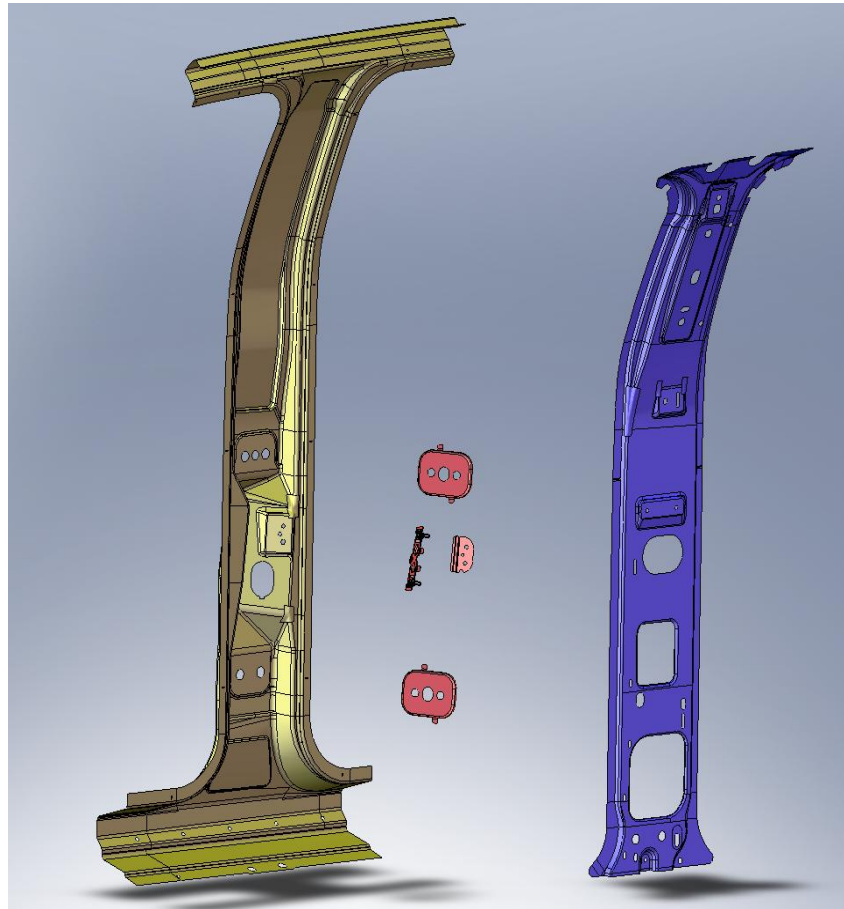


**Final Report**  
**ME 450: Design and Manufacturing III**  
**Fall 2007**

*Design of Automotive Center Pillar Reinforcement to Resist  
Roof Crush in F-Series Crew Cab*



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## **1 ABSTRACT**

A major role of automotive engineers is to improve fuel efficiency and vehicle safety. However, it is very difficult to improve both of these requirements at the same time. Our team was asked to aid with the design of structural reinforcements in hopes to improve the roof crush strength, but minimize the weight of the automobile body center pillar, also known as the B-pillar. This design would be able to resist roof crush during vehicle rollover accidents when subjected to forces defined by the United States government regulation FMVSS 216. In addition, the design will be able to resist larger forces. Our group focused on the Ford F-150 Crew Cab.

## **2 INTRODUCTION**

The B-pillar of a car is the structure located between the front and rear doors of the cab. It does not only house electrical wiring and connection spots for the passenger seat belts, but it provides structural support for the cab in case of a side collision or rollover of the vehicle.

Our group has been asked by Shawn Morgans, Body Structure Technical Leader of The Ford Motor Company, to create a reinforcement design for the B-pillar of the F-Series Crew Cab truck line. This redesign will help prevent catastrophic roof crush during a rollover. The motivation behind the design of this reinforcement is to help Ford meet the increased demands of a soon to be implemented rollover test by the Federal Motor Vehicle Safety Standard (FMVSS). This new vehicle standard states the roof of a vehicle must support 2.5 times the unloaded vehicle's weight, with a maximum allowable displacement of 4.1 inches [6]. The current issues we must deal with when augmenting the current B-pillar design is to determine the location of yielding on the B-pillar, determine the loads under which the B-pillar begins to elastically and plastically deform, and determine how the geometry of the B-pillar affects the critical buckling load of the pillar.

## **3 INFORMATION SEARCH**

Since our project involves a very close look at a subject that we are not experts in, an information search was a very large part of identifying the problem.

### **3.1 FMVSS 216**

Our testing implementation must meet certain requirements stated by the United States government. These standards are presented by FMVSS 216, which we found on the National Highway Traffic Safety Administration (NHTSA) website. The current standard states that the test must apply a load 1.5 times the curb weight of the vehicle, with a maximum allowable displacement of 5 inches. The test fixture must also be placed at a 25° roll angle, as well as a 5° pitch angle [8]. A visual representation of the FMVSS 216 test can be found in Appendix A.

### **3.2 B-pillar Structure**

To gain a basic understanding of the physical structure of the B-pillar we did an extensive search on current designs implemented by different automobile manufacturers. Mainly we looked at models from Ford and Audi. Also, we met with our project mentors, Dr. Darrell Kleinke, Shawn Morgans and Professor Jwo Pan, who are all experts in auto body design. Professor Pan provided us with a lecture he presented to our ME450 class, which contains useful information regarding the reinforcement of the B-pillar. Our mentors gave us information ranging from CAD files to current research being done, specifically on the B-pillar. Figure 1 shows the CAD drawing of the current B-pillar in the Ford F-150 Crew Cab. A dimensioned drawing of the B-pillar can be found in Appendix B and Appendix C.



**Figure 1: CAD model of Ford F-150 B-pillar.**

### **3.3 Materials**

Once we identified the basic issues surrounding roof crush resistance, we knew we needed to reinforce the B-pillar with some type of material. We first needed to research different types of materials to identify which materials would perform best for our application. Using the internet, we found information on foams such as structural foam, polyurethane, and also metallic foams such as aluminum foam. Another solution is changing the whole pillar material itself rather than adding reinforcement. Therefore, we searched for information on different types of steel such as high strength, high carbon steels, or other high strength steel alloys.

### **3.4 Completed Research**

To aid in our research and solution to the problem, we wanted to explore completed research on similar topics. Using the college of engineering journal database, such as ISI Web of Knowledge, we found many completed research papers involving the reinforcement of automobile pillars. These journals also explored the application of different structural foams. The research served as a valuable tool to increase our knowledge of B-pillar reinforcement, as well as the properties and possible uses of structural foams.

## **4 CUSTOMER REQUIREMENTS AND ENGINEERING SPECIFICATIONS**

Based on the information that we searched and provided by our sponsor for this project, we have determined the customer requirements and translated them into engineering specifications by using Quality Function Deployment (QFD).

### **4.1 Quality Function Deployment**

QFD is a flexible and comprehensive group decision-making technique used in product development. As a team, we had discussions to identify our customers, determine the customer requirements and determine the weights for each requirement. Also, we used the current Ford B-pillar as a benchmark for design improvements. Then, we generated the engineering specifications and correlated customer requirements to the engineering specifications.

We cross-correlated the engineering specifications to each other and set the engineering target. Figure 2 shows the QFD that we have constructed for the B-pillar reinforcement design.

#### **4.1.1 Customer Requirements**

Ford Motor Company is our sponsor and the manufacturer for which we are designing the B-pillar reinforcement. Since this project involves automotive body construction, the car buyer, passenger and other automotive consumers, are other groups of customers that need to be considered to determine their requirements.

From the discussions with our sponsor, we need to design a central pillar reinforcement that has the following criteria:

- Able to resist roof crush during rollover accidents
- Minimize weight
- Minimize cost
- Appropriate materials

In addition to the requirements set by Ford, we have considered a few other requirements that are important in developing the project. The B-pillar reinforcement must have the ability to resist side impact, must be easy to manufacture and repair, and have a long fatigue life. The appearance of the B-pillar reinforcement is less required, due to the fact that the B-pillar is not a class-A surface for the automotive body [6].

The customer requirements are located at the left side of the QFD and we determined the weights for each requirement based on customer priorities and their needs.

#### **4.1.2 Benchmark**

We used the current B-pillar for the Ford F-150 as a benchmark for our design. We used a scale of one to five to evaluate the current B-pillar against each of the customer requirements, whether they are satisfied or not. The benchmark is important to reveal any area for improvements that we may consider for our project. We need to improve the ability to resist the roof crush by using stronger materials, or changing the reinforcement geometry based on safety requirements.

#### **4.1.3 Engineering Specifications**

Based on the customer requirements, we translated them into engineering specifications by setting quantified values to each requirement. These requirements have been set by Ford Motor Company and based on the discussions with Shawn Morgans and Dr. Darrell Kleinke for structural body construction. These specifications must conform to the NHTSA requirements for the new roof crush test FMVSS 216. The engineering specifications and their target values are listed in Table 1.

The major concern for the customers is the safety of the vehicle. According to the test regulation, the B-pillar reinforcement needs to be designed so that it can resist a minimum load of 2.5 times the vehicle's curb weight applied to the roof. For this project, we need to design it for three times the weight, due to safety factors. The maximum allowable displacement is also set to be 4.1 inches. For the Ford F-150 Crew Cab, the test load is about 15,564lbs. The reinforcement strength must be higher than the strength of the mild steel (210 GPa) that is currently used by Ford. The cost for manufacturing and development needs to be minimized and targeted to be less than \$15 per vehicle. The weight of the B-pillar with the reinforcement is targeted to be 21 lbs. Lightweight materials need to be used because minimizing the vehicle weight will increase fuel economy. For manufacturing processes, the target value for the number of parts is four. This is to minimize the assembly and the installation time. This will also minimize the manufacturing cost of the B-pillar. The materials used must also be compatible with the assembly method,

which is spot welding. The reinforcement must fit into the B-pillar geometry and must be minimized. The current B-pillar average dimensions are 8.0 inches in length, 47.0 inches in height, and 1.8 inches in thickness [6].

Engineering Specifications	Target Value
Minimum load for roof crush test	15,564 lbs
Maximum allowable displacement	4.1 inches
Manufacturing and development cost	≤ \$15 per vehicle
B-pillar weight	21 lbs
Reinforcement dimensions	≤ 8 in. x 47 in. x 1.8 in.
Compatibility with assembly method	Spot welding
Number of reinforcement parts or	4 parts
Time to assemble/install	minimum
Material strength	210 GPa

**Table 1: Engineering Specifications and their target values for B-pillar reinforcement [6].**

#### **4.1.4 Customer Requirement to Engineering Specifications Correlation**

After determining both customer requirements and engineering specifications, we put correlation values for each pair of both requirement and specification to determine their strength or weakness when related to each other. For our B-pillar design, the ability of to resist roof crush is strongly related to the material strength, the minimum test load that the roof can withstand and the displacement when the load is applied.

#### **4.1.5 Engineering Specifications Cross Correlation**

On top of the QFD, the engineering specifications are correlated to each other with either positive, negative or no correlation. This correlation shows the effects on each specification when one engineering specification is changed. For the B-pillar, the roof can resist to higher load when stronger material is used and when the dimensions are changed. These effects are useful as they provide indirect dependencies of the customer requirements on the engineering specifications.

#### **4.1.6 Engineering Target**

With the QFD, we determined the most important engineering specification that needs to be satisfied according to the related customer requirements and arranged them according to their importance rating. In order to maximize the B-pillar's resistance to failure, the most important engineering specification that needs to be met is the material strength. The next two most important specifications to meet are withstanding the minimum test load and reducing the amount of displacement during the FMVSS 216 test. The other specifications in order of importance are the material cost, the material weight, the number of parts, the reinforcement dimensions, the assembly method and the installation time.

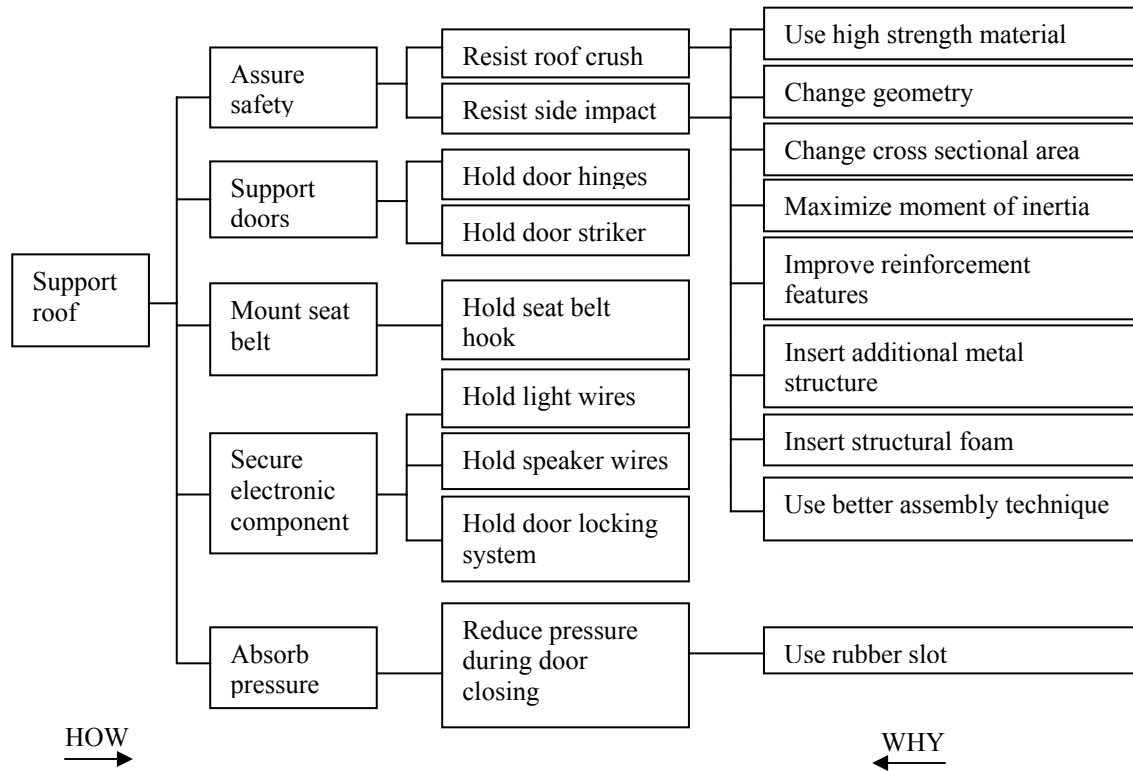




## 5 CONCEPT GENERATION

Before we generate the different concepts, we constructed a Function Analysis System Technique (FAST) diagram to understand the functions of the B-pillar. Then we generated the design concepts in a Morphological chart. Finally, we sketched the design concepts before making the concept evaluation and selection.

### 5.1 Function Analysis System Technique Diagram (FAST)



**Figure 3: Function Analysis System Technique Diagram for B-pillar reinforcement concept generation.**

The FAST diagram was very important in facilitating our design concept generation by understanding the functions of the B-pillar. After constructing the QFD diagram, we brainstormed and created the FAST diagram to identify the basic and subsidiary functions of the B-pillar reinforcement as shown in Figure 3. The main functions of the B-pillar are to support the roof, to assure safety and to support the doors. The B-pillar also provides support to the seat belt, secures the electronic components and absorbs pressure when the vehicle doors are closed. We organized the functions mentioned above in the FAST diagram by selecting the task function, identifying the basic and supporting functions, expanding the diagram by stating the solutions to the functions, and verifying the diagram by reversing the direction of the diagram from right to left.

