USING CAE TO EVALUATE A STRUCTURAL FOAM DESIGN FOR INCREASING ROOF STRENGTH

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ABSTRACT

In recent years, there has been increased discussion of the strength of vehicle roofs in rollover crashes. NHTSA recently revised the federal roof strength requirement and the IIHS has published an even more stringent roof strength goal. While working to increase roof strength, automakers are also working to reduce vehicle mass for improved fuel economy and other benefits. Developing technology to achieve both of these goals is challenging. This paper investigates the use of CAE to evaluate the addition of structural foam to an existing design to maintain or increase roof strength. A concept solution that combines nylon and structural foam material was developed and analyzed using an explicit finite element model and later tested on a body-in-white to evaluate the CAE predictions. The main evaluation method was the FMVSS 216 test procedure. Through CAE analysis and actual testing, the modifications were found to have increased roof strength. A performance target was set and a conceptual steel-only assembly was created in CAE to meet this target. The foam/steel assembly met the performance target but at a reduced weight compared to the steel-only assembly. These analyses demonstrated that CAE is useful for predicting the performance of foam/steel assemblies and that foam/steel assemblies can yield greater strength with lower mass than a steel-only assembly. Questions regarding field performance and the feasibility of mass-production must still be addressed.

INTRODUCTION

Rollover accidents accounted for less than 2.4% of the total number of accidents in 2009 [2], and yet government statistics show that about thirty three percent of all fatal crashes involve a rollover [1,2]. After going through a review process, the National Highway Traffic Safety Agency (NHTSA) roof strength standard, FMVSS 216, was recently revised to require car and light truck roofs to withstand a higher load. The IIHS (Insurance Institute for Highway Safety) has recently announced that even higher loads will be needed for a vehicle to get its “Good” rating. Automakers are therefore working hard to meet the challenge of increasing strength while minimizing adverse consequences. Because fuel economy and weight distribution are important considerations, the challenge is to increase roof strength with minimum increase in vehicle weight and minimum effects on performance. To do all this, critical areas of each vehicle need to be examined to determine the most efficient use of added mass.

In the last several years, CAE has been extensively used to predict test outcomes and determine solutions for crash performance. It is a useful tool to alter a “structure” before building and testing it so that the number of crash tests on expensive prototype vehicles can be reduced. This study will present the latest roof strength test requirements and test procedures to show the critical areas for meeting the new strength requirement. A composite of nylon and structural foam will be introduced as one candidate solution including its application procedure. There will be a discussion on the possible solutions tried and their result using LS-DYNA. Finally the test and CAE correlation results will show that CAE can be an effective tool to predict roof strength performance for new materials such as structural foam.

NHTSA’S FMVSS 216 REQUIREMENT REVIEW

The old requirement for measuring roof crush strength is described at the NHTSA’s website [3]. FMVSS No. 216 seeks to reduce the risk of death and serious injuries in rollover crashes. The standard currently applies to vehicles with a GVWR (Gross Vehicle Weight Rating) of 2,722 kilograms (6,000 pounds) or less. A steel plate is placed at an angle in contact with the roof. A gradually increasing force is applied through the plate. The vehicle passes the test if the plate moves not more than 127 mm or 5 inches when the force equals 1.5 times the unloaded vehicle weight. This is commonly also referred to as the Strength to Weight Ratio or SWR.

The new requirement increases the force the roof must withstand at 127 mm of displacement to 3 times the vehicle’s unloaded weight. In addition, both sides of the roof are to be tested, first on one side and then the other. The new standard also broadens the scope of covered vehicles to include those up to GVWR of 4,536 kilograms (10,000 pounds).

