorbing and intrusion characteristics. The current vehicle was considered to be the base line model. Parts from the selected areas were then either removed or replaced by new designs including the structural foam. The criterion for evaluation for the frame rail area was to keep the same level of energy absorption as the base line with no change in the mode of deformation. Similarly, the A-Pillar area was evaluated for intrusion in the longitudinal direction. Both models were considered having met the target if they performed at the same level as their corresponding base line model. This paper will be roughly divided into two parts discussing the front frame rail and the A-pillar designs respectively.

STRUCTURAL FOAM APPLICATION ON PARTS

Before going into the details of the actual models and the results, the method of structural foam application and how it is an integral part of the design process is explained.

Structural foam is a high strength, low-density epoxy material. It is malleable and adheres to a carrier. Any metal can be a carrier for the structural foam, but steel is normally used (see Figure 1). The carrier can be as thin as the aluminum foil normally used in the kitchen up to about a millimeter. Typically it is 0.6 mm to 0.8 mm thick. The structural foam itself is typically 4 mm thick but more can be applied if a gap between surfaces needs to be filled. The carrier with the foam is installed during the body assembly, then cures and typically expands 50% from its original thickness during the paint baking process.

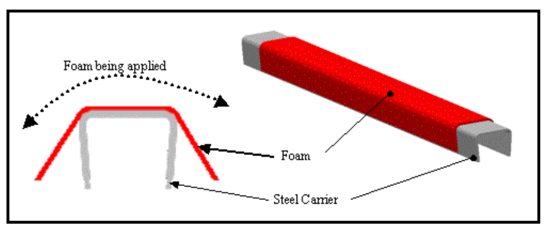

Figure 1. Epoxy structural foam is applied to the steel carrier before heat treatment.

The foam is constrained between the carrier and another part of the car body. Heat treatment expands the foam within this cavity without air gaps and it hardens upon cooling (see Figure 2).

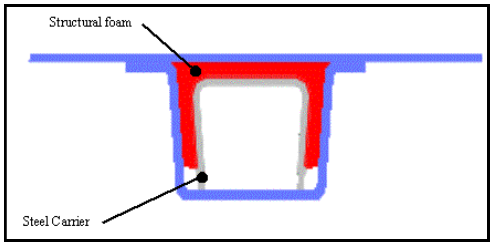

Figure 2. Example of foam application

The properties of the foam were modeled using the LS-DYNA material number 24 (MAT_PIECEWISE_LINEAR_PLASTICITY).

FRONT FRAME RAIL ANALYSIS

Model Background

The front left side frame of the model was extracted from the full car model and crushed statically using LS-DYNA to determine how much force was being transmitted through the side frame cross-section.

In the x direction, the model includes part of the front side frame and its connecting parts to the lower dashboard and the front floor (-40 mm to 1050 mm with reference to the front shock tower). In the y direction, the model was cut off from the side sill to just after the front floor frame (-660 mm to –300 mm if the center line is taken as y=0). Parts of the lower dashboard, lower dashboard stiffener, outrigger front side and the front floor were included in the model.

Boundary Conditions

The front floor was constrained in all directions (see Figure 3).

The front side frame cross section was rigidly attached to a steel plate used for crushing the side frame at a velocity of 1000 mm/sec. The model was run for 250 ms (milliseconds) since the maximum intrusion in the lower dashboard was not expected to exceed 250 mm. Force through the back plate used to crush the model was used to calculate the energy absorbed by the side frame.

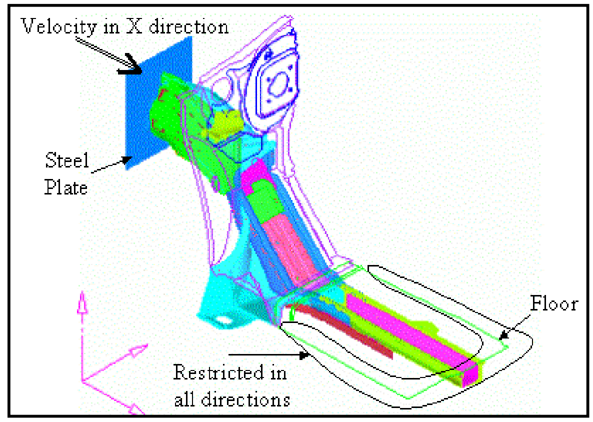

Figure 3. Boundary conditions of the static crush model used for frame rail analysis.