### 5.2 Morphological Chart

The Morphological chart is an effective technique to generate high-level conceptual designs based on the B-pillar functions. From the FAST diagram, we took the function of the B-pillar to resist the roof crush because our main focus is to improve the strength of the B-pillar during vehicle rollover accident. For the concept generation, the materials used for the reinforcement should satisfy the requirement to maximize the strength and moment of inertia of the B-pillar, to

increase the critical load, and at the same time to minimize the cost and weight. The concepts generated are illustrated in the Morphological chart in Figure 4.

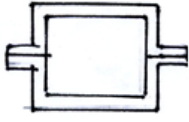
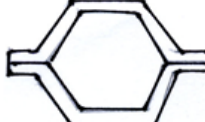

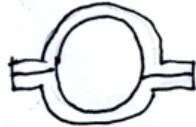
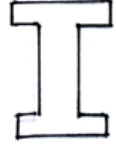


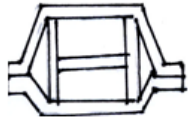

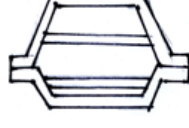
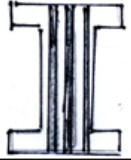
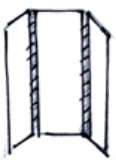


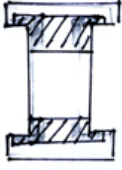
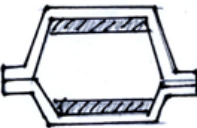
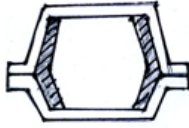
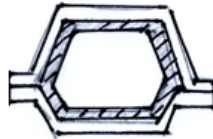
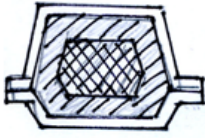
	Concept 1	Concept 2	Concept 3	Concept 4
Geometry of cross-section	Rectangular 	Hat section (symmetrical) 	Unsymmetrical 	Circular 
Metal reinforcement	Whole 	Half 	Critical Area 	High strength steel, high carbon, low carbon, Tailored steel
Placement of metal reinforcement	H-section 	X-section 	Parallel 	Steel rods 
Type of foam reinforcement	Structural foam	Aluminum foam	Polyurethane foam	
Placement of foam reinforcement	Corners 	Whole 	Critical Area 	Top and Bottom 
Placement of foam reinforcement (cross-section)	Outer and inner sides 	Sides 	Surround 	Fill cavity with foam 

Figure 4: Morphological chart based on the function of the B-pillar to resist the roof crush.

Based on the CAD model and material data given by Shawn Morgans, we generated the concepts with the symmetrical or unsymmetrical B-pillar hat section geometry [7]. Different shapes of cross-sections such as a hexagon and octagon were also considered for the concepts. We also generated the concepts based on different types of metal reinforcement, either by changing the current materials or by putting additional metal structure in the B-pillar to improve the strength. High strength tailored steel, high strength low alloy, high strength high carbon, or low carbon steel are the options for the metal reinforcements. Another type of reinforcement that our team has come out with is inserting foam into the B-pillar with structural foam, aluminum foam, or polyurethane [4]. We then made conceptual designs for the placement of the metal and foam reinforcement at certain areas of the B-pillar to increase its ability to resist the roof crush.

## 6 CONCEPT EVALUATION AND SELECTION

We narrowed down our design choices to the top concepts by comparing, combing, and refining our high-level designs. We had to do an extensive amount of research in order to decide which options were the best for our re-design. Our design concepts consisted of a material change of the B-pillar and the reinforcement placement of the selected material.

### 6.1 Material Reinforcement

The first step of our design process is to select the type of material. The goal of the material selection is to minimize cost and weight, and at the same time maximize the strength of the B-pillar. This is probably the most important step of the design process because according to our QFD, material strength, the minimization of the testing load and the maximum allowable displacement of the B-pillar are the most important features of our new design. Our team decided to look into structural foam, aluminum foam, polyurethane, and the addition of more steel to the B-pillar.

#### 6.1.1 Structural Foam

Most structural foams utilize an adhesive that expands by heat activation. This creates a uniform body structure that increases the strength and stiffness of the B-pillar. As you can see in Figure 5, there is a huge difference in using structural foam, when there is an applied force, compared to having a hollow section. In the figure, CBS is a type of structural foam known as composite body solutions [5]. Usually the carrier material is made out of nylon.

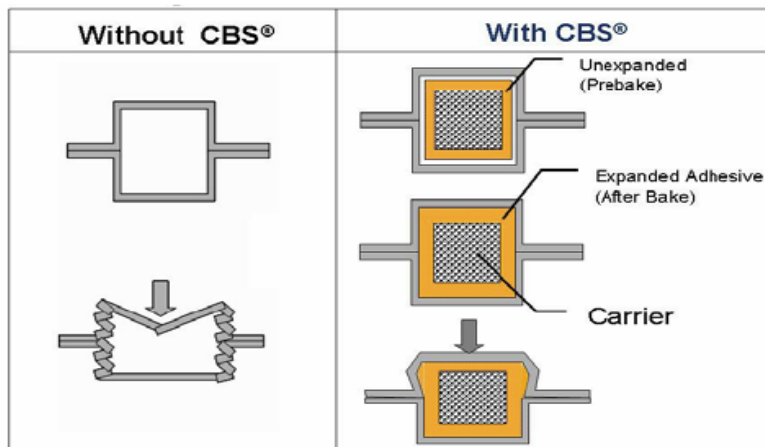


Figure 5: How adding structural foam helps reinforce a rectangular cross section [5].

Also, Figure 6 shows the comparison between two sections, one that has structural foam reinforcement and one that has no structural foam. These results are shown in a force-displacement diagram. This section is put under a typical bending collapse mode. As you can see, the maximum load is much more severe when there is structural foam present, compared to when the section is hollow. One can assume then that the structural foam application is much more effective when it is integrated into the B-pillar. Structural foam in a B-pillar will be highly effective because during the roof crush testing, the section is put under very high loads [4]. Structural foam is thought of as a fairly cheap alternative material, when compared to adding an additional metal structure.

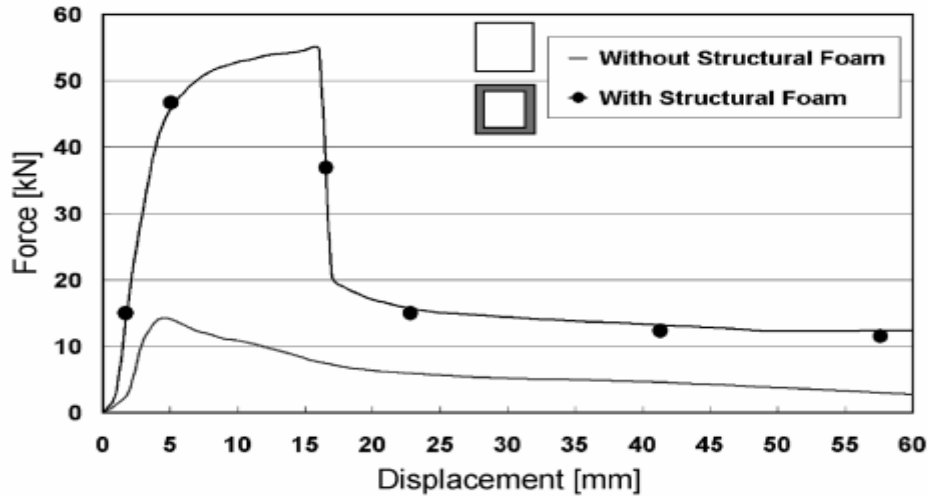


Figure 6: Force-displacement diagram with and without structural foam [4].

### 6.1.1.1 Polyurethane

Polyurethane is the material that most structural foam is made out of. It is a type of low density foam that can be used to decrease the weight and increase the strength of the B-pillar. As you can see in Figure 7, when the density of the foam used is low, as with the case of polyurethane, the buckling wave,  $H/h$ , is reduced. This decrease of wavelength increases the magnitude of the mean crushing force. It also produces a significant increase in the bending stiffness of the B-pillar [1]. The type of structural foam our team looked at was BETAFOAM 87100 produced by Dow Chemical. The datasheet of the material with all of the material properties can be found in Appendix D.

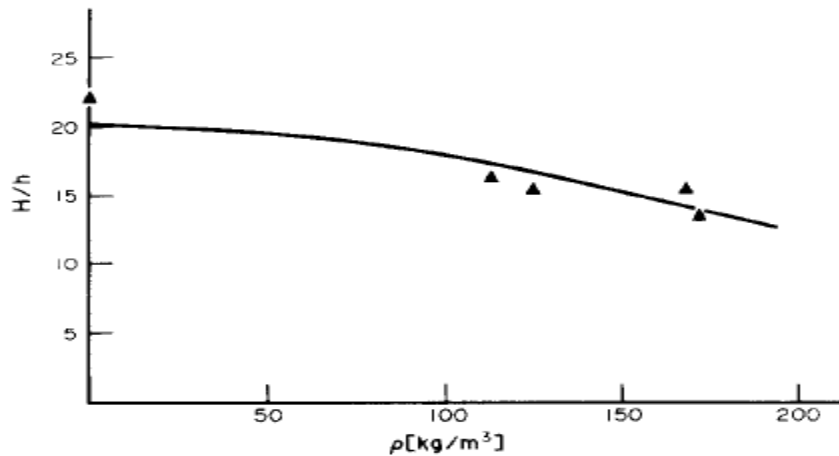


Figure 7: Density vs. wavelength of polyurethane during bending test[1].

### 6.1.2 Aluminum Foam

It has been found that filling a column with aluminum foam can increase energy absorption. This is due to the fact that the increase of the energy will be absorbed by the large deformation of the filler material, in this case the aluminum foam. Figure 8 shows the stress-strain curve for aluminum foam.

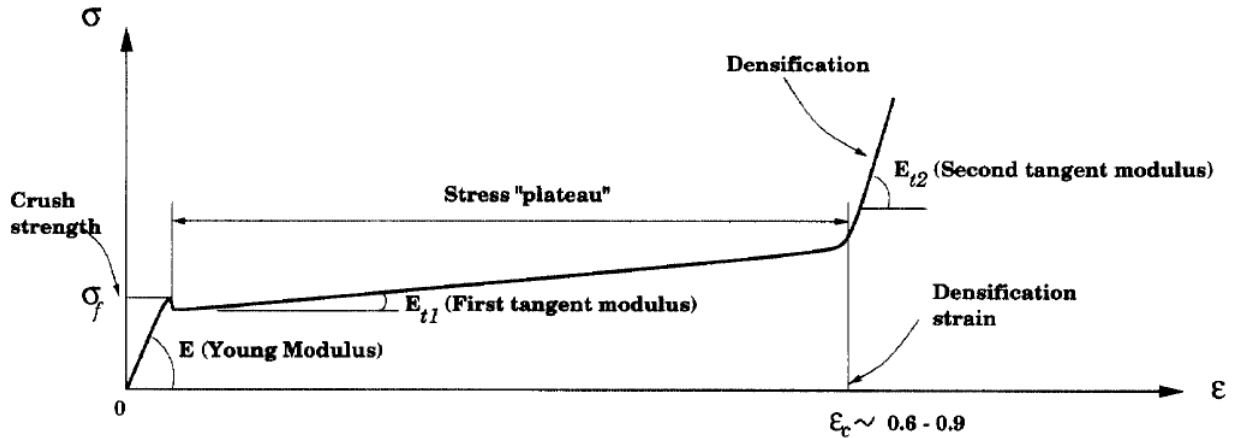


Figure 8: Stress-strain curve of aluminum foam [9].

As you can see, aluminum foam has the same characteristics of a highly porous cellular solid. It has an initial elastic regime, followed by an extended plastic region. At very high strains, there is a densification response, which causes the stress to increase again. This process allows for aluminum foam to have a very high compressive strain. Having a high compressive strain allows the foam to be a good material for energy absorption [9]. Figure 9 shows the values of a crush load being put onto a box column. The values come from the following equations:

$$P_m = 14\sigma_o t^{2/3} b^{1/3} \quad (\text{Eq. 1})$$

$$P_{m,f} = 14\sigma_o t^{2/3} b^{1/3} + b^2 \sigma_f \quad (\text{Eq. 2})$$

Where  $\sigma_o$  is the flow stress of the column material,  $\sigma_f$  is the compressive strength of the aluminum foam,  $b$  is the column width and  $t$  is the column thickness. As you can see from these equations, by having an aluminum foam filler, the force that the column can withstand will increase. The crush load of an empty box column can withstand 16.9kN. However, when filled with aluminum foam, this number increases by 20% to 20.3kN [9].

Type of Column	Strong axis orientation	$P_m$ [kN]	$\Delta P_m$ [kN]	% Increase
Empty box column		16.9		
Al honeycomb filling	$T = y$ axis	18.6	1.7	10%
	$T = z$ axis	18.1	1.2	7%
	$T = x,z$ axis	18.6	1.7	10%
Al foam filling	$T = x,y,z$ axis	20.3	3.4	20%
Theoretical prediction	Empty box Eq. (1)	16.9		
	filled box Eq. (5)	18.8	1.9	11%

Figure 9: Crush load of a column with and without aluminum foam [9].

Also, aluminum foam is thought of as a very expensive product. Most companies sell the product anywhere from \$1 to \$500 per square inch. This price depends on the tolerances of the product, as well as the complexity of the foam needed.

#### 6.1.4 Additional Steel

By adding additional HSLA or DP600 steel, we would have a very cheap and simple solution to our problem. This idea could work because this is the material that is already inside the B-pillar

and we know that it can withstand the roof crush testing. By adding more low carbon steel, either by making the B-pillar more thick, or creating a reinforcement structure within the B-pillar, the material strength will increase.

## 6.2 Reinforcement Placement

Our next step of the design process is where to put our selected material. If we decide to use foam, we would fill the entire B-pillar cavity with the foam and some kind of carrier material. If we are to use the additional steel, we would create some kind of structure within the B-pillar, such as an I-beam, H-beam or an X-section. These concepts were generated and shown in the Morphological chart in Figure 4. Some of these designs can be seen in Section 7. This process will have to be checked by maximizing second moments of inertia, minimizing weight and checking the finite element analysis results, shown in Section 8.

## 6.3 Pugh Chart

We arrived at our top choice by using a Pugh chart. Figure 10 shows the chart.

Criteria	Weighting	Structural Foam	Aluminum Foam	Additional Steel
Minimize test load	9	+	+	+
Maximum allowable displacement	9	+	+	+
Low cost	3	-	-	+
Material weight	6	+	+	-
Reinforcement dimensions	1	-	-	+
Compatibility with assembly method	3	-	-	+
# of Reinforcements	1	-	-	+
Material strength	9	S	S	+
Total		16	16	29

**Figure 10: Pugh Chart**

As you can see above, the best choices from the criteria from our QFD, would be adding the additional steel in some kind of reinforcement structure. This is because all of this type of reinforcement minimizes the test load, maximizes the allowable displacement, and it is fairly easy to add to the existing structure. Also, out of all the other options, adding more steel to the existing structure is the cheapest alternative. From this step, we will use FEA to determine which design works best. We will still look at structural foam to see if the assumptions made in our Pugh chart is off. These results can be found in Section 8, which exhibits our engineering analysis.