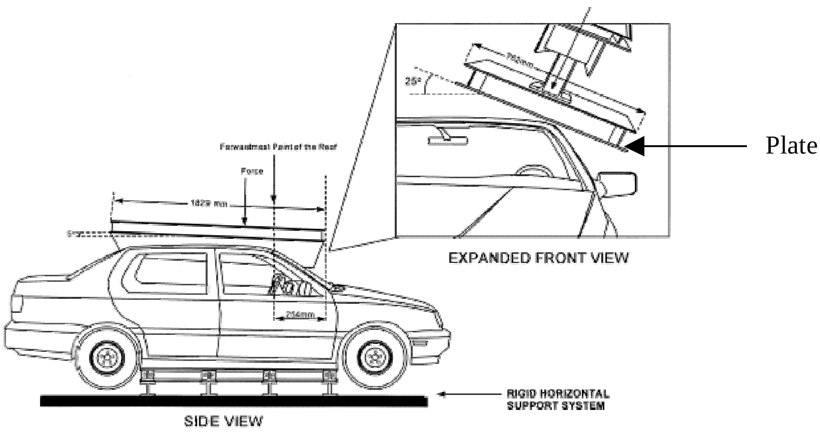

Figure 1: Vehicle boundary conditions for FMVSS 216 roof strength test

The plate shown in Figure 1 is unchanged. It remains a flat rigid block measuring 762 millimeters by 1892 millimeters and is positioned longitudinally at an angle of 5 degrees to the horizontal towards the front of the vehicle. Its lateral axis is at an outboard angle of 25 degrees below the horizontal. The first contact point of the plate to the roof is 254 millimeters from the front of the plate. Force is applied perpendicularly to the plate’s surface at a speed of 13 mm per second [4].

IIHS ROOF STRENGTH REQUIREMENT

The new IIHS (Insurance Institute of Highway Safety) evaluation procedure [5] is the same as NHTSA’s but the vehicle roof needs to be able to withstand the weight of the unloaded vehicle up to 4 times its weight [6] in order to achieve a ‘GOOD’ rating. The load has to be met by only one side of the vehicle. The rating distribution given on the result achieved by the vehicle is shown in Figure 2.

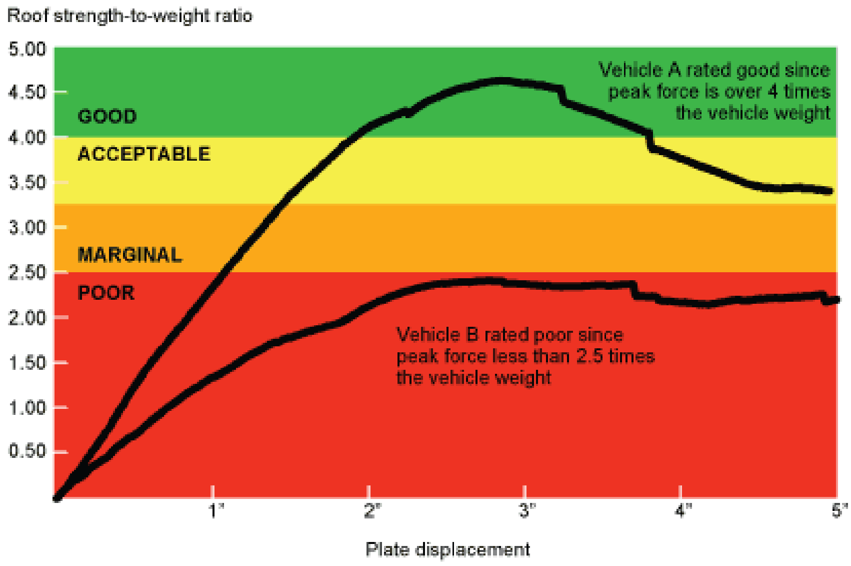

Figure 2: IIHS ratings shown in graphical form

OBJECTIVE OF THIS STUDY

The objective of this study was to determine whether a steel and structural foam assembly could be accurately modeled to predict its performance in NHTSA's roof strength test. The success of the study would be determined by the correlation of the CAE with an actual test of a modified body-in-white. A performance target would have to be set, and both the CAE and test designs would be required to meet that target.

MODEL SETUP

A finite element model of the Honda Pilot was used for this study. Windshield glass, the sun roof structure and glass and the front and rear doors were added to a model of a body-in-white. The model was constrained at three locations along the side sill – at the edges and the center under the B-pillar. A rigid plate was modeled and positioned according to the dimensions of the testing requirement on the left side of the vehicle (Figure 3). The average mesh size of the model was about 7 millimeters. This was considered to be the base model. This finite element model was evaluated against an actual physical test and was found to be sufficiently correlated for this activity. The difference in the roof strength peak force between the test and CAE was 0.4%.