The base model included all parts used to improve offset performance. This was the model as described above. The parts shown in Table 1 were then removed from the base model before adding the structural foam design (see Figure 4).

Table 1.
Parts removed from the Base Model

	Part Name	T (mm)	Mass (kg)
1	Rear End Frame Stiffener	2.0	0.41
2	Front Side Frame Rear End Reinforcement	2.0	0.24
3	Bulkhead Floor Frame	2.0	0.07
4	Frame Reinforcement	1.8	1.15
5	Lower Reinforcement	3.2	1.34
6	Bulkhead Rear End Frame Stiffener	2.0	0.08
7	Rear End Frame Stiffener	1.8	0.44
8	Rear Support Stiffener	1.6	0.79

As mentioned before, the structural foam design consisted of two inverted U-shaped steel carriers 0.8 mm thick: one for the dashboard lower region and the other for the front floor region.

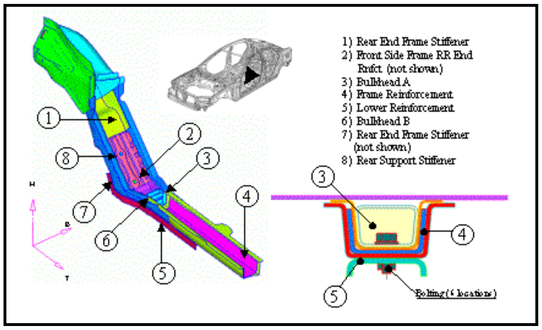

Figure 4. Pictures of parts removed from base model.

Both carriers were covered with structural foam over most of their surfaces. The structural foam parts were then placed in the existing vehicle structure in the dashboard lower sub-assembly and the front floor sub-assembly. The carriers were designed in such a way that they would fit exactly into the sub-assemblies and allow for foam expansion. This brought the two carriers together at their ends to form a continuous section. They were joined together using structural foam (see Figure 5). Parts added are listed in Table 2.

Table 2.
Design parts added to the model

	Part Name	T (mm)	Mass (kg)
1	Structural Foam	4.0	0.52
2	Steel carrier	0.8	0.94
3	Small bracket	2.0	0.21

The foam would expand during heat treatment and form a strong bond with the adjoining steel parts making the carrier immovable. A small steel bracket was added towards the top of the frame rail to ease the assembly process.

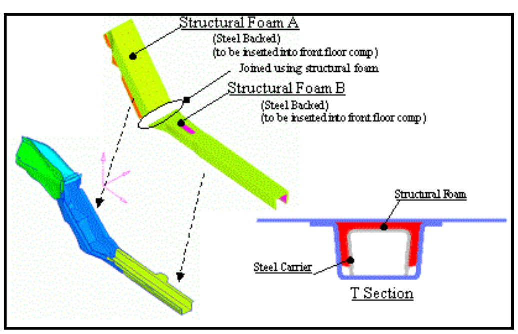

Figure 5: Carrier and foam structure being inserted into the frame.

Results – Front Frame Rail

Figure 6 shows the final form of the baseline and structural foam models at 250 milliseconds. The frame rail deformation was found to be quite similar in the dashboard lower area in both cases. The floor frame rail was slightly bent in the foam model.

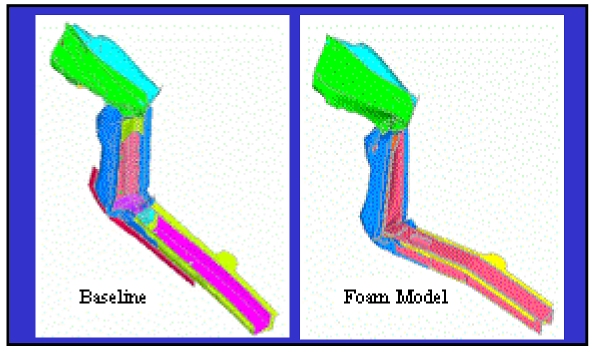

Figure 6. Comparing base line and structural foam model results.