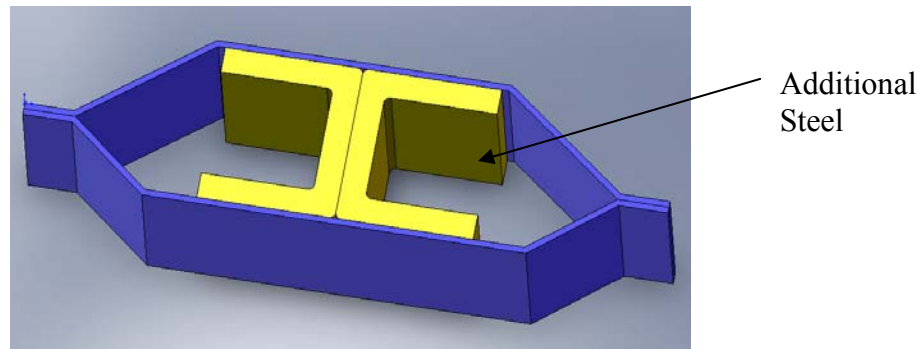
## 7 SELECTED CONCEPTS

Of all the possible design choices, our top ones all consisted of maintaining the existing B-pillar geometry. We decided to look at either using additional steel as a structural reinforcement or strategically placing polyurethane structural foam inside the B-pillar.

### 7.1 I-Beam

Our first design was just making a simple I-beam structure that would be spot welded inside the B-pillar. Figure 11 shows a drawing of this design. We found the optimal thickness of the material by maximizing the moment of inertia of the I-beam within the B-pillar. This design is our optimal design because it has the largest moment of inertia and it costs the least.

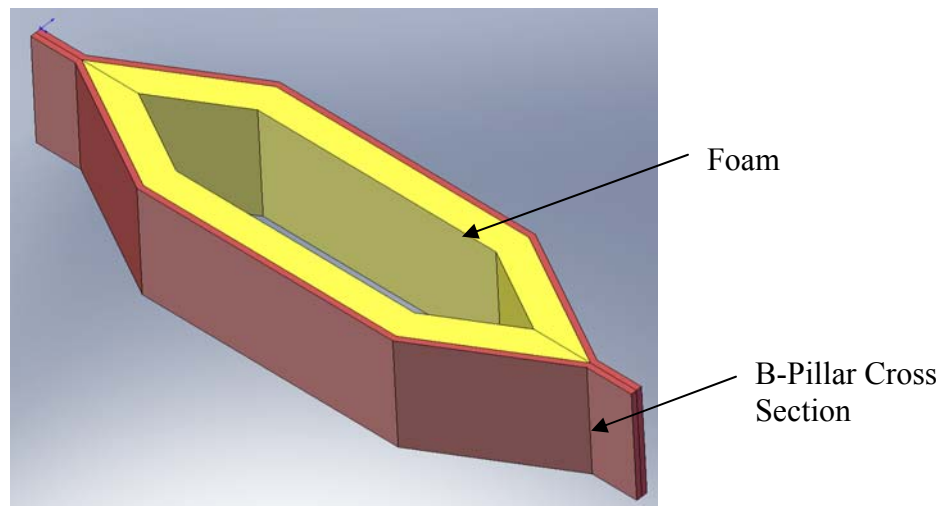
A dimensioned drawing of this design can be found in Appendix E. Our team decided to prototype this design.



**Figure 11: Concept Design #1**

### 7.2 Fill Cavity with Foam

The first design we looked at was filling the entire cavity with structural foam. Our team looked at either filling the entire cavity with foam or filling 50% of the cavity with foam. This concept increases the moment of inertia of the B-pillar, but also strengthens the joints where the spot welds are located. This is achieved by playing a layer of foam all around the inside of the B-pillar, as you can see in Figure 12. A dimensioned drawing of the cross section can be seen in Appendix D. The foam our team decided to use was BETAFOAM 87100, produced by Dow Chemical. The datasheet for this material can be found in Appendix F.



**Figure 12: Concept Design #2**

### 7.3 Fill Cavity with Foam and Nylon Carrier

Our final choice to reinforce the B-pillar is to find the location on the B-pillar where it first begins to fail and fill that area with a composite body solution that will help to delay failure in the weakest part of the B-pillar, and in turn help delay overall failure in the B-pillar structure during loading. Figure 13 displays this design. The carrier material, which is the material found in the middle of the cross section, is made out of nylon. A dimensioned drawing of this section can be found in Appendix G.

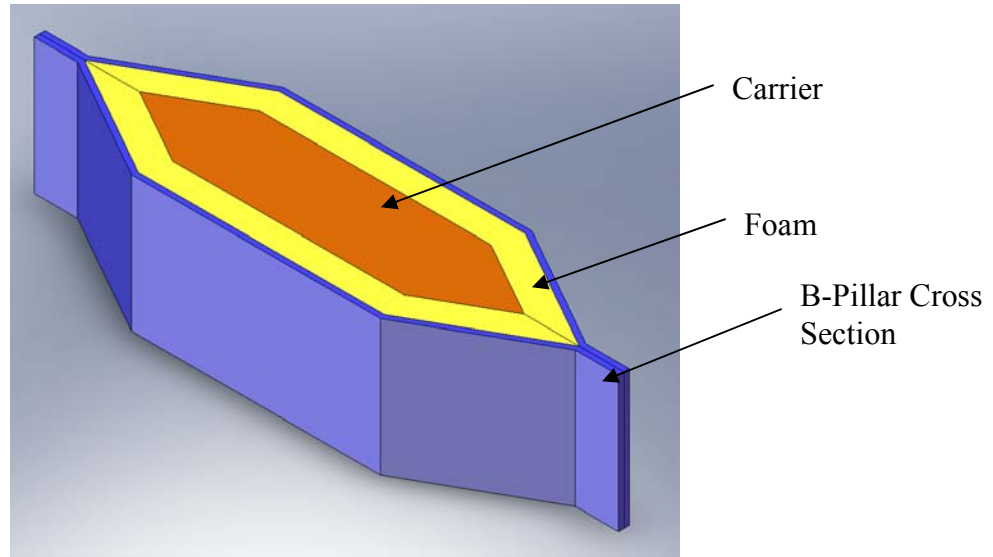


Figure 13: Concept Design #3

## 8 ENGINEERING ANALYSIS

For each selected concepts, we made the engineering analysis on the cross section focusing on the moment of inertia of the B-pillar, foam reinforcement, foam with nylon carrier reinforcement and metal reinforcement. We made the analysis based on the principal of statics and mechanics of materials in order to perform a parametric study of the moment of inertia ( $I$ ) for each reinforcement concept. The complete mathematical analysis is listed in Appendix J. The moment of inertia is crucial in determining the critical buckling load and optimizing the parameters of the design. We also created a finite element analysis model for stress, force and moment analysis.

### 8.1 Moment of Inertia of B-pillar

The analysis on the cross section of the simplified model of the B-pillar was done by first calculating the centroid because the outer and inner panels of the B-pillar are not symmetrical as shown in Figure 14.

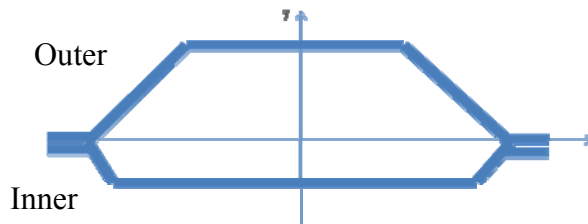


Figure 14: Cross section of the B-pillar

The centroid for the surface area of the B-pillar cross section was calculated by subdividing the area into differential elements  $dA$  and computing the moments of these area elements about each of the coordinate axis as shown as equations 3 and 4 [3].

$$\bar{x} = \frac{\int_A x dA}{\int_A dA} \quad (\text{Eq. 3})$$

$$\bar{y} = \frac{\int_A y dA}{\int_A dA} \quad (\text{Eq. 4})$$

Once the centroid was determined, we proceeded with the moment of inertia calculation by dividing the area into six rectangular parts. The B-pillar is a thin walled structure and the moment



of inertia of each part was determined by using the parallel-axis theorem about its centroidal axis as given by equations 5 and 6 [3].

$$I_x = \bar{I}_x + Ad_y^2 \quad (\text{Eq. 5})$$

$$I_y = \bar{I}_y + Ad_x^2 \quad (\text{Eq. 6})$$

Where  $A$  is the area of the part and  $\bar{I}$  is the moment of inertia. As you can see in equation 7 the moment of inertia of a rectangle is:

$$\bar{I} = \frac{1}{12}bh^3 \quad (\text{Eq. 7})$$

Where  $b$  is the base of the rectangle and  $h$  is the height. Also, as you can see in equation 8, the moment of inertia of a triangle is:

$$\bar{I} = \frac{1}{36}bh^3 \quad (\text{Eq. 8})$$

Where  $b$  is the base of the triangle and  $h$  is the height. In equations 5 and 6,  $d_y$  is the fixed distance between the parallel  $x$  and  $x'$  axes, and  $d_x$  is the fixed distance between the parallel  $y$  and  $y'$  axes. Then, the moment of inertia of the B-pillar was determined by summing the moment of inertia of the individual parts, yielding the total moment of inertia of  $I_x$  to be  $4.047\text{E-}07 \text{ m}^4$  and  $I_y$  to be  $5.452\text{E-}06 \text{ m}^4$ .

## 8.2 Moment of Inertia for Structural Foam Reinforcement

One of our concepts is to reinforce the B-pillar by filling the cavity with foam. We calculated the area of cavity by dividing it into four parts as shown in Figure 15. The calculated area is  $0.007 \text{ m}^2$ . Then the moment of inertia was calculated by using the parallel-axis theorem with Equation 5 and 6 for 100% foam. Once we have determined the  $I$  for 100%, the  $I$  for 50% foam was then calculated by subtracting the  $I$  of the rectangular hollow section that has 50% of the total area of the cavity as shown in Figure 16. The CAD models with dimensions of the B-pillar with foam reinforcement are shown in Appendix F and G.



Figure 15: 100% foam reinforcement

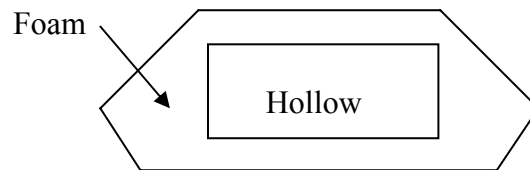
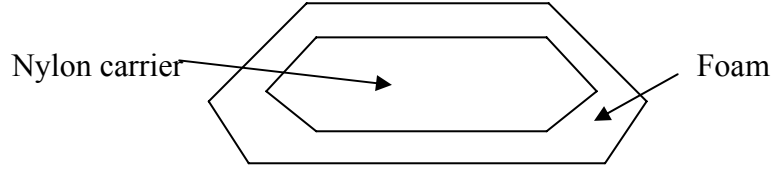


Figure 16: 50% foam reinforcement

The calculated moment of inertia for 100% foam is  $1.430\text{E-}06 \text{ m}^4$  for  $I_x$  and  $1.229\text{E-}05 \text{ m}^4$  for  $I_y$ . For 50% foam,  $I_x$  is  $8.189\text{E-}07 \text{ m}^4$  and  $I_y$  is  $1.037\text{E-}05 \text{ m}^4$ .

## 8.3 Moment of Inertia for Structural Foam with Nylon Carrier Reinforcement

Another concept is to reinforce the B-pillar by filling structural foam with a nylon carrier in the middle of the cavity. We first calculated the area that need to be filled with 70% nylon and 30% foam. Figure 17 shows the approximate shape of the foam with the nylon carrier. After determining the dimensions, we calculated the  $I$  for both foam and nylon by using the parallel-axis theorem based on the geometry. The CAD models with dimensions of the B-pillar with foam and nylon carrier reinforcement are shown in Appendix H.

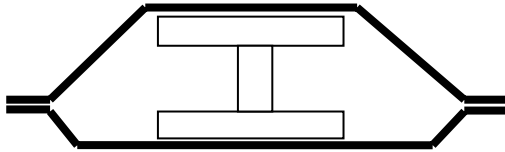


**Figure 17: Structural foam with nylon carrier reinforcement**

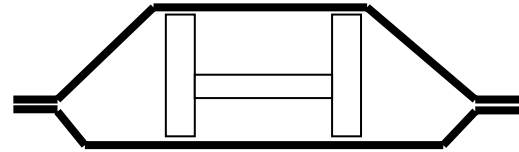
The calculated moment of inertia for 70% nylon carrier is  $8.432\text{E-}07 \text{ m}^4$  for  $I_x$  and  $5.274\text{E-}06 \text{ m}^4$  for  $I_y$ . For 30% foam,  $I_x$  is  $5.869\text{E-}07 \text{ m}^4$  and  $I_y$  is  $7.019\text{E-}06 \text{ m}^4$ . We performed similar analysis for the 80% nylon carrier and 20% foam. For 80% nylon, the moment of inertia was determined to be  $1.065\text{E-}06 \text{ m}^4$  for  $I_x$  and  $6.888\text{E-}06 \text{ m}^4$  for  $I_y$ . For 20% foam,  $I_x$  is  $3.655\text{E-}07 \text{ m}^4$  and  $I_y$  is  $5.405\text{E-}06 \text{ m}^4$ .

#### 8.4 Moment of Inertia for Metal Reinforcement

Based on the meeting with our sponsor, metal reinforcement can be a good solution to slow down the buckling of the B-pillar. We chose two different configurations which are I and H beams to be analyzed as shown in Figure 18 and 19. The 'M' and 'X' shaped reinforcements do not meet the requirement for the ease of manufacturing and assembly. For both I and H cross-sections, we calculated the thickness,  $t$ , of the beam that optimizes the moment of inertia. Then, the moment of inertia was calculated by using the parallel-axis theorem as given by equations 5 and 6. The thickness of the I and H beams were determined to be 4mm. The  $I_x$  is  $4.407\text{E-}07 \text{ m}^4$  and the  $I_y$  is  $4.878\text{E-}07 \text{ m}^4$  for the I beam based on the calculated thickness. The  $I_x$  is  $9.032\text{E-}08 \text{ m}^4$  and the  $I_y$  is  $9.239\text{E-}07 \text{ m}^4$  for the H beam. The CAD models with dimensions of the B-pillar with metal reinforcement are shown in Appendix E.



**Figure 18: I beam reinforcement**



**Figure 19: H beam reinforcement**

#### 8.5 Moment of Inertia for B-pillar with Reinforcement

In order to determine the total moment of inertia of the B-pillar with both foam and steel, we would need to know the flexural rigidity,  $EI$ , of the B-pillar. This comes from the following equation

$$\frac{1}{\rho} = \frac{M}{EI} \quad (\text{Eq. 9})$$

Where  $\rho$  is the radius of curvature,  $M$  is the internal moment in the beam,  $E$  is the material's modulus of elasticity and  $I$  is the beam's moment of inertia. This equation is proved by the procedure found in Appendix K[3]. For our case, we will sum the elastic modulus and moment of inertia for each separate material found in the B-pillar to find the total flexural rigidity.

We calculated the total moment of inertia by using the derived equation from stress-strain relationship for different material with different modulus of elasticity ( $E$ ) as given by Equation 10.

$$E_{\text{total}}I_{\text{total}} = E_1I_1 + E_2I_2 + E_3I_3 \quad (\text{Eq. 10})$$

By using the derived formula, we calculated the moment of inertia of the B-pillar with each reinforcement and the results are shown in Table 2.

	<b>I<sub>x</sub>(E-07m<sup>4</sup>)</b>	<b>I<sub>y</sub> (m<sup>4</sup>)</b>	<b>E*I<sub>x</sub>(Pa*m<sup>4</sup>)</b>	<b>E*I<sub>y</sub>(Pa*m<sup>4</sup>)</b>	<b>Increase in I<sub>x</sub> %</b>
B-pillar	4.047E-07	5.452E-06	8.498E+04	1.145E+06	-
with 100% foam	4.095E-07	5.484E-06	8.641E+04	1.157E+06	1.20
with 50% foam	4.066E-07	5.475E-06	8.580E+04	1.155E+06	0.49
with 70%carrier,30%foam	4.117E-07	5.457E-06	8.810E+04	1.168E+06	1.73
with 80%carrier,20%foam	4.137E-07	5.472E-06	8.854E+04	1.171E+06	2.24
with I-Beam	8.454E-07	5.940E-06	1.775E+05	1.247E+06	108.91
with H-Beam	4.950E-07	6.376E-06	1.039E+05	1.339E+06	22.32

**Table 2: Moment of Inertia of the B-pillar with reinforcement**

Note that the foam and foam with nylon have smaller moment of inertia compared to the metal reinforcement due to the values of  $E$  of foam and nylon are much smaller than that of the steel. The H-beam has a lower moment of inertia compared to the I-beam with the same thickness.