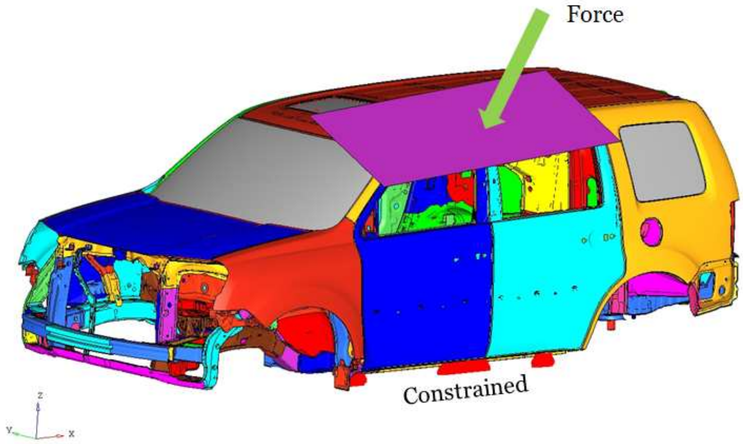

Figure 3: Model Setup

SETTING A TARGET

Based on past experience, it was known that the critical areas of importance for increasing roof strength were the B-pillar, A-pillar, front roof rail, and the related joints connecting those parts. Increases are typically made by increasing the thickness or material grades of steel parts or by adding additional reinforcements in select areas, or both. The basis of this study however, was to use structural foam to increase the load-carrying capacity of the body in those critical areas as well. A judgment was made that the base model would remain unchanged in terms of all its part thicknesses and material specifications. Extra parts would be added to increase roof strength. This was done to simplify fabrication of the body-in-white that would have to be created and tested to determine the accuracy of the CAE prediction.

To evaluate whether structural foam would work, a performance target had to be set. A higher performance target was based on an all-steel solution, which would have been infeasible. The goal was for the structural foam solution to achieve the same performance as the steel solution, but with lower weight. Using the CAE model, the thickness of the B-pillar inner and outer were increased by several grades. This was a practically infeasible solution due to the availability of material and forming and layout issues, but used to set a target in the virtual domain. The modified model was evaluated using a simulated FMVSS 216 protocol (see Figure 4). The load-carrying capacity of the modified roof model was increased by 13.9% when compared to the base model.