Figure 7 shows the Force vs. Displacement curve of a point on the rigid wall pushing the frame in the x direction. The area under each curve is the energy absorbed by that model.

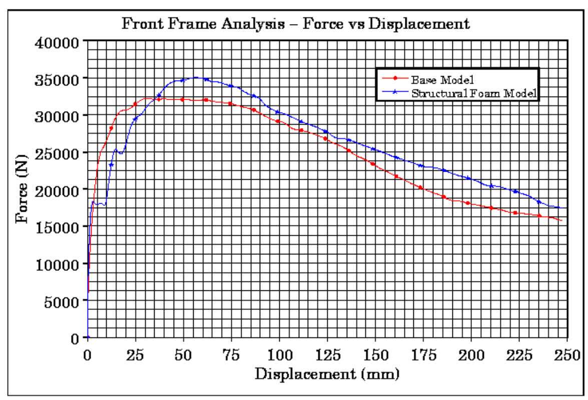

Figure 7. Force vs. Displacement Graph showing front frame rail results.

Comparing the mode of deformation and the energy absorbed from the force vs. displacement graph, it was concluded that although slightly different, the structural foam model was close to the baseline model.

Table 3.
Weight difference between the base and the structural foam model

Model	Mass (kg)
Base Model (removed)	-4.52
Structural Foam Model (added)	1.67
Weight savings	-2.85

A-PILLAR ANALYSIS

One of the criterions of evaluation of the offset analysis is the A-Pillar intrusion. The A-Pillar to roof joint area was identified as a potential application for the structural foam. The purpose of this analysis was to investigate if a few parts can be made thinner and be replaced by structural foam while still maintaining the same stiffness in the A-Pillar area. The objective was to have the structural foam design perform as well as the base line design while producing a lighter vehicle.

Model Background

Similar to the front frame rail, the left half of the white body was used for this analysis (cut off at y=0). The remaining model was further reduced in size by removing elements from the front and rear of the vehicle (at x=-200 and x=2800 relative to the front shock tower). This was considered to be a large enough model to capture the front floor and rear panel deformation. A flat rigid wall was used to perform a static crush analysis using LS-DYNA.

Boundary Conditions

The nodes at y=0 were placed in symmetric boundary condition while the rear nodes were restrained in all directions. The front of the model was attached to a rigid plate, which was used for crushing the model at a velocity of 1000 mm/sec. The model was run for 250 milliseconds. The boundary conditions are summarized in Figure 8.

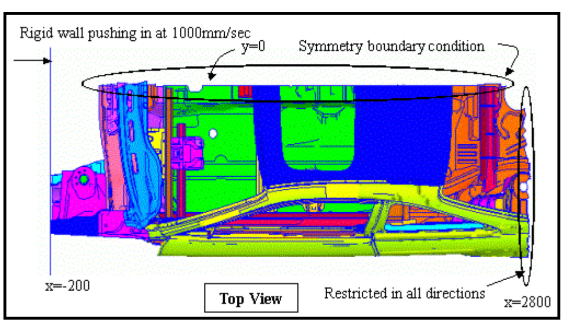

Figure 8. Boundary conditions of the A-Pillar static crush model.

In an offset collision, the front side frame absorbs most of the load. The upper members of the front shock tower sub-assembly also absorb some load. The collapse of these parts causes a deformation in the upper roof parts between the A and B-Pillars. To evaluate this effect, two points were chosen to measure the deformation. Figure 9 shows the points used for measurement and the location of the structural foam added in the counter measure ideas.

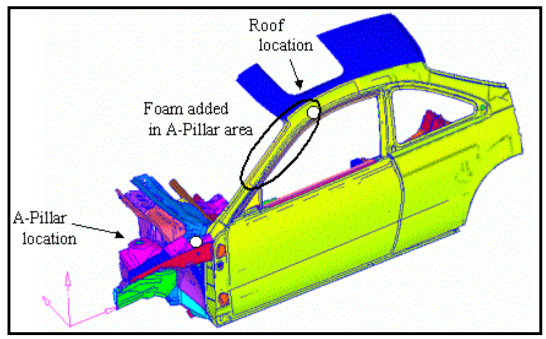

Figure 9. Displacement measurement locations and the area where structural foam was added in the counter measure ideas.