## 8.6 Critical Buckling Load

Buckling occurs about the principal axis of the cross section having the least moment of inertia (the weakest axis) [3] which is along the x-axis for the B-pillar. To calculate the critical loads causing the B-pillar to buckle in the elastic region, we used Equation 11 called Euler buckling equation

$$P_{cr} = \frac{\pi^2 EI}{(L_e)^2} \quad (\text{Eq. 11})$$

Where  $P_{cr}$  is the critical maximum axial load on the column just before it begins to buckle,  $E$  is the modulus of elasticity of the material,  $I$  is the moment of inertia of the column's cross sectional area and  $L_e$  is the effective length of the column ( $0.5 \times \text{Length}$  for fixed ends). By using the  $E$  and the calculated  $I$  for each reinforcement, we were able to calculate the  $P_{cr}$  as listed in Table 3.

	<b>P<sub>crx</sub> (N)</b>	<b>P<sub>cry</sub> (N)</b>	<b>P<sub>crx</sub> (lbf)</b>	<b>P<sub>cry</sub> (lbf)</b>	<b>Increase in P<sub>crx</sub> %</b>
B-pillar	1.636E+06	2.205E+07	3.679E+05	4.956E+06	-
with 100% foam	1.664E+06	2.228E+07	3.741E+05	5.009E+06	1.68
with 50% foam	1.652E+06	2.225E+07	3.714E+05	5.001E+06	0.96
with 70%carrier,30%foam	1.697E+06	2.249E+07	3.814E+05	5.055E+06	3.67
with 80%carrier,20%foam	1.705E+06	2.255E+07	3.833E+05	5.069E+06	4.19
with I-Beam	3.419E+06	2.402E+07	7.686E+05	5.400E+06	108.91
with H-Beam	2.002E+06	2.578E+07	4.500E+05	5.796E+06	22.32

**Table 3: The critical load for B-pillar buckling in x-axis and y-axis for the elastic region.**

We used the elastic buckling, in order to estimate the what would happen in the plastic region. However, there are some methods in order to estimate plastic buckling. We can modify the Euler equation above, in order to incorporate inelastic buckling, by substituting the material's tangent modulus  $E_t$  for  $E$ . The tangent modulus is the material's Young's modulus during the plastic region of the stress-strain curve. Therefore the Euler equation becomes Equation 12 [3]:

$$\sigma_{cr} = \frac{\pi^2 E_t}{(L_e / r)^2} \quad (\text{Eq. 12})$$

Where  $r$  is the radius of gyration, which is Equation 13:

$$r = \sqrt{\frac{I}{A}} \quad (\text{Eq. 13})$$

We would need more time for the project, as well as a better understanding of the material in order to calculate a full plastic region stress analysis. Further analysis needs to be done to examine the plastic collapse characteristics of the B-pillar.

### 8.7 Weight and Cost Analysis

Based on information from our sponsor we chose two companies in order to supply us with the material we need. For our steel reinforcement, we are going to be purchasing from Arcelor-Mittal. For the foam reinforcement, we are going to be purchasing the structural foam from Dow Chemical and the nylon carrier insert from Permacel Automotive.

Analysis on the weight of material used for the reinforcement was done in order to fulfill the lightweight requirement for our design. We calculated the mass per unit length by multiplying the density of the material with the cross-sectional area by using Equation 14.

$$\text{density, } \rho = \frac{\text{mass}}{\text{Area} \times \text{unit length}} \quad (\text{Eq. 14})$$

The density and the mass of the reinforcement are listed in Table 4.

Material	Density (g/cc)	Density (g/m <sup>3</sup> )	Reinforcement	Mass/unit length(kg/m)
Steel	7.87	0.0053	100% Foam	4.315
Foam	0.6	0.0029	50% Foam	2.157
Nylon	1.17	0.000066	70% Nylon, 30% Foam	7.184
			80% Nylon, 20% Foam	7.594
			I-beam	8.310
			H-beam	5.729

**Table 4: Density of materials and mass of reinforcement per unit length.**

After determining the mass, we calculated the cost for each type of reinforcement for a unit length. Table 5 shows the cost of material and the cost for each reinforcement type.

Material	Cost (\$/lb)	Cost (\$/g)	Reinforcement	Cost/unit length(\$/m)
Steel	1.0	0.0022	100% Foam	22.83
Foam	2.4	0.0053	50% Foam	11.42
Nylon	1.3	0.0029	70% Nylon, 30% Foam	23.73
			80% Nylon, 20% Foam	23.86
			I-beam	18.32
			H-beam	12.63

**Table 5: Cost of materials and cost of reinforcement per unit length.**

The cost for the I beam is the lowest because the steel is the cheapest material and the weight of the reinforcement for the I beam is lower than that of the H beam.

### 8.8 I-beam Thickness Analysis

For the I-beam that will be designed, the moment of inertia, critical load, weight and cost are greatly dependent on the thickness of the I-beam. As shown in Table 6, the increase in thickness will increase the moment of inertia and of course will increase the weight and cost too. We chose

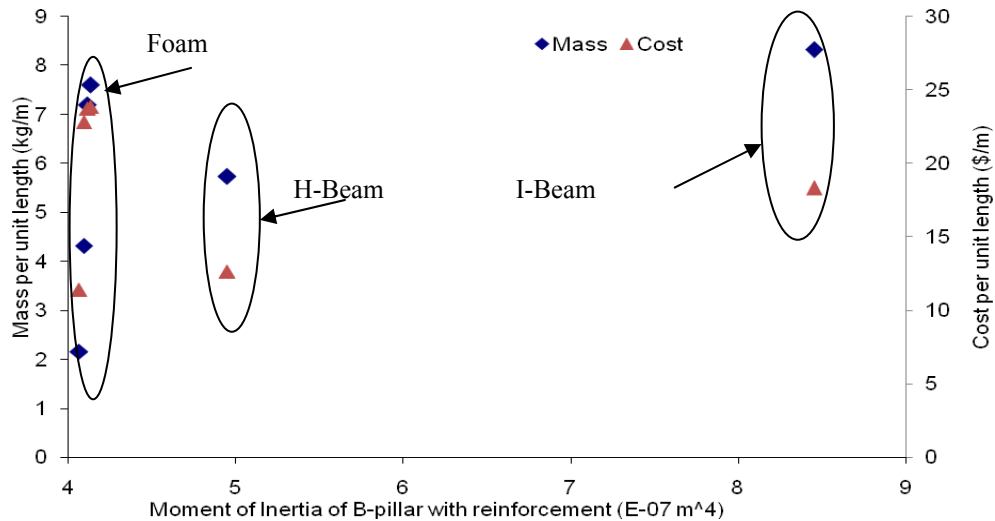
the I-beam with 5/32 inches thick because it gives more than 100% increase in moment of inertia,  $I_x$ .

Thickness (in)	Thickness (mm)	$I_x$ (mm <sup>4</sup> )	Increase in $I_x$ (%)	Weight (kg/m)	Cost (\$/m)
1/16	1.59	6.032E-07	49.07	3.42	7.54
1/8	3.18	7.701E-07	90.29	6.68	14.72
5/32	3.97	8.427E-07	108.24	8.25	18.19
3/16	4.76	9.087E-07	124.55	9.78	21.56

**Table 6: The moment of inertia, weight and cost of the I-beam according to the thickness.**

### 8.9 Optimization

By plotting the mass against the moment of inertia of the different reinforcements and the cost against the moment of inertia of the reinforcement, we were able to determine the optimize reinforcement type. As shown in Figure 20, even though the foam reinforcement is the lightest in weight, it is more expensive and has a lower moment of inertia than that of the metal reinforcement. Both the H-beam and the I-beam are low in cost and have a high moment of inertia. However, the reason why the H-beam has a higher moment of inertia is because it is thicker, which in turn causes it to have a higher mass per unit length. Since it has a higher mass per unit length, it will be more costly, when compared to the I-beam structure. Therefore, our team chose to go with the I-beam structure because it will fulfill the requirement for both a low cost material, as well as having a high moment of inertia.



**Figure 20: Optimization of the reinforcement selection.**

### 8.10 Design for Manufacturing and Assembly (DFMA)

For the design that we selected, we need to design it so that it follows the design for manufacturing and assembly guidelines. The purposes of following the guidelines is for the ease of manufacturing and the ease of assembly to optimize all the manufacturing functions and to assure the best cost, quality, reliability, regulatory compliance, safety, time-to-market, and customer satisfaction. Table 7 shows the DFMA for the selected concepts.

Concepts	Guidelines	Changes to design
Metal reinforcement	Minimize part counts	Reduce from three parts to two 'C' sections I beam
	Standardize to reduce part variety	Use standard steel thickness (5/32 inch) [2]
	Maximize part symmetry	Both 'C' sections are symmetrical
	Part insertion	Welding and assembly in one orientation.
	Avoid sharp corners	$R=3/8 t \geq 0.06$ inch
Foam and carrier reinforcement	The guidelines are provided by the supplier for foam and nylon insertion	

**Table 7: DFMA for metal, foam and nylon reinforcement.**

### 8.11 Failure Mode and Effects Analysis (FMEA)

The purpose of an FMEA is to look for potential failures, find the effect of those failures and then design preventive actions. Our team optimized our design in order to combat our failure modes. The part that fails in our design is the B-pillar. The major goal of our project was to optimize the reinforcement in order to combat the failure modes during the FMVSS 216 test. The two failure modes are yielding and buckling. The reason why the B-pillar yields is because the B-pillar reaches its yield strength during the test. The B-pillar also buckles because the forces applied causes a bending moment. Our project introduced a structural reinforcement in order to increase the time until both yielding and buckling. The entire FMEA analysis can be found in Appendix I.

### 8.12 Design for Environment (DfE)

In today's climate of pollution and other environmental harm, new designs and their designers need to take into account the design's effect on the environment. This is called DfE or design for environment. Even though our project has limited possibilities for DfE, we still took this into consideration when designing our prototype. We considered physical optimization, optimization of material use, optimization of distribution, reducing impact during use, and optimization of end-of-life systems. Any design we choose is in effect a physical optimization, as we are adding a reinforcement the will increase the effectiveness and lifetime of the B-pillar. Material use is being minimized in the I-beam design. Also, the steel in the reinforcement can be recycled once the automobile is no longer useful. Using the I-beam as our final design optimizes distribution, since the I-beam would be manufactured in house and wouldn't require transportation. Whereas if the foam reinforcement is used, it would likely be manufactured by a secondary company shipped the production plants. This increases pollution because of transportation and there will be pollution from the manufacturing process of the foam. Since we will be adding reinforcement to a localized area rather than the entire pillar, weight will be reduced as well as energy consumption. Finally, adding a steel reinforcement made of the same material as the pillar is a good design for disassembly, since the steel will all be the same. Recycling would be simple, with no disassembly necessary. If the foam reinforcement was added, it would need to be removed before the steel could be recycled. This would add another step in the recycling process.

## 9 FINAL DESIGN

Finding a solution to our problem involved generating many ideas, eventually narrowing them down to one. Using engineering analysis of buckling modes and moments of inertia we came up with two concepts of pillar reinforcement: an internal I-beam reinforcement and an internal foam reinforcement with nylon carrier. Optimizing the moment of inertia as well as minimizing cost, we found the best reinforcement design for roof crush resistance to be the internal I-beam, as you can see in Section 8.8.

When choosing our final design, we also spoke with our sponsors and used their experience in making our decision. When speaking with them we learned that they have experienced issues with the application of structural foam in their automobiles. When baking the foam to cause it to expand, there have been issues with continuity between individual pillars. This is important since Ford wants all their pillars to be standardized, resisting the same force and having the same properties. When using structural foam, after the baking process, it is difficult to get every pillar to be exactly the same, either because of the placement of the foam and carrier or because of different expansion during the baking process. Also once the foam is baked, it is difficult to tell what position the foam ended up in. This information became another good reason to choose the I-beam as our final design as we can ensure that every pillar will come out almost exactly the same.

### 9.1 I-Beam

From our analysis of moments of inertia and buckling modes we found the I-beam to be the best to resist buckling. Since Ford already stamps most of its steel parts, adding a new stamping process for the I-beam reinforcement would be simple. Implementing the reinforcement into the current B-pillar would also be simple. A small side-loop would be added to the production line which will allow for fastening of the I-beam reinforcement into the pillar which will be explained in more detail in section 10.3. Also material cost is much lower for steel rather than structural foam with a nylon carrier (Table 5). Where the steel beam fails is in its material weight. The foam with nylon carrier would potentially have a much lower weight. However looking at cost and ease of manufacturing, it is much more advantages to use the steel I-beam for reinforcement.

Figure 21 shows a cross-section of the I-beam reinforcement with measurements. The beam will be constructed out of HSLA steel, with a thickness of 5/32 inches, which has the best strength to cost ratio as well is also commonly used in the production of the trucks.

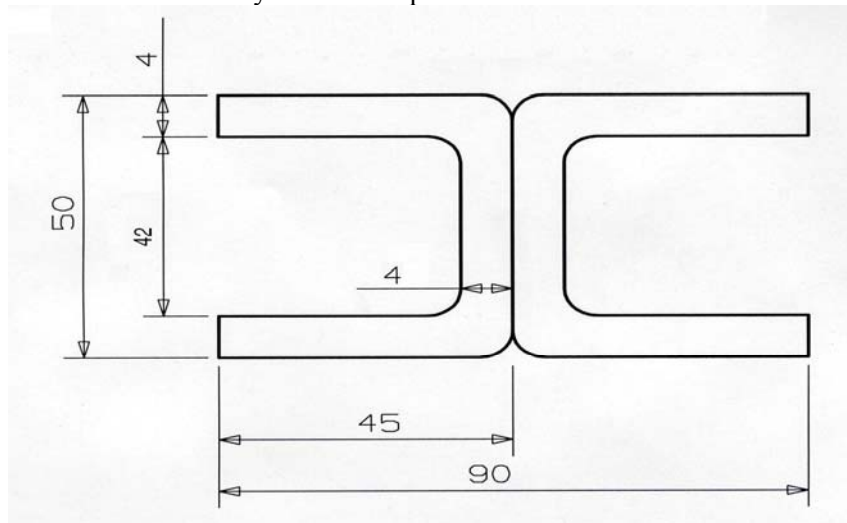


Figure 21: Engineering Drawing of I-Beam Cross-Section

## 9.2 Prototype

Since the actual B-pillar has a complex bend to its shape, creating a prototype that would be identical to the production model would involve building a die and stamping out the I-beam. Since this isn't feasible for us we decided to modify the production design to allow us to create a mock up I-beam. Figure 22 shows a CAD drawing of our mockup design. As you can see, it consists of two I-beams welded at a 15° angle, which is the average angle of curvature in the B-pillar. The length of the beam from bend to top will be 100mm where as the bottom section will be 150mm in length. We will also have the virtual model used for the FEA as a virtual prototype.