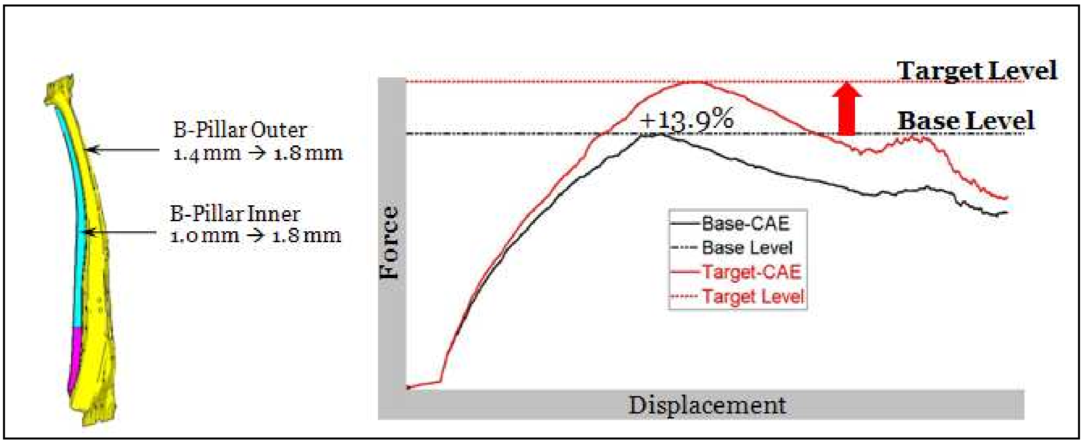

Figure 4: Setting a target

STRUCTURAL FOAM APPLICATION PROCESS

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. Carriers can be of several different types of materials, such as metal and nylon. The specific carrier chosen for a solution depends on its application and what it needs to do. The carrier is then attached to the vehicle using spot weld tabs, push pins, or molded metal clips. The structural foam itself is typically 3 to 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, and during a baking process, the foam typically expands 50% from its original thickness and cures. The whole reinforcement (foam and carrier) is typically designed to fit in the space between parts such that a gap is filled once the structural foam has expanded and bonded to the surrounding structure.
For simplicity, Figures 5 and 6 show the application process using a steel carrier.

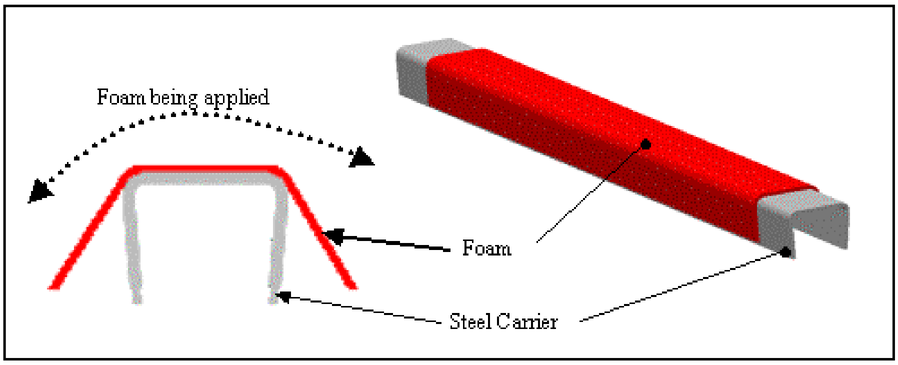

Figure 5: Structural foam applied to the steel carrier before heat treatment.

As shown in Figure 6, heat treatment expands the foam within the cavity, fills the gaps, and hardens upon cooling. The carrier is now bonded to the body and stiffness is increased.

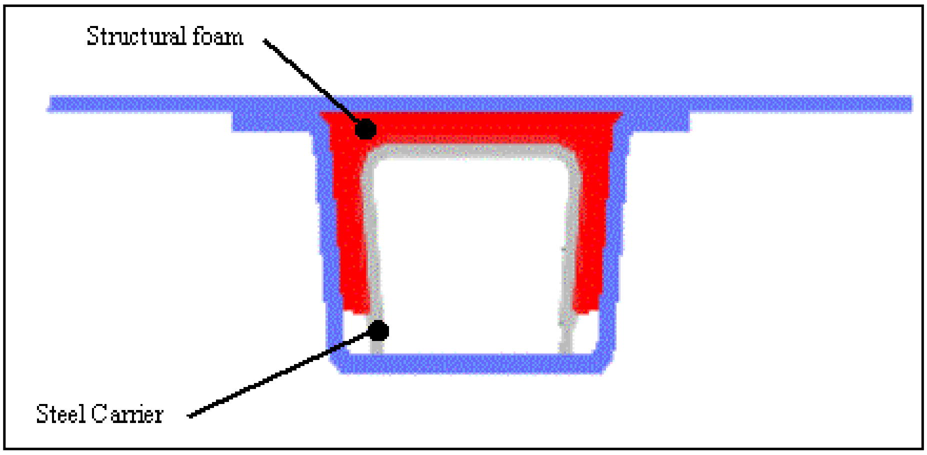

Figure 6: Example of the foam application

Structural foam can be applied to a vehicle in two different stages of development. In the early stages, the structural foam part and carrier can be designed in to reduce weight and possibly material grade. In later stages, when most of the structure and feasibility analysis is done and very difficult to change, the structural foam can be used as reinforcement in areas that need extra strength for a particular reason.

NYLON INSERT WITH STRUCTURAL FOAM DESIGN

In this research work, a mass production vehicle was used as the base structure because an existing design was needed to determine, through laboratory testing, whether the structural foam was successfully simulated. For that reason, it was decided to use foam that was adhered to a nylon carrier that could be inserted into the upper B-pillar area of the base structure. The properties of the foam, as given by the foam supplier, were modeled using the LS-DYNA material number 26 (MAT_HONEYCOMB).