Iterations: Design changes made to the Base model

All the modifications made to the Base model were in the area where structural foam was added. One part had its geometry changed while two other parts were varied in thickness and grade of steel. The list of these parts and their gauges are shown in Table 4.

Table 4.
Base Model design parts modified for iterations

	Part Name	T (mm)	Steel
1	Stiff Front Pillar Up	0.8	Mild
2	Rail Roof Side Rnf	1.6	Mild
3	Pillar Front Inner Up	2.0	Mild

First Iteration

The Stiff Front Pillar Up was redesigned into the shape of a carrier such that it would extend beyond its previous length. It would also support the bonding of the 6 mm structural foam between itself and the side panel outer. The Rail Roof Side Reinforcement and the Pillar Front Inner Up were decreased in thickness by 0.2 mm each to 1.4 mm and 1.8 mm respectively. Both of these parts were also changed to high strength steel (see Figure 10).

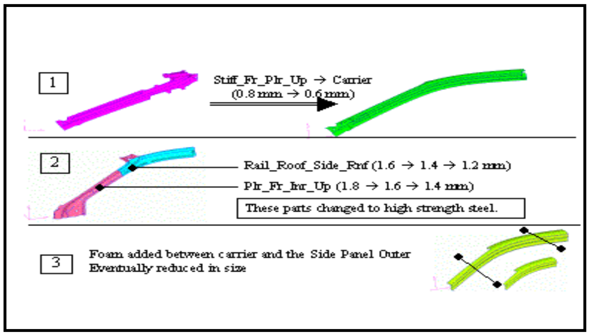

Figure 10. Parts shown in Table 4.

Part of the vehicle structure showing how the parts and the structural foam are assembled is shown in Figure 11.

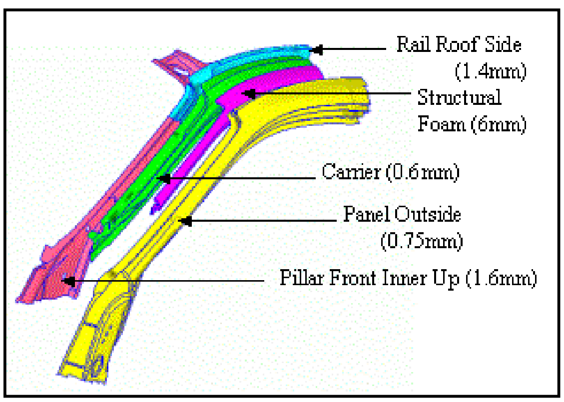

Figure 11. How it comes together.

The results of this first iteration (discussed later in the paper) came out to be much better than the base model. Since the objective was to maintain the current base model performance, another design change was evaluated.

Second Iteration

The thickness of the two parts in the first iteration was further reduced by 0.2 mm. The final gauges of the Rail Roof Side Reinforcement and the Pillar Front Inner Up were 1.2 mm and 1.4 mm respectively. Both parts were still maintained as high strength steel. The structural foam was shortened in both directions along the A-Pillar and along the roof rail between the A and B-Pillar (see figure 12).

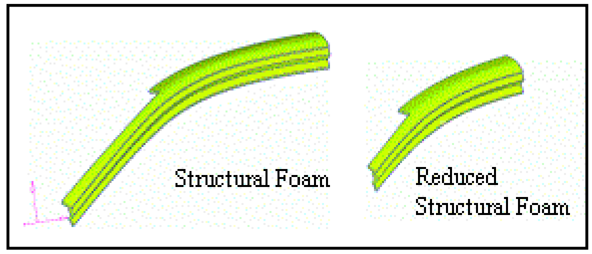

Figure 12. Difference in the structural foam between the First and Second Iterations.

Results – A-Pillar

After running for 250 milliseconds, the deformed model looked as shown in Figure 13. The mode of deformation was similar to what would be seen in an offset collision. The front door and the side panel outer between the A and B-Pillars were deformed as expected. Though not a replacement for the crash test, the static crush analysis performed well enough to have confidence in the model.