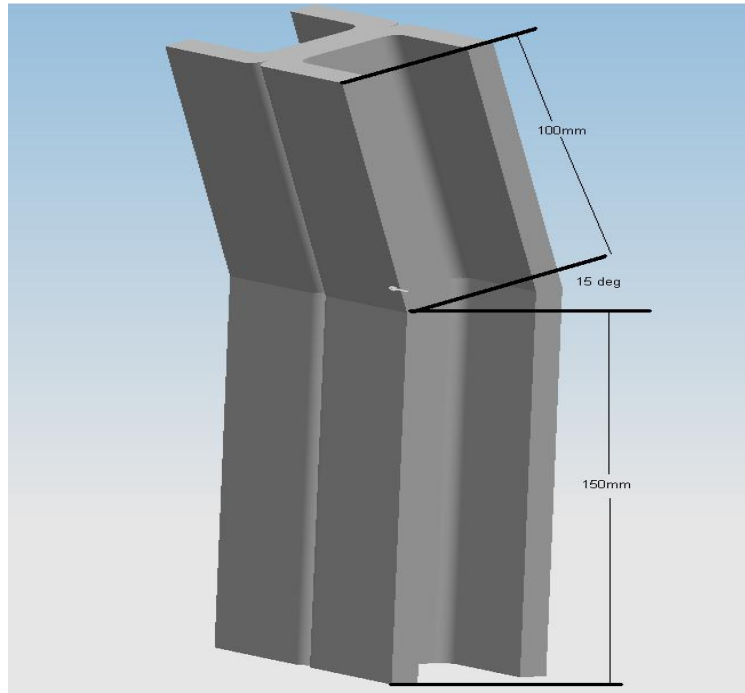


Figure 22: CAD drawing of prototype with lengths

## 9.3 Bill of Materials

Our team came up with a bill of materials for our prototype. The prototype was made out of a standard HSLA steel sheet, that is 5/32 inches thick. Table 8 shows the bill of materials.

Quantity	Part Description	Purchased From	Part Number	Price (each)
1	steel sheet (5/32") - HSLA	Arcelor Mittal	N/A	\$1.00/lb

Table 8: Bill of Materials

## 10 MANUFACTURING AND TESTING

Our project required us to create a virtual test bench, as well as future manufacturing plans for mass production of our reinforcement design. Also, for our design expo we manufactured a mock-up prototype of the I-beam reinforcement.



## 10.1 Mock-Up Production

The prototype B-pillar we will create is intended for display purposes only, and not for any type of physical testing. We have received a pair of B-pillars from our sponsor at Ford, and kept one completely assembled to show expo attendees what a B-pillar looks like. We disassembled the second one to help demonstrate a physical representation of our final design within an actual B-pillar. For construction, we will be using the disassembled B-pillar along with scrap steel found at the Wilson Student Team Project Center. We took two pieces of steel, bent them into two C-sections and welded the two C-sections together to form an I-beam. This process was done twice for both the upper and lower section of the I-beam. We then welded the two I-beams together at a 15° angle. All welding and disassembling was done at the Wilson Student Team Project Center. Figure 23 shows a picture of our mock-up prototype. Our team didn't make a die for the prototype in the machine shop because we were limited by time, as well as inadequate facilities.

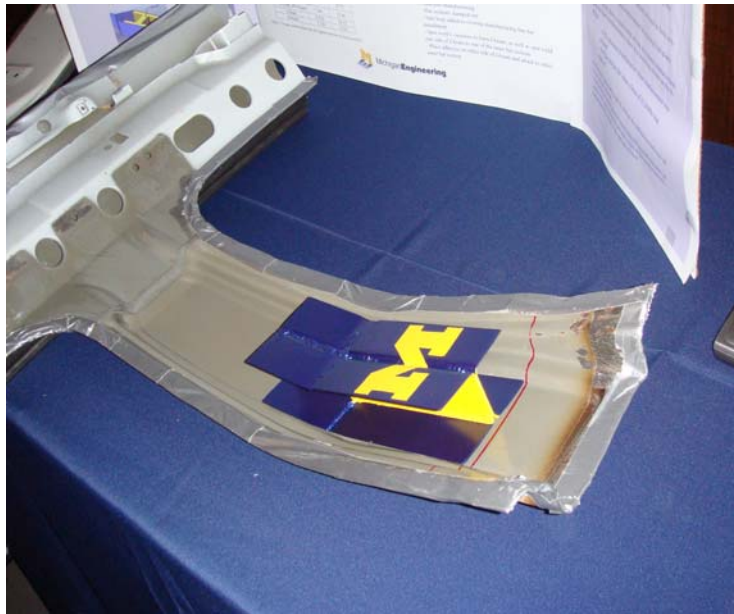
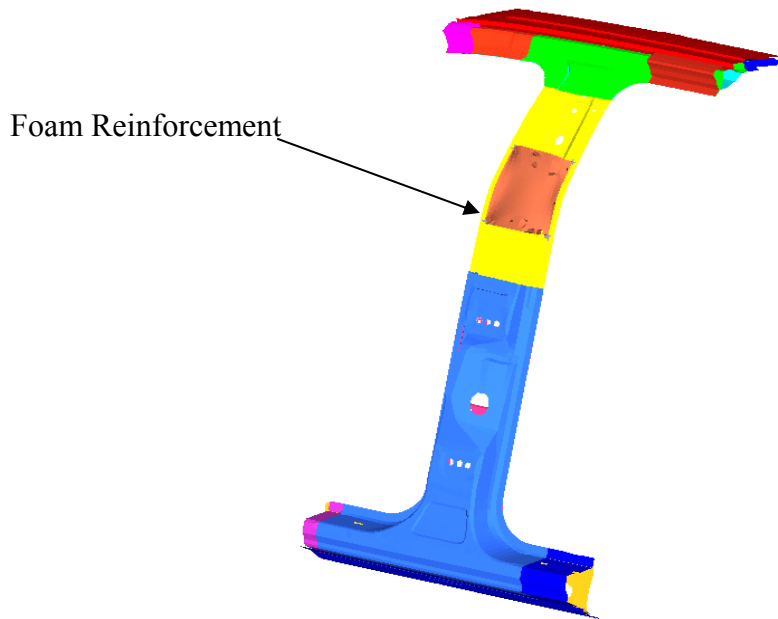


Figure 23: Mock-up prototype attached to B-Pillar

## 10.2 Virtual Testing

For actual testing purposes, we took an FEA model provided by Ford and applied our reinforcement ideas into this model using Altair's Hypermesh package. The tests that were run on our virtual test model are the same that are run on other virtual models of B-pillars designed to withstand the FMVSS-216 test, mainly a distributed load was placed at an angle on the top of the B-pillar, increasing in load until the B-pillar deforms to the maximum allowable distance required for passing. It is this test data that we analyzed to ensure that our design meets the project criteria. Figure 24 shows the Hyper Mesh drawing of the foam reinforcement, one of the reinforcement ideas that we will be testing.

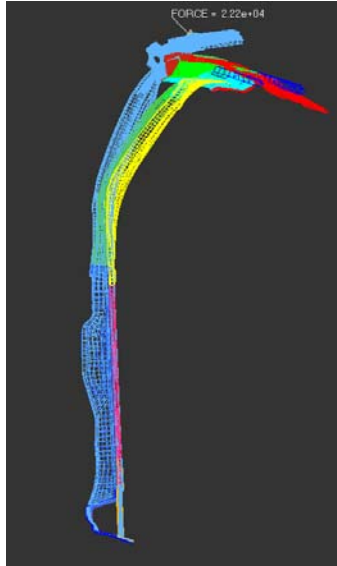


**Figure 24: Hyper Mesh drawing of foam**

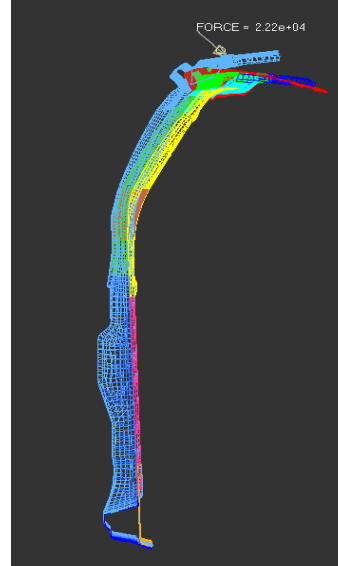
### **10.2.1 Finite Element Analysis**

Since it would take too much money and time to actually create a functional prototype to test in life like conditions, our team opted to use Altair's Hypermesh FEA package to test the resultant deformation of our B-Pillar with, and without the I-Beam reinforcement under test loads. Using the Hypermesh geometry of the B-Pillar provided to us by our contact at Ford, we created two different set-ups of the test. The first test we ran was without any kind of reinforcement within the B-Pillar, placing a load of 5,000lbs on top of the B-Pillar and noting the resulting deformation. The next test we ran was with the I-Beam reinforcement inside the B-Pillar, loading it again with 5,000lbs and again noting the deformation. Comparing the two values, we found that the B-Pillar with the reinforcement deformed 42.2% less than the B-Pillar without the reinforcement. This percentage in displacement was calculated using the Y-displacement component of the B-Pillar, with positive Y point in towards the passenger. This component of the displacement was used because this displacement orientation would be the one that would have the most directed impact on the B-Pillar during testing, taking into account the position of the plate.

One of the main issues that arose with the testing was the actual application of the test conditions using the model provided. The geometry provided from Ford only the B-Pillar itself: having no defined material properties within the model, and none of the surrounding structures of the car. We fixed the material property issue by using data provided to us by Ford of the steel used within the B-Pillar. The issue of simulating the rest of the car around the B-Pillar was a bit more difficult to solve. We ended up constraining the degrees of freedom of sections of the B-Pillar to simulate a structure there that would prevent movement and deformation. A secondary issue that needed to be addressed was the fact that during loading, Hypermesh couldn't properly simulate plastic deformation within the beam. Because of this fact, we opted to compare deformation data from the B-Pillar tests, giving us an estimate of the effects of the reinforcement on the B-Pillar deformation. Figures 25 and 26 show the deformation in the computer software used. Appendix L shows the data obtained from the FEA model.



**Fig 25: Deformation of B-Pillar without reinforcement**



**Fig 26: Deformation of B-Pillar with reinforcement**

### 10.3 Mass Production Manufacturing

Our prototype is intended for mass production for all F-150 Crew Cab vehicles. The overall manufacturing of the B-pillar itself will change little. The hat sections of the B-pillar will still be stamped out in the same way, but there will be an added ‘side-loop’ to the manufacturing line intended to be used to install our reinforcement. This loop will contain a separate area used for spot welding our I-beam sections together, and then spot welding them into the outer hat section. When this spot welding is completed, a layer of adhesive will be applied to the other flange of the I-beam. Once this process is completed, this hat section will then be passed back into the original B-pillar manufacturing loop, where the outer hat will then be spot welded to the inner hat sections, and the adhesive covered flange of the I-beam will be pressed firmly against the inner hat section. This completed B-pillar will be passed down the line and installed into the rest of the vehicle body.

Our prototype will not harm anyone. It will only increase the safety of the passenger. However, our prototype will increase the cost of the car. Our team felt that this increase in cost was a necessity because the company will save money in the long run by not paying out law settlements and initiating recalls.

## 11 DISCUSSION FOR FUTURE IMPROVEMENTS

Our project performed very well under the testing conditions designed for us by Ford. The I-beam design is low cost, can withstand a large load and it is easy to manufacture. As you can see in the testing analysis in section 10.2.1, the I-beam performed very well when subjected to a testing load. A major weakness of the design is that it is heavier than the other design concepts our team came up with. The foam was 7.6 kg/m, while the I-beam weighed 8.3 kg/m. Our team thought that minimizing cost and minimizing displacement was more important than minimizing weight. Also, the weight differences weren’t that significant. A small modification we would make to the I-beam would be that it perfectly conforms to the body of the B-Pillar. Our I-beam prototype was just a mock-up in the sense that it didn’t perfectly fit into the B-Pillar. The design was very simple, so if this project is continued, we would recommend that the next team make the design a little more complex.

We also recommend researching a little more into the foam reinforcement. We were scared away from it because we weren't sure if it would cook fully in the B-Pillar. If that can be harnessed and one can find a way to allow the foam to be evenly distributed inside the B-Pillar, it would definitely be a great alternative to steel.

Ford can definitely take this technology and integrate it into their current manufacturing plans. The I-beam will save lives and it will allow the car to pass the new FMVSS 216 testing. It will make the car a little heavier. However that increased weight will offset the costs Ford would have to pay if people are killed in roll-over accidents. This technology can only help the auto industry because money will be saved from existing law suits.

Future teams should look at ways to determine the plastic deformation of the B-Pillar. The term wasn't long enough for us to look at both elastic and plastic, so we just looked at elastic. Not to mention, our course load at the University doesn't teach us about plastic deformation. That subject is taught at a graduate level. However if a team focused solely on plastic, testing could be done in an FEA model and plastic deformation data could be found. Future teams should also look at different types of redesigns. One could take sheets of foam and use that as reinforcement. Also, maybe teams should look at changing the geometry of the B-Pillar. We were told by Ford not to look in that direction. However, if a team's job is to design the entire body of the car, they should definitely look at different geometry's of B-Pillars in order to maximize the moments of inertia to increase the force that it can withstand.

## **12 PROJECT PLAN**

A well thought out schedule is very important to the success of this project because there are many steps and goals in the design process. There has been a timeline set by our project coordinators in order to meet these goals. In order to keep on schedule, our team constructed a Gantt chart, as seen in Figure 27.

### **12.1 Gantt Chart**

The Gantt chart includes the major dates in the design process, from the beginning of the project, to the end. This includes the four design reviews, the design expo, as well as the final report. The Gantt chart is also used to keep track of holiday dates and dates when group members will be unavailable.

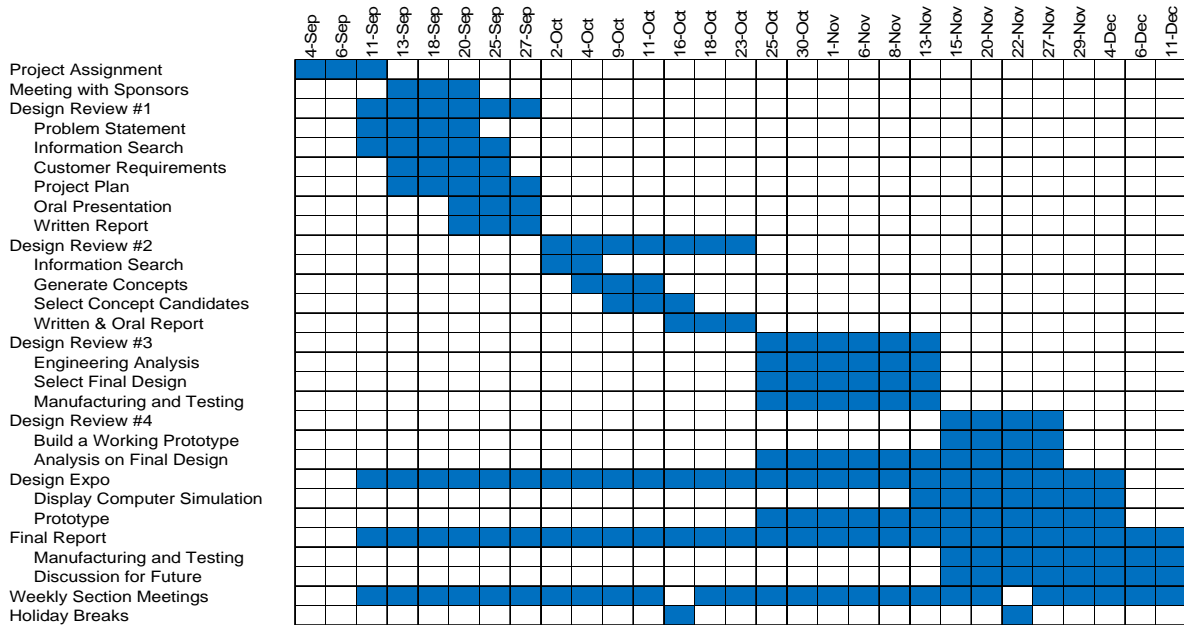


Figure 27: Gantt Chart

Early tasks for this project involve generating new ideas for the reinforcement of the B-pillar. After designing several possible solutions, we will need to analyze each model using finite element analysis and non-linear system analysis. Once a solution is chosen, we will need to create our design in the virtual world using a CAD software program. After developing our design, we developed a virtual test bench to test the performance of the B-Pillar in a virtual roof crush. This testing was done by creating a FEA model and testing the design in Hypermesh. We then created a mock-up of the I-beam design to show at the design expo. Our team met all goals laid out by the Gantt chart.