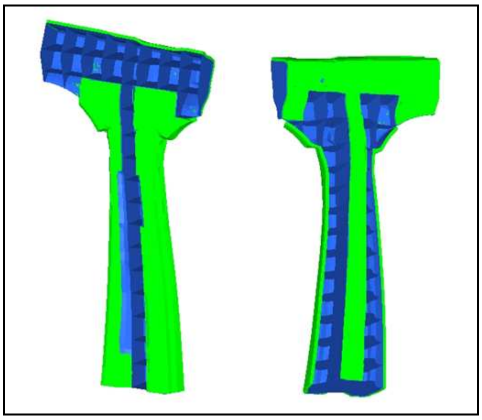

Figure 7: Inside and outside view of the Nylon insert with Structural Foam

As shown in Figure 7, the insert consists of two materials: the nylon (represented in blue) and the structural foam (represented in green). The nylon is a 33% glass-reinforced material that is molded into a shape with ribs that can be of different thicknesses along its length. The rib thickness and pitch can be tuned to a degree to vary the strength of the nylon. In this study, the rib thickness was kept at 2 mm. There are areas designed into the nylon where the structural foam is cut and molded onto the nylon. The carrier and foam structure is designed to fit inside the parts of the vehicle while leaving about 3 mm space all around it for Electrocoat flow. As mentioned before, the carrier can easily be attached to the vehicle using a push pin that goes into an existing hole or adding a weld tab to the nylon so it can be correctly placed in the vehicle. As shown in Figure 8, for this study, a push pin was used to attach it to a hole on top of the B-pillar inner.

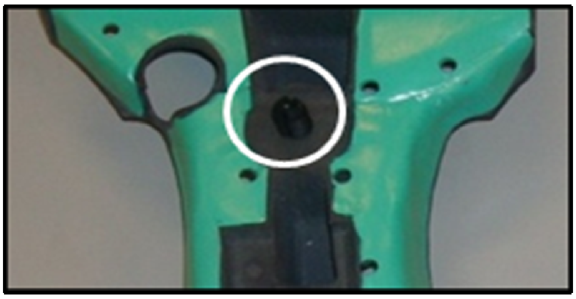

Figure 8: Attachment method of actual part

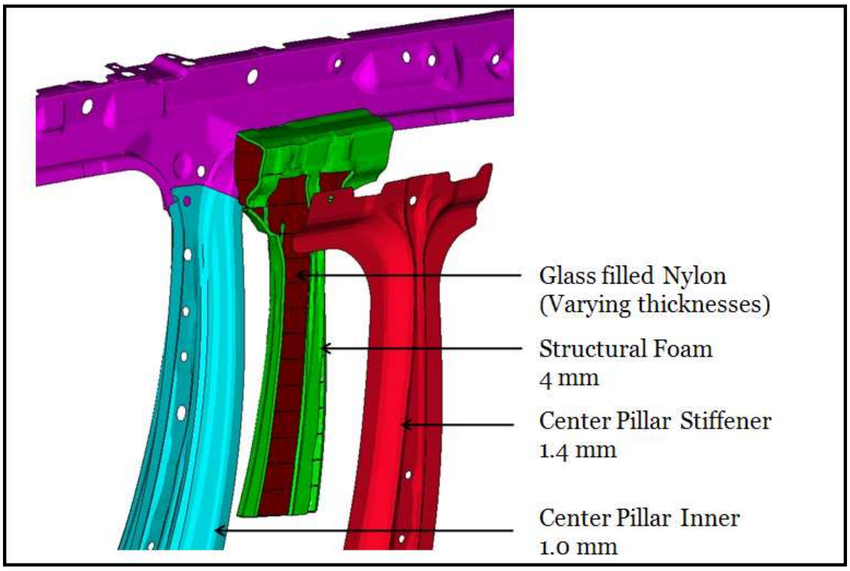

Figure 9: Exploded view of assembly

The nylon and structural foam fit between the B-pillar inner and the B-pillar stiffener with a small gap that filled during expansion of the structural foam. The structural foam bonded with both the nylon and the steel parts forming a section through the upper B-pillar. See Table 1 for mass information.