Figure 13. The crushed model.

The other criterion used to evaluate this analysis was the intrusion of the base of the A-Pillar. The displacement of this point was measured in the x-direction (See Figure 14).

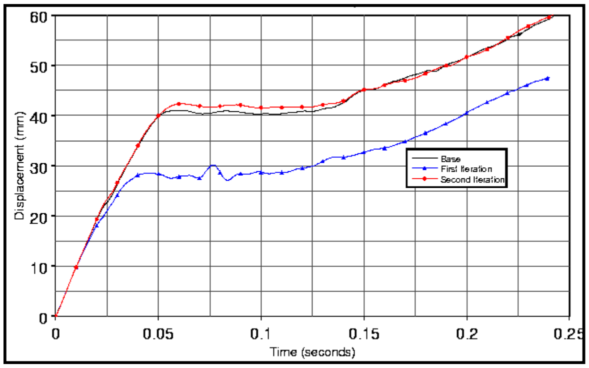

Figure 14. Graph of intrusion at the base of the A-Pillar.

From the graph, one can see that the first iteration performed much better than the base model in terms of displacement in the x-direction. The second iteration falls almost on top of the base model thereby meeting the objective of the analysis.

A second point used for further confirmation lay between the A and B-Pillars on the Rail Roof Side and its displacement was measured in the y-direction. Though not one of the criterions of evaluation, it was a good check to see how much this point intruded into the cabin (see Figure 15).

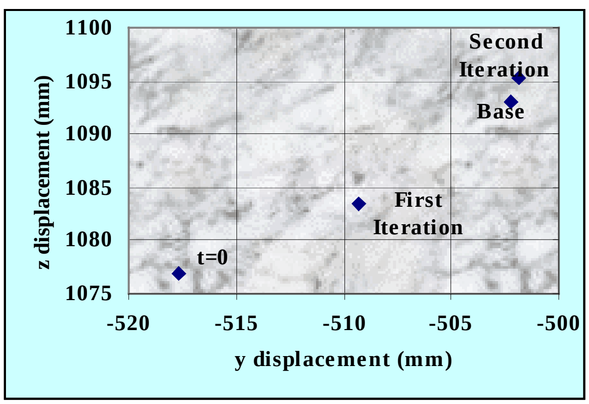

Figure 15. Displacement of the point on Rail Roof Side in the y-direction.

The graph in Figure 15 shows four points. The point near the lower left hand corner is the position at the zero time step. In other words, it is the position of the model (or automobile) at rest. The first iteration had a lower displacement in both the y and z-directions when compared to the base model. The base model displacements compare well with the Second Iteration and both those points can be found at the upper right corner of the graph.

The data from both graphs (Figures 14 and 15) collectively indicates that the First Iteration is best while both iterations meet or exceed the performance of the base model.

Due to the gauge down, there was a considerable weight savings between the two parts. The carrier added some weight since it was extended. On the whole, there was a reduction of 0.85 kg taking both the left and right sides into account. The break down is shown in Table 5.

Table 5.
Weight savings for the A-Pillar analysis

Part Name	Gauge (mm)	Base (kg)	Iter (kg)	Difference (kg)
Rail Roof Side	1.8->1.4	1.479	1.109	-0.370
Pillar Fr Inr Up	1.6->1.2	2.694	2.096	-0.598
Stiff Fr Pillar Up	0.8	0.687	0.000	-0.687
Carrier	0.6	0.000	0.989	0.989
Structural Foam	6.0	0.000	0.242	0.242
Total				**-0.424**

CONCLUSION

The front frame rail static crush analysis showed a mode of deformation similar to an offset crash. The performance of the structural foam model was similar to the base model and was considered to have met the set target. In addition, the new design saved 2.85 kg from the base model.

The A-Pillar intrusion decreased significantly in the first iteration after initial thickness reductions and introduction of structural foam. The second iteration with high strength steel and 0.4 mm decreased thickness in two parts was considered equivalent to the base model when comparing A-pillar intrusion numbers. The weight was reduced by 0.42 kg.

ACKNOWLEDGEMENTS

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REFERENCES

LS DYNA Keyword User’s Manual, Version 940.