### 13 CONCLUSIONS

Our team has been requested to design the central pillar reinforcement for the Ford F-Series Crew Cab to improve its resistance to roof crush during rollover accidents. The purpose of the new design is to fulfill the new FMVSS 216 criteria and minimize the weight and cost at the same time. We did an information search to obtain a better understanding of the physical structure of the B-pillar and identify the problems related to rollover accidents through experts from Ford, professors, research papers and reliable websites. One major problem to the current design is buckling at the door latch or striker area on the B-pillar. Our reinforcement will help to slow down the buckling and allow the B-pillar to withstand larger loads.

By generating the ideas and evaluating each design concepts, we conducted a parametric study to make comparison between the foam, foam and nylon, I-beam and H-beam reinforcements based on their cross-sectional moment of inertia, critical buckling load, cost and weight. Based on our engineering analysis on the elastic deformation, we determined that the I-beam reinforcement will increase the moment of inertia and critical buckling load by 108%. Also, it reduces the deformation by 42% as the test was conducted in the FEA software. We can conclude for these results that the new design will be able to withstand the new FMVSS 216 testing criteria. For the design expo, our mock-up prototype was made by welding two C-sections steel with a thickness of 5/32 inches to form an I-beam. For large scale manufacturing, the I-beams will be stamped out and then spot welded to one side of the inner hat section of the B-pillar and will be connected to the other side by an adhesive.

In the future, we expect further analysis on the inelastic deformation will be done on the B-pillar with the reinforcement. Future teams could also do more research on the foam reinforcement to see if it is in fact a more viable option compared to the steel reinforcement. Also, an actual test could be conducted to determine the performance of the reinforcement when is attached to the vehicle.

## 14 ACKNOWLEDGEMENTS

We would like to thank the following people for their input and help on this project:

Jwo Pan, Professor, Department of Mechanical Engineering  
Shawn Morgans, Body Structure Technical Leader, Ford Motor Company  
Dr. Darrell Kleinke, University of Michigan, Ford Motor Company  
Michael Lee, Wilson Center, University of Michigan

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## **16 PROJECT TEAM BIOGRAPHIES**

### **16.1 Thor Fraser**

Thor Fraser was born and raised in the Washington, DC area, specifically College Park, MD. During his high school years he played at the position of center and defensive tackle for High Point High School's football team, was a member of the National Honor Society, and was a member of several student groups. During this time he became increasingly interested in math and science, and in particular the application of these two subjects towards developing things to further humankind. So when it came time to enroll in Michigan, Mechanical Engineering seemed a logical choice for his major. After Michigan, Thor hopes to find a position with a company on the west coast utilizing his interests in statics and properties of materials.

### **16.2 Darren Goldenberg**

Darren is from Jericho, NY. He is majoring in mechanical engineering, with a minor in economics. Prior coming to Michigan he was a three sport athlete at Jericho High School, where he was the treasurer of the National Honor Society, as well as Homecoming King of his senior class. Standing at 5'7" and 170lbs his senior year, Darren was the starting right guard on his high school's football team, where was elected as the most improved player at the end of the season. He decided to pursue mechanical engineering because his strongest subjects were math and science, and he always had a strong interest in designing and building objects. During his spare time, he is devoted to Michigan football and the New York Mets. His hobbies include playing IM sports, as well as researching about the history of college athletics. Darren claims to know everything about the history of football. Upon graduation, he plans on getting a job in a large manufacturing company, and then going to business school to get an MBA. He eventually wants to work for a consulting company.

### **16.3 Muhammad Yazid Mat Isa**

He is originally from Serdang, located just south of Kuala Lumpur, Malaysia. His interest in engineering was inspired by his father who is currently working in the electrical engineering field. He went to boarding school from the 7<sup>th</sup> to the 11<sup>th</sup> grade focusing in engineering and science subjects. Being well rounded in academics and extracurricular activities, he was then accepted to Petronas University of Technology and sponsored by Petronas Oil and Gas Company. After finishing his first semester, he was awarded a scholarship by the Government of Malaysia to pursue mechanical engineering in the United States. He chose the University of Michigan, as it is one of the best engineering schools in the U.S. He enjoys spending his free time playing soccer and tennis. He also enjoys traveling during school breaks and snowboarding during the winter. For his career goals, he hopes to gain working experience in automotive design or in the oil and gas industry either in the United States or Malaysia. If possible, he would like to pursue a master's degree.

### **16.4 Alex Steinhauser**

Alex, originally from Sterling Heights, MI, is majoring in mechanical engineering at the University of Michigan. Alex attended Warren Mott High School as well as the Macomb Mathematics, Science, and Technology Center for four years where in his senior year he was the captain of both the varsity golf and varsity tennis team. He was also a three-year member of the National Honor Society. Alex's love of design began when he was young playing with Lego. As he got older he enjoyed disassembling broken toys as well as building remote control cars. This, teamed with his preference towards math and science, drove him to attend the school of

engineering, and major in mechanical engineering. Alex plans to graduate with his degree in engineering and work in the automotive industry. He then plans to attend business school to receive his MBA, and eventually work for himself or a small consulting firm.



APPENDIX A: FMVSS 216 Diagram

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49 CFR Ch. V (10-1-04 Edition)

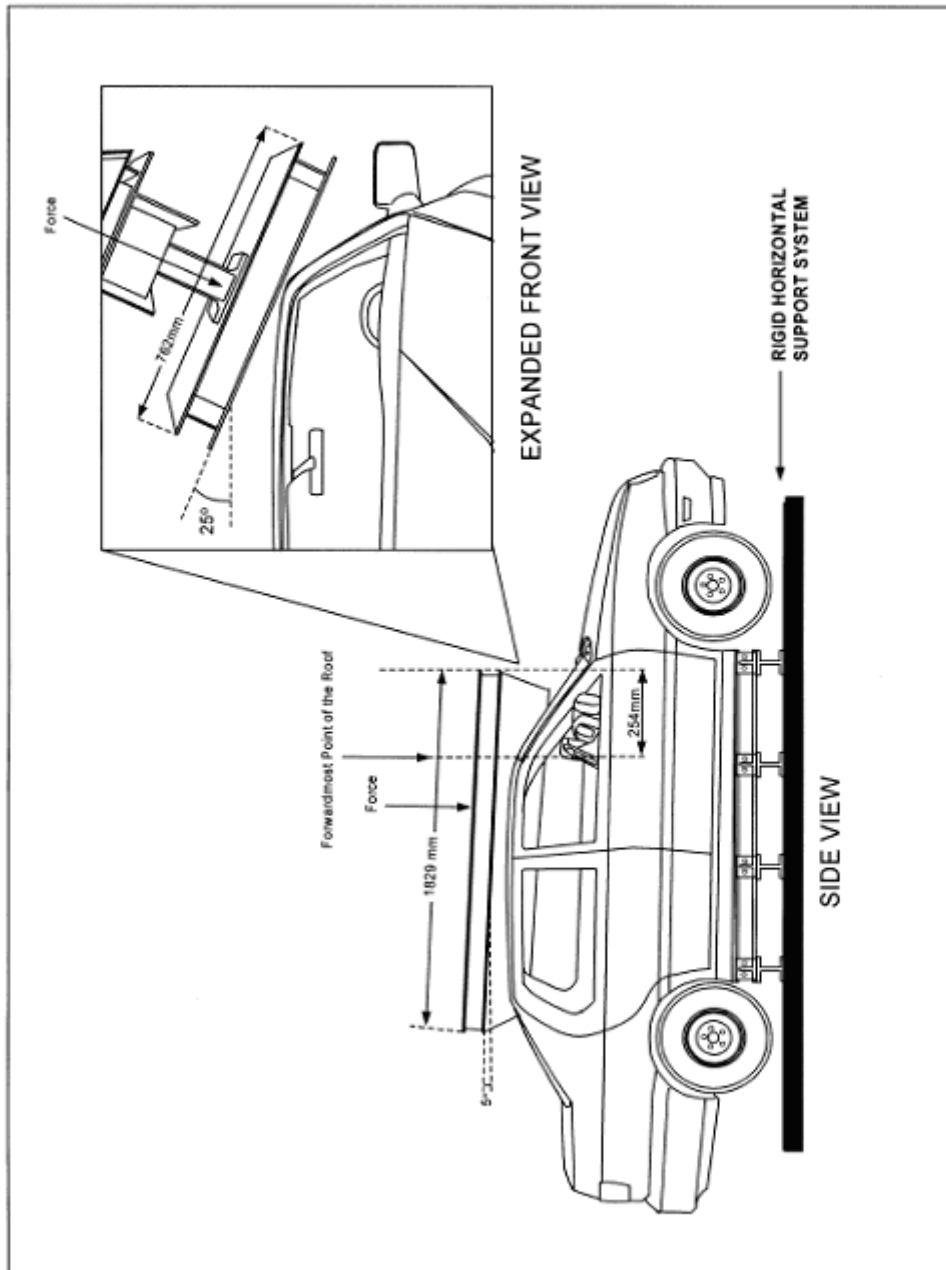
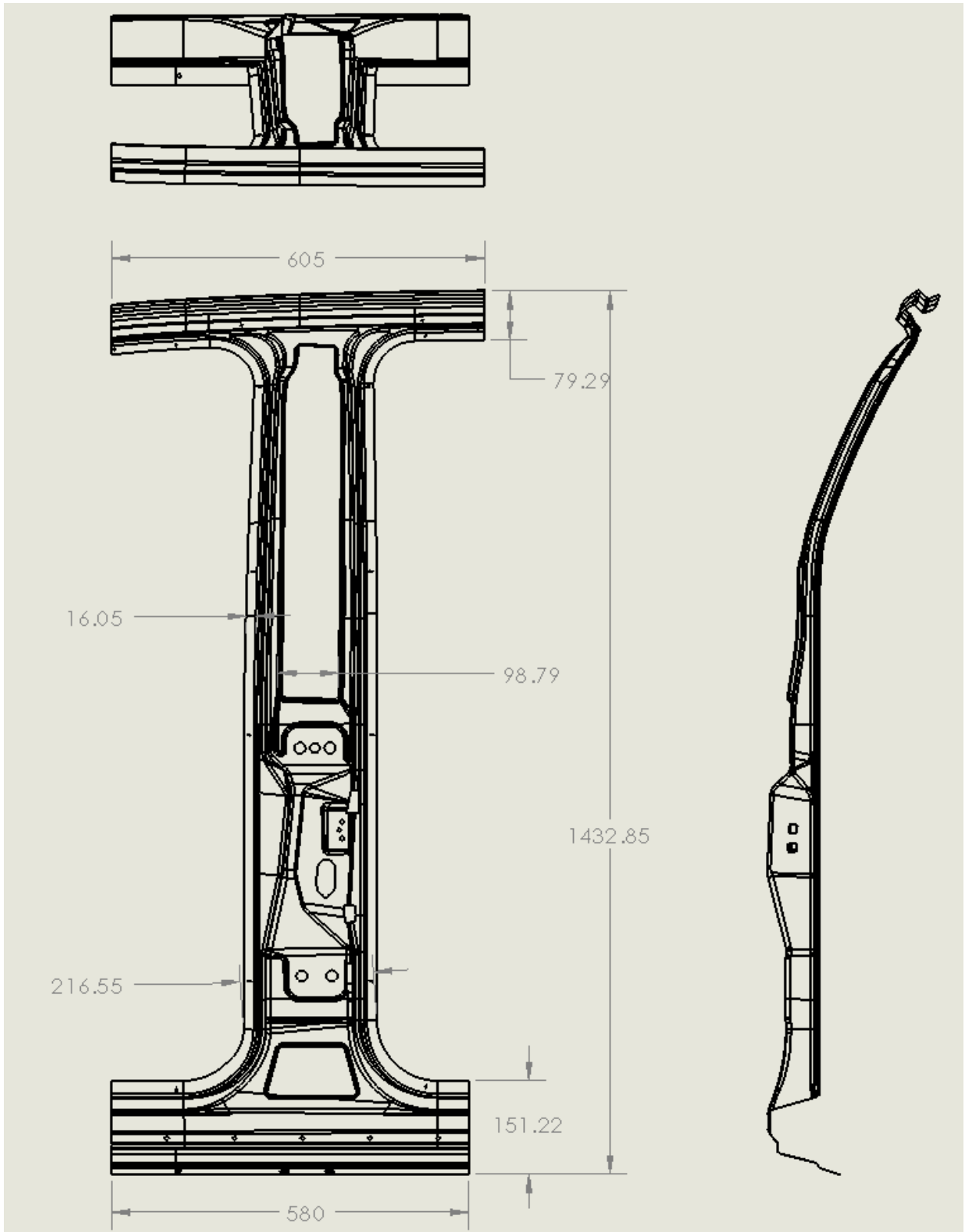


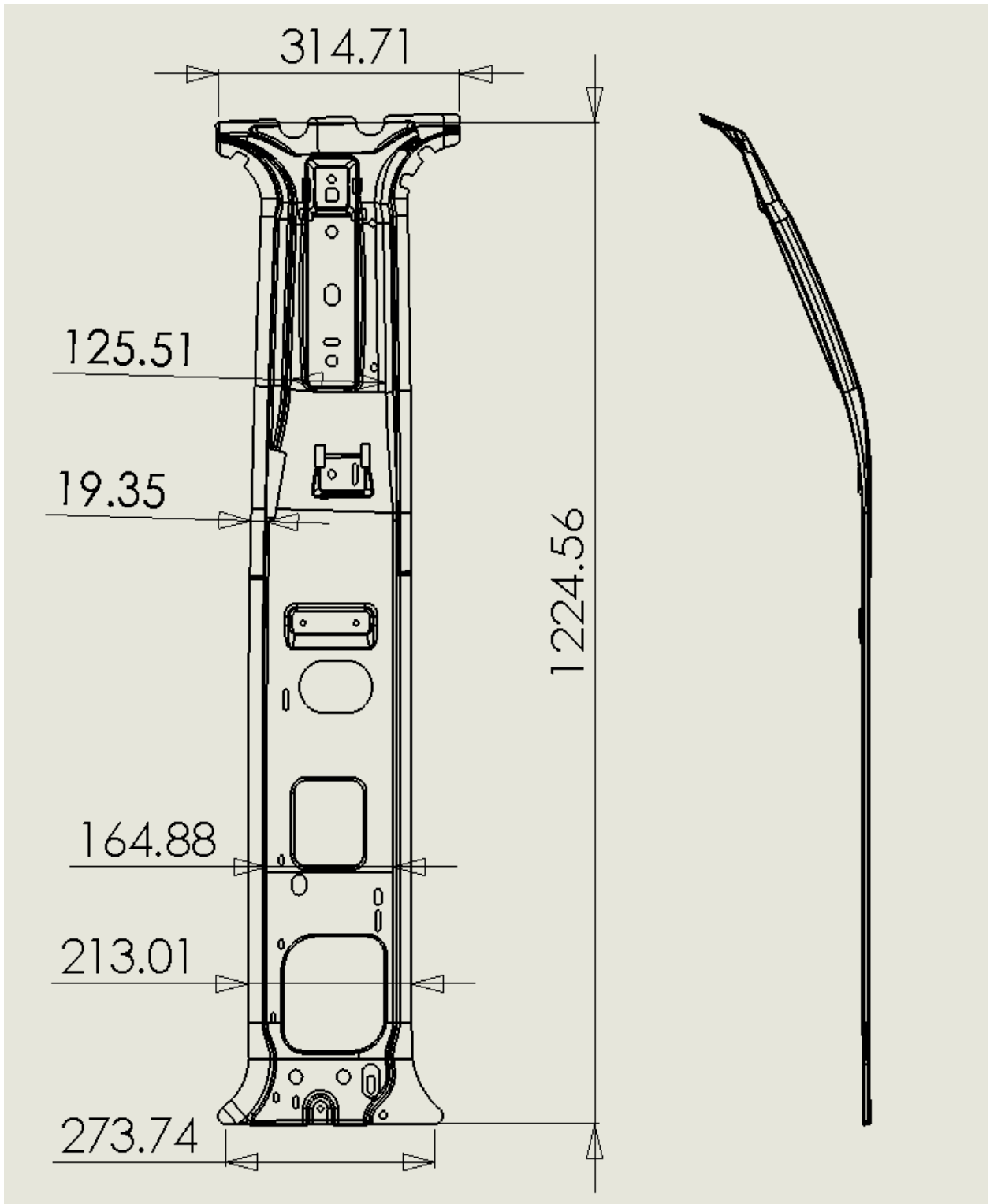
Figure 28: A diagram of the FMVSS 216 test to show how the load is applied [8].