Table1: Parts added to Base model

Parts Added to Base (L & R sides)	Mass (kg)
Nylon	1.48
Structural Foam	0.28
Total	**1.76**

CAE ROOF STRENGTH RESULTS

The base design was the mass production model with no modifications in design, material, or thicknesses of any of the parts. As shown in Figure 9, the new nylon and structural foam insert was attached inside the confined space between the B-pillar inner and B-pillar outer and analyzed using LS-DYNA. Figure 10 shows the resulting force versus displacement curve. By adding the nylon and structural foam, increasing the mass by 1.76 kg, the CAE predicted an increase in performance of the model by about 15.1% from the base design. There was also some increase in stroke at the peak load when compared to the base model results.

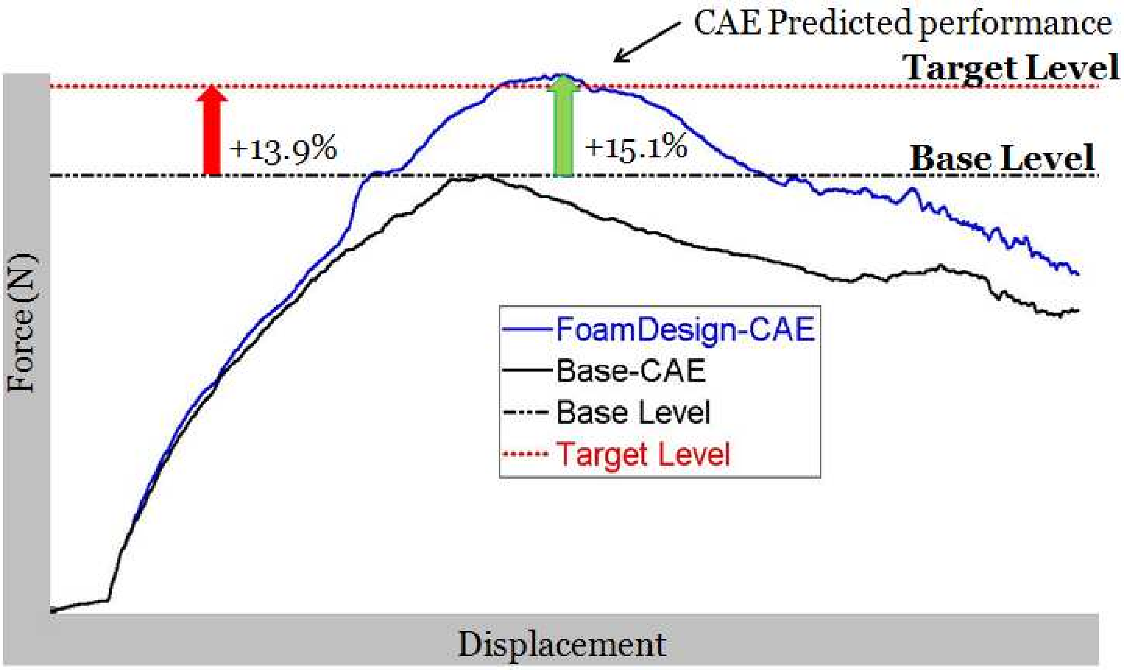

Figure 10: Force versus Displacement Curve

Figure 11 shows a CAE comparison of the B-Pillar on the base model (left) and the B-Pillar with the nylon and structural foam insert (right). These pictures show that the base model (without the structural foam insert) buckled around the middle of the B-pillar while the model with the added nylon/foam insert stopped that buckling from occurring. The insert helped the B-pillar model retain its section and resist a higher load.