**APPENDIX B: B-Pillar Outer Dimension**



**Figure 29: Dimensioned Drawing of Outer Hat Section of B-pillar (mm)**

**APPENDIX C: B-Pillar Inner Dimension**



**Figure 30: Dimensioned Drawing of Inner Hat Section of B-pillar (mm)**

APPENDIX D: FOAM DATASHEET



**BETAFOAM™ 87100/87124**  
Structural Foam

**Description**

BETAFOAM™ 87100 and BETAFOAM™ 87124 are two components used to make a high-density, all-water blown rigid polyurethane foam. These components were engineered to produce a foam for increasing stiffness of body structure cavities. Foam is produced by the rapid mixing of both components under high shear conditions. The foam has adhesion to primed metal surfaces.

**Specifications**

BETAFOAM™ 87100/87124 meets General Motors GM9982296 and DaimlerChrysler MS-DC-839 specifications.

**Typical Applications**

BETAFOAM™ 87100/87124 is used to increase the stiffness and/or the crashworthiness of automotive body structure cavities.

**Application Technique**

BETAFOAM™ 87100 and BETAFOAM™ 87124 can be pumped from bulk containers into heated meter mix and dispense equipment. The proper mix ratio is in turn dispensed manually or robotically through an impingement mix gun. Adequate ventilation is recommended while dispensing this system.

**Safety Precautions**

Keep away from heat, sparks, and open flames. Use only with adequate ventilation. Avoid breathing vapors. If swallowed, call physician immediately. For eye contact, flush with water for 15 minutes and get medical attention. For skin contact, wash with soap and water. Refer to Material Safety Data Sheet for details.

**Packaging**

BETAFOAM™ 87100 and BETAFOAM™ 87124 are available in 55-gallon metal drums and 300-gallon high-density polyethylene totes.

**Storage**

BETAFOAM™ 87100 and BETAFOAM™ 87124 must be stored in airtight, dry containers at temperatures between 50°F - 100°F (10°C - 38°C).

**Storage Stability**

Shelf life is dependent upon storage temperature of the material. Shelf stability is assured for one hundred and eighty (180) days from the date of shipment when stored according to the above storage requirements.

**Cured Physical Properties**

Free Rise Density, lbs/ft <sup>3</sup> (kg/m <sup>3</sup> )**	24.0 (384)
Volume Expansion, % Minimum**	294

**Uncured Physical Properties**

	BETAFOAM™ 87100	BETAFOAM™ 87124
Composition	MDI & PMDI Isocyanate	Polyether/ Polyol Blend
Appearance	Brown	Clear-Yellow-Green
Flash Point, °F (°C) per ASTM D-92	>300 (150)	>300 (150)
Weight per Volume, lbs/gal (g/cc)	10.23 (1.23)	8.60 (1.03)
Viscosity, (cps) @ 77°F (25°C) RVT, #1, 50 RPM	185	185
Mix Ratio		1:1 by Volume 1:0.85 by Weight
Gel Time, sec**		30 - 40
Tack Free Time, sec**		180 - 210

**Performance Properties**

Compression Strength* per ASTM D1621 @ Ambient, psi (kPa)	1320 (9100)
Compression Modulus per ASTM D1621 @ Ambient, psi (kPa)	45,000 (345,000)
Water Absorption, % per ASTM C272 (Test Method B)	0.76
Dimensional Stability per ASTM D2126, %	
48 hours @ 250 °F (121 °C)	4.0
28 days @ 158 °F (70 °C)	0.4
28 days @ 158 °F (70 °C) and 100% RH	0.8
28 days @ -15 °F (-26 °C)	1.0
Aged Weight Loss, per ASTM D2126, %	
28 days @ 158 °F (70 °C)	1
28 days @ 158 °F (70 °C) and 100% RH	-2.0
28 days @ -15 °F (-26 °C)	-1.1
Adhesion per GM9982296 (e-coated substrate)	All Samples Pass/ No Adhesion
24 hours at RT	Loss of Adhesion
2 H Cycles	
168 hours @ 100 °F (38 °C) and 100% RH	
336 hours @ 158 °F (70 °C)	
Cold Impact per GM 9011P (e-coated substrate)	All Samples Pass/ No Adhesion
Flammability per SAE J369	PASS/SE***
Fogging per GM9305P	PASS

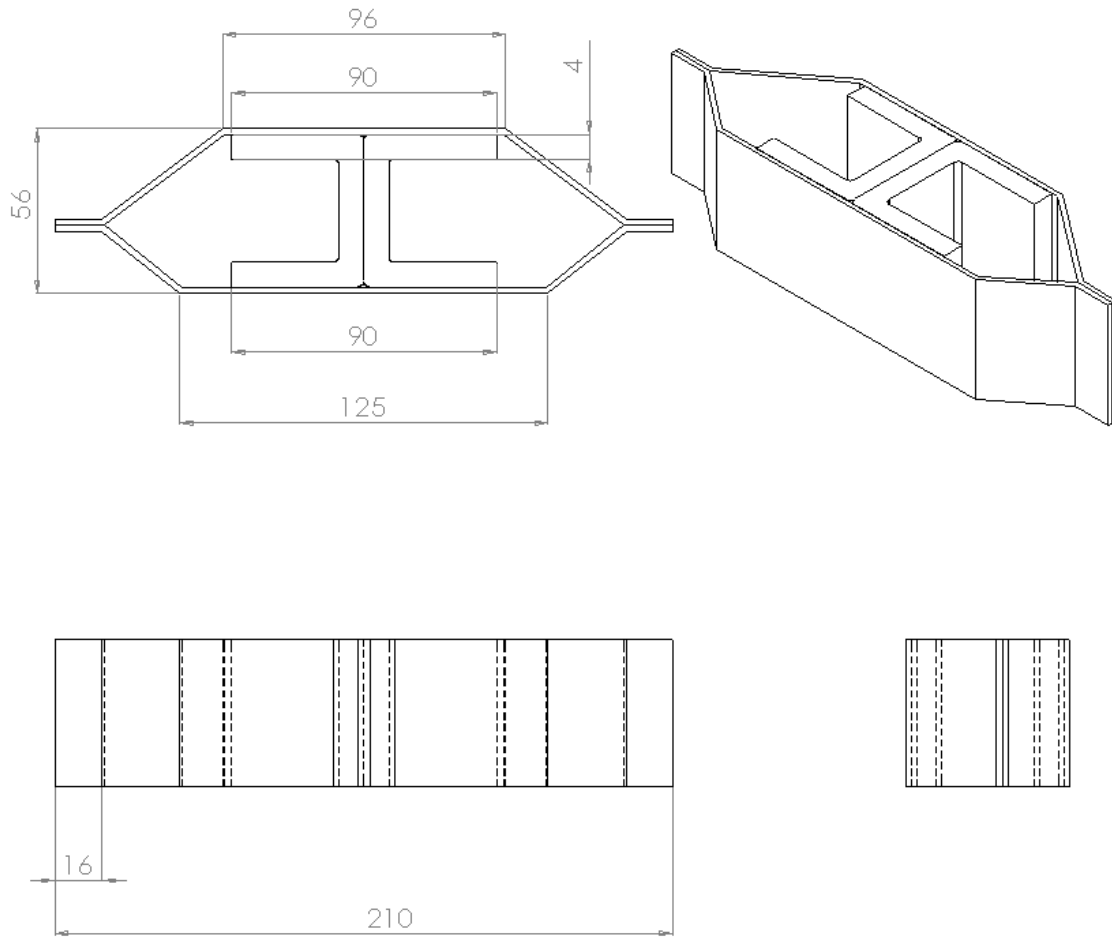
\*For 2"x2"x1" skinless samples  
\*\*Dependent upon dispensing equipment parameters  
\*\*\*This numerical flame spread is not intended to reflect hazards presented by this or any other material under actual fire conditions

™ Registered trademark of The Dow Chemical Company, Inc.

All values are typical and not intended for specification use.

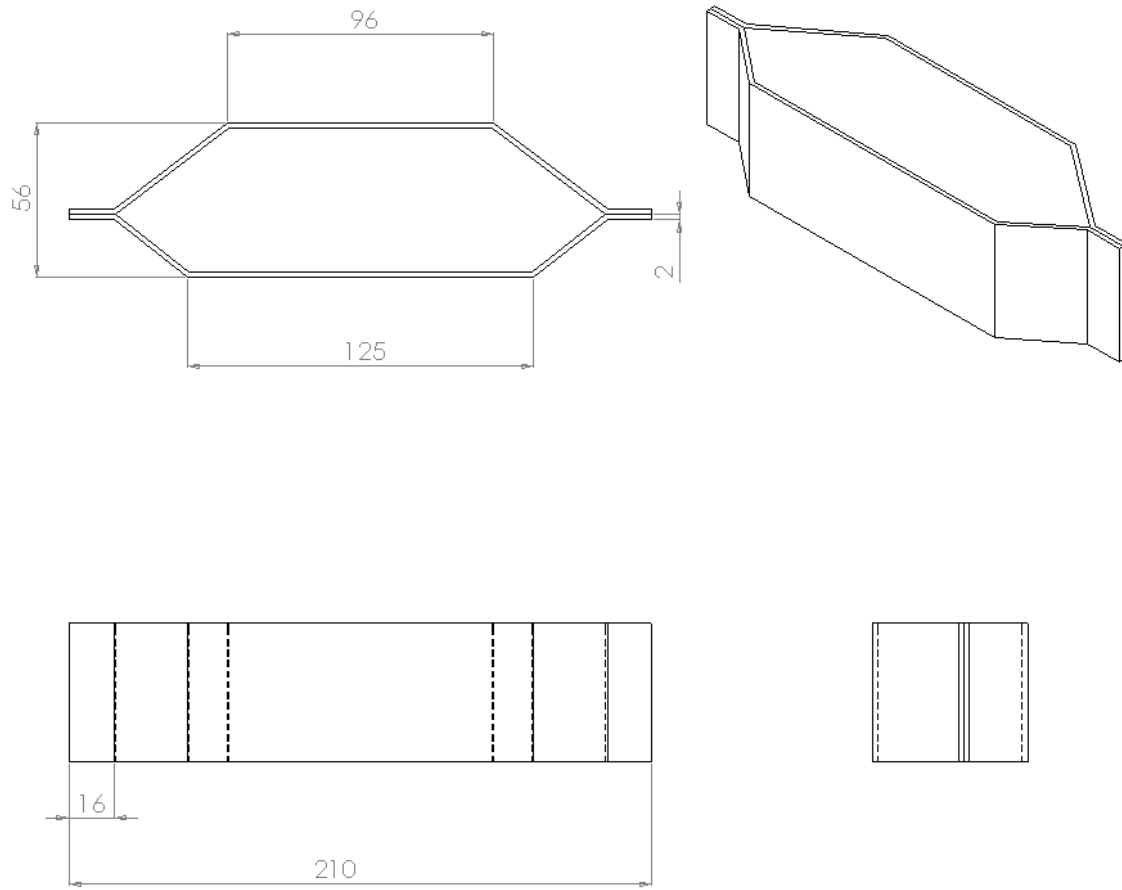
Figure 31: Foam Datasheet

**APPENDIX E: Concept Design #1 (I-Beam)**



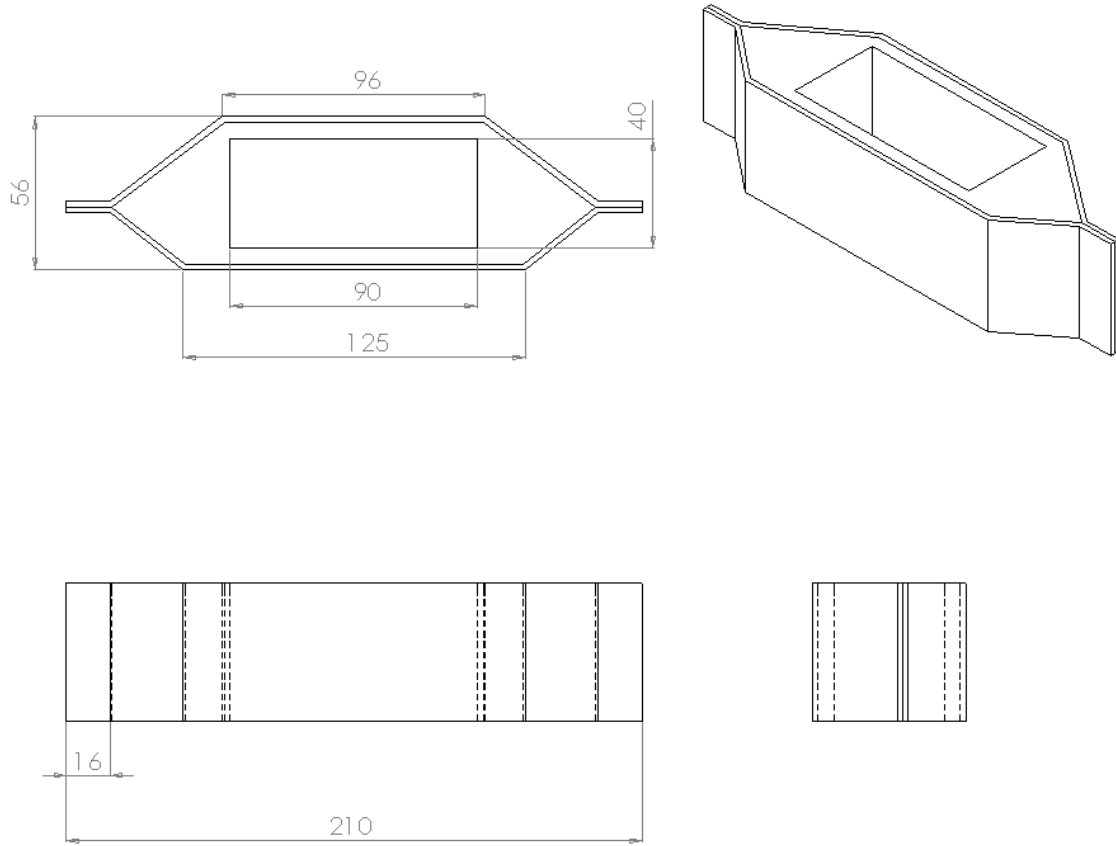
**Figure 32: Dimensioned Drawing of Concept #1 (mm)**

**APPENDIX F: Concept Design #2 (100% Foam)**



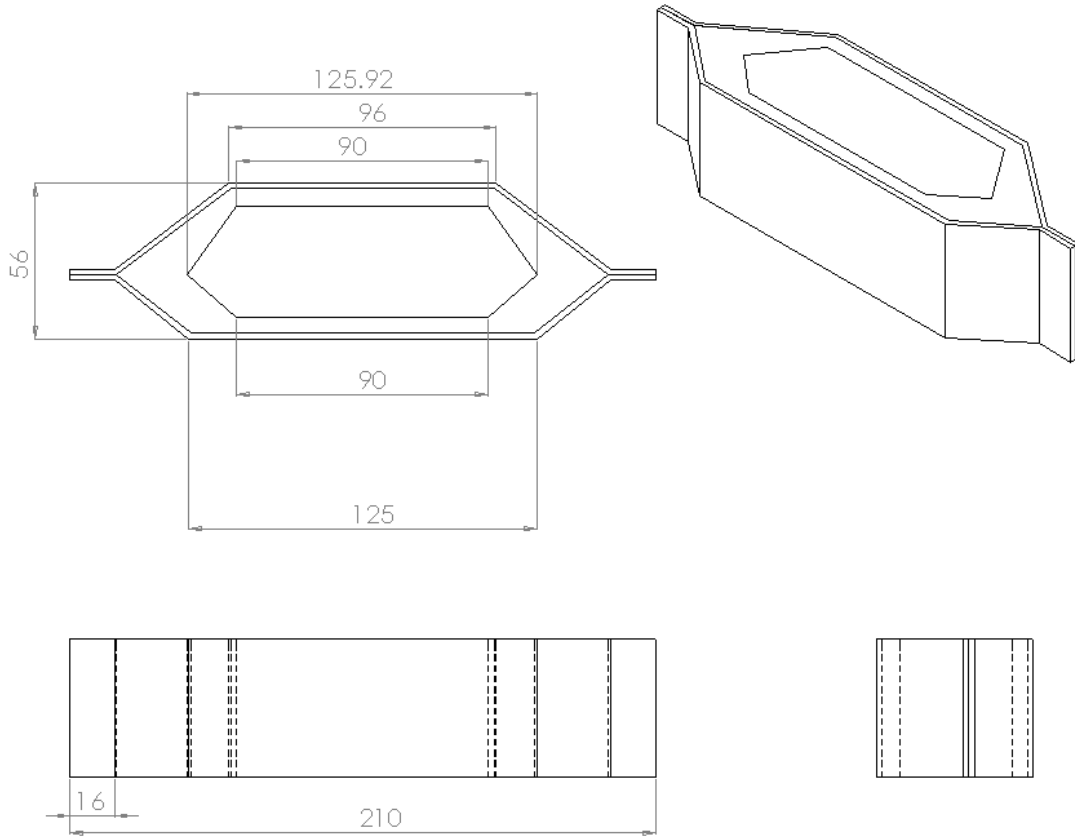
**Figure 33: Dimensioned Drawing of Concept #2 (mm)**

**APPENDIX G: Concept Design #3 (50% Foam)**



**Figure 34: Dimensioned Drawing of Concept #3 (mm)**

**APPENDIX H: Concept Design #4 (Foam w/ Carrier 70/30)**



**Figure 35: Dimensioned Drawing of Concept #4(mm)**

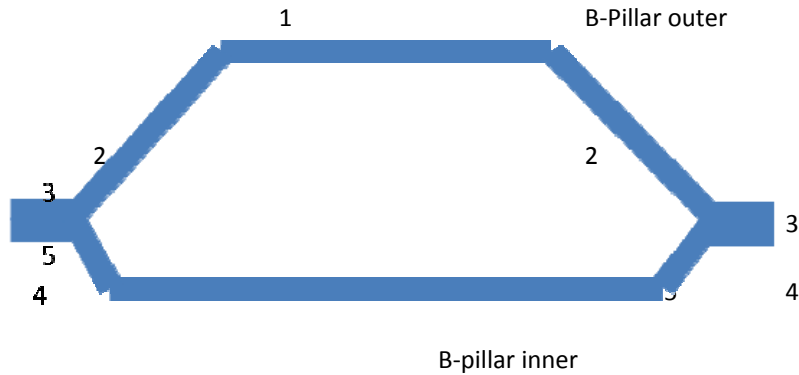


**APPENDIX I: FMEA**

Part Function	Potential Failure Mode	Potential Effect of Failure	Severity	Mechanism(s) of Failure	Occurrence	Current Design Controls	Detection	Recommended Actions	RPN	New S	New O	New D	New RPN
B-Pillar  Structural Member Of Car Chassis  Located Between Front and Rear Doors Provides Structural Support Houses Electrical Wires, Seat Belt Supports, 'Striker'	Yielding	The B-pillar will yield when the material reaches its yield strength	10	Material does not have high yield strength	9	FMVSS 216 test	1	Make material with a high yield strength to increase the time until plastic deformation	90	10	9	1	90
	Buckling	The B-pillar will buckle throughout the entire FMVSS 216 test because a constant downward force is applied	10	The geometry of the B-pillar causes it to buckle at a certain point	9	FMVSS 216 test	1	By adding a reinforcement to the inside of the B-pillar we will increase the time until buckling	90	10	9	1	90

**Figure 36: FMEA**

**APPENDIX J: ENGINEERING ANALYSIS SPREADSHEET**



**B-Pillar Outer**

section	Length(mm)
1	92
2	53
3	16

**B-Pillar Inner**

section	Length(mm)
4	16
5	36.5
6	125

Thickness	2	mm
Area	920	mm <sup>2</sup>

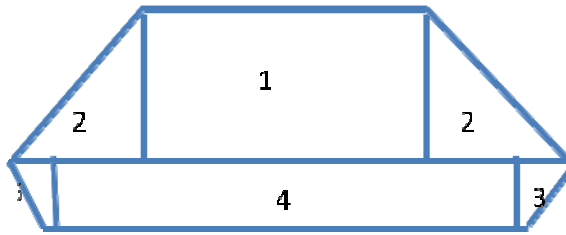
**Calculation of Centroid**

	mm (from origin)	
x centroid	105	(symmetric)
y centroid	26.066304	

**Calculation of Moment of Inertia of B-pillar (Parallel axis theorem)**

x-axis			y-axis		
Section	mm <sup>4</sup>	mm <sup>4</sup>	Section	mm <sup>4</sup>	m <sup>4</sup>
1	154805.33		1	129781.33	
2	60187.667		2	991814.33	
3	21.333333		3	603541.33	
4	277.33333		4	603541.33	
5	33051.333		5	2797562.7	
6	156333.33		6	325520.83	
<b>Total I<sub>bx</sub></b>	<b>404676.33</b>	<b>4.047E-07</b>	<b>Total I<sub>by</sub></b>	<b>5451761.8</b>	<b>5.452E-06</b>

**FOAM REINFORCEMENT**



**Calculation for 100% Foam**

x-axis			y-axis		
Section	Length(mm)	Height(mm)	Section	Height(mm)	Length(mm)
1	90	29	1	29	90
2	41	29	2	29	41
3	123	23	3	23	123
4	24.5	23	4	23	24.5
Total Area	7191.5	mm <sup>2</sup>			
	0.0071915	m <sup>2</sup>			

**Moment of Inertia of 100% Foam**

	mm <sup>4</sup>	m <sup>4</sup>
1	658590	
2	145548.13	
3	566743	
4	59211.954	
<b>Total Ix 100%</b>	<b>1430093.1</b>	<b>1.43E-06</b>

**Moment of Inertia of 100% Foam, IFy**

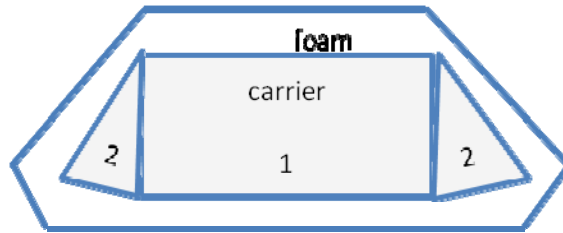
	mm <sup>4</sup>	m <sup>4</sup>
1	1761750	
2	4207964.8	
3	3566661.8	
4	2756324.9	
<b>Total Iy 100%</b>	<b>12292701</b>	<b>1.229E-05</b>

**Calculation for 50% of Foam**



x-axis			y-axis		
Hollow section	Length(mm)	Height(mm)	Hollow section	Length(mm)	Height(mm)
Area(mm <sup>2</sup> )	80	45	Area(mm <sup>2</sup> )	45	80
3595.75			0		
Area Foam					
0.0035958					
Moment of Inertia			Moment of Inertia		
	mm <sup>4</sup>	m <sup>4</sup>		mm <sup>4</sup>	m <sup>4</sup>
hollow section	611100		hollow section	1920000	
<b>Total Ix 50%</b>	<b>818993.09</b>	<b>8.19E-07</b>	<b>Total Iy 50%</b>	<b>10372701</b>	<b>1.037E-05</b>

**Foam with Carrier**



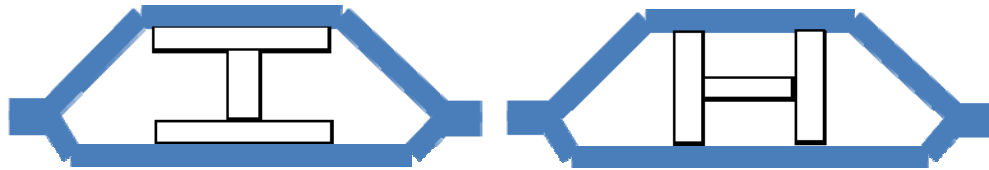
**Calculation for 70% carrier 30% foam**

x-axis			y-axis		
	Area		Carrier	Area(mm <sup>2</sup> )	
Carrier	5034.05	mm <sup>2</sup>	Carrier	5034.05	
	0.0050341	m <sup>2</sup>			
Foam	0.0021575	m <sup>2</sup>			
section	length(mm)	height(mm)	section	length(mm)	height(mm)
1	90	46	1	46	90
2	20	46	2	46	20
Moment of Inertia			Moment of Inertia		
	mm <sup>4</sup>	m <sup>4</sup>		mm <sup>4</sup>	m <sup>4</sup>
1	734160		1	2794500	
2	109071.11		2	2479503.2	
<b>Ix 70% carrier</b>	<b>843231.11</b>	<b>8.432E-07</b>	<b>Iy 70% carrier</b>	<b>5274003.2</b>	<b>5.274E-06</b>
<b>Ix 30% foam</b>	<b>586861.98</b>	<b>5.869E-07</b>	<b>Iy 30% foam</b>	<b>7018698.2</b>	<b>7.019E-06</b>

**Calculation for 80% carrier 20% foam**

x-axis			y-axis		
	Area		Carrier	Area(mm <sup>2</sup> )	
Carrier	5753.2	mm <sup>2</sup>	Carrier	5753.2	
	0.0057532	m <sup>2</sup>			
Foam	0.0014383	m <sup>2</sup>			
section	length(mm)	height(mm)	section	length(mm)	height(mm)
1	90	49	1	49	90
2	27	49	2	49	27
Moment of Inertia			Moment of Inertia		
	mm <sup>4</sup>	m <sup>4</sup>		mm <sup>4</sup>	m <sup>4</sup>
1	886777.5		1	2976750	
2	177796.5		2	3911449.5	
<b>Ix 80% carrier</b>	<b>1064574</b>	<b>1.065E-06</b>	<b>Ix 80% carrier</b>	<b>6888199.5</b>	<b>6.888E-06</b>
<b>Ix 20% foam</b>	<b>365519.09</b>	<b>3.655E-07</b>	<b>Ix 20% foam</b>	<b>5404501.9</b>	<b>5.405E-06</b>

**Metal Reinforcement**



I Beam

H Beam

**I-beam**

	1	2	3	Area	
	mm	mm	mm	mm <sup>2</sup>	
b	90	90	8	1056	
h	4	4	42		
dy	26	20	3		
dx	0	0	0	total	
	mm <sup>4</sup>	mm <sup>4</sup>	mm <sup>4</sup>	mm <sup>4</sup>	m <sup>4</sup>
Ix	243840	144480	52416	440736	<b>4.4074E-07</b>
Iy	243000	243000	1792	487792	<b>4.8779E-07</b>

**H-beam**

	1	2	3	Area	
	mm	mm	mm	mm <sup>2</sup>	
b	4	4	82	728	
h	50	50	4		
dy	3	3	3		
dx	43	43	0	total	
	mm <sup>4</sup>	mm <sup>4</sup>	mm <sup>4</sup>	mm <sup>4</sup>	m <sup>4</sup>
Ix	43466.6667	43466.66667	3389.3333	90322.6667	<b>9.0323E-08</b>
Iy	370066.667	370066.6667	183789.33	923922.667	<b>9.2392E-07</b>

**Young's Modulus**

	GPa	Pa	Density (g/cc)	Density (g/m <sup>3</sup> )
Steel	210	2.1E+11	7.87	7870000
Foam	1	1000000000	0.6	600000
Nylon	3	3000000000	1.17	1170000

**Moment of Inertia with the reinforcement**

	Ix (m <sup>4</sup> )	Iy (m <sup>4</sup> )	E*Ix(Pa*m <sup>4</sup> )	E*Iy(Pa*m <sup>4</sup> )	Increase in Ix %
B-pillar	4.047E-07	5.452E-06	8.498E+04	1.145E+06	
with 100% foam	4.095E-07	5.484E-06	8.641E+04	1.157E+06	1.201
with 50% foam	4.066E-07	5.475E-06	8.580E+04	1.155E+06	0.485
with 70%carrier,30%foam	4.117E-07	5.457E-06	8.810E+04	1.168E+06	1.730
with 80%carrier,20%foam	4.137E-07	5.472E-06	8.854E+04	1.171E+06	2.241
with I-Beam	8.454E-07	5.940E-06	1.775E+05	1.247E+06	108.911
with H-Beam	4.950E-07	6.376E-06	1.039E+05	1.339E+06	22.320

**Calculation of Critical Load for Buckling (EULER)**

$P_{cr} = \pi^2 * E * I / L_e^2$

$L_e$  = effective length (0.5\*L) for fixed ends beam

	0.716	m			
	<b>Pcrx (N)</b>	<b>Pcry (N)</b>	<b>Pcrx (lbf)</b>	<b>Pcry (lbf)</b>	Increase in Pcrx %
B-pillar	1636490.234	22046644	367897.64	4956282.7	
with 100% foam	1664029.389	22283363	374088.688	5009499.31	1.683
with 50% foam	1652261.499	22246390	371443.161	5001187.4	0.964
with 70%carrier,30%foam	1696505.419	2.249E+07	381389.59	5055162.93	3.667
with 80%carrier,20%foam	1705030.174	22548654	383306.031	5069139.04	4.188
with I-Beam	3.419E+06	2.402E+07	7.686E+05	5.400E+06	108.911
with H-Beam	2.002E+06	25782939	450011.401	5796235.38	22.320

**Mass per unit length**

	(g/m)
100%	4314.9
50%	2157.45
70/30	7184.3085
80/20	7594.224
I-beam	8310.72
H-beam	5729.36

**Cost Analysis**

			<b>Total cost per unit length</b>	
	(\$/lb)	(\$/g)	<b>(\$/m)</b>	
Foam	2.4	0.005291094	100 foam	22.8305428
Nylon	1.3	0.002866009	50 foam	11.4152714
Steel	1	0.002204623	70,30	23.7294954
			80,20	23.8579172
			I beam	18.3220013
			H beam	12.6310767

APPENDIX K: DERIVATION OF CURVATURE/MOMENT RELATIONSHIP

$$\begin{aligned} \epsilon &= \frac{(ds' - ds)