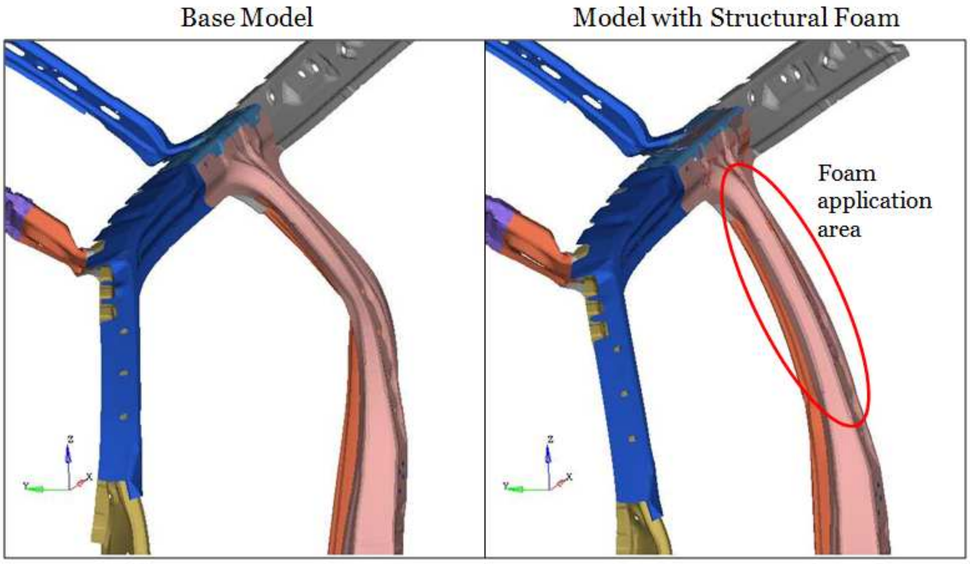

Figure 11: CAE comparison of Results (B-pillar)

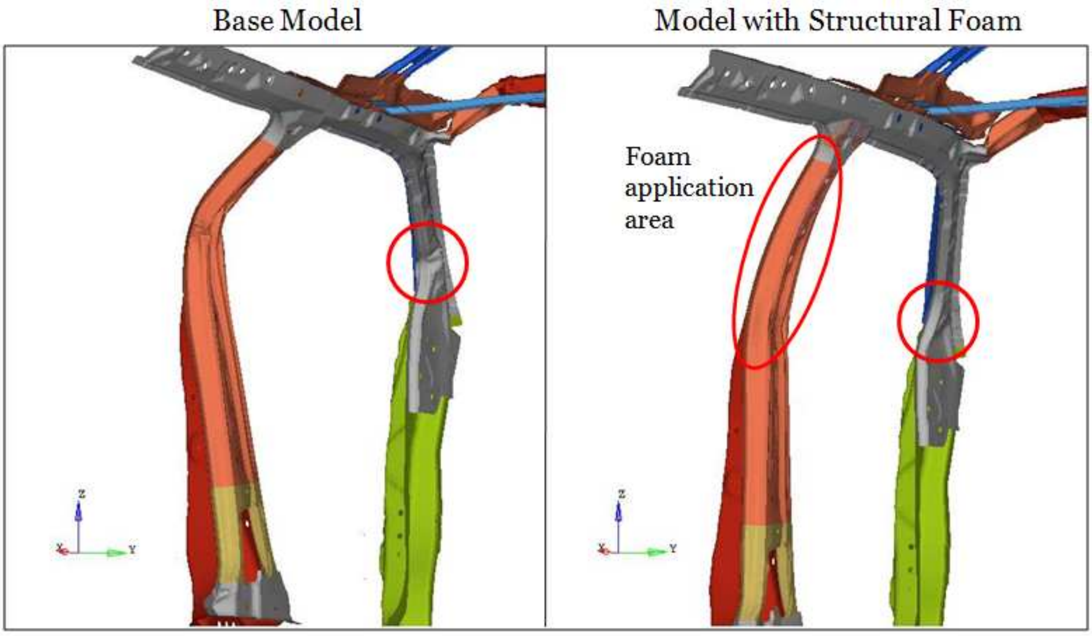

Figure 12: CAE comparison of Results (A-Pillar)

As shown in Figure 12, looking at the structure from the inside of the model, the deformation of the A-pillar was also affected by the increased strength of the B-pillar. The deformation point in the A-pillar moved downwards due to the change in load path from the stiffened B-pillar. Overall, the vehicle structure with the added parts appears to be less deformed than the base model.

CORRELATING TO TEST

After conducting this CAE analysis, the next step was to correlate the CAE predictions to laboratory testing. For that, a prototype part was manufactured and added to a mass produced body-in-white. The materials of the prototype part were the same as would be for a mass produced part. The insert was placed in the body before it was welded closed. Its position in the vehicle was confirmed through the visual inspection of the push pin attachment and proper welding of the surrounding parts.

This vehicle was tested using the NHTSA FMVSS 216 procedure as described earlier in this paper (only a single-sided crush was performed). The resulting performance was compared to the base design and is shown below in Figure 13. The performance of the vehicle with the nylon and structural foam part was improved by 15.4% when compared to the base design. Since the CAE prediction was 15.1%, this was considered to be acceptable correlation.

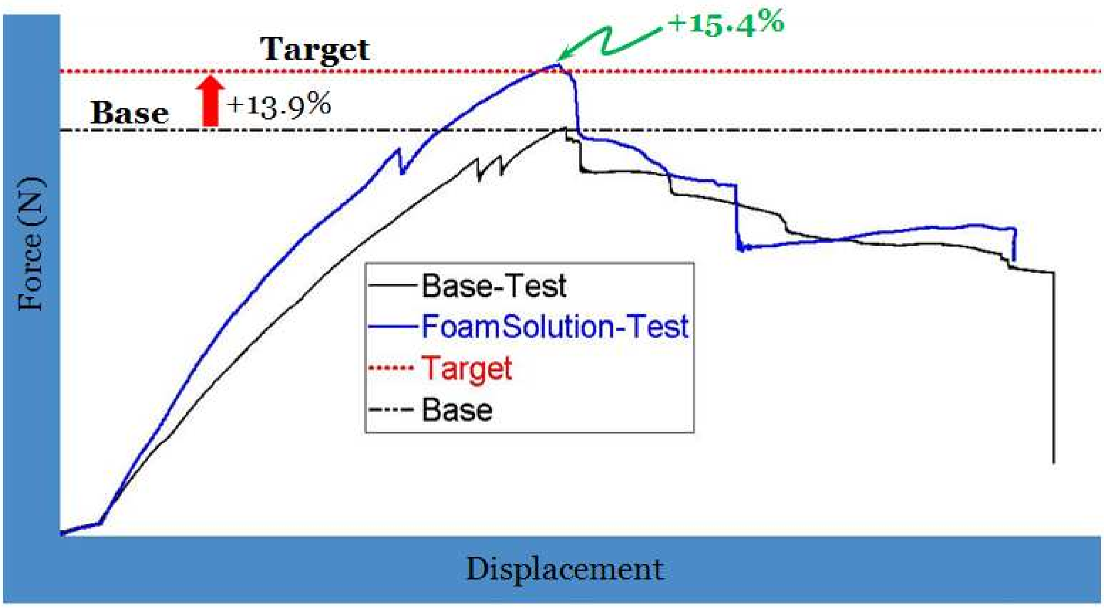

Figure 13: Comparing Test Results – Foam Solution versus Base Design

COMPARING TO STEEL SOLUTION

The steel solution used to set-up the target had an increase in mass of 4.87 kg from the base. As shown in Table 2, the nylon and structural foam solution was lighter than the steel solution.

Table 2: Mass Comparison

Comparison	Mass (kg)
Steel Solution	4.87
Structural Foam Solution	1.76
Mass Difference	3.11

CONCLUSIONS

A study to specifically increase the roof strength of a vehicle was set up in a controlled environment such that the performance of a nylon/structural foam part could be predicted using CAE and confirmed through actual testing.

A prototype nylon part combined with structural foam was designed to be placed in the upper B-pillar area for maximizing performance of roof strength.

The tested performance of the added parts matched well with the predicted performance of the vehicle. It has been shown that LS-Dyna can be used effectively to determine performance of the structural foam.

ACKNOWLEDGEMENTS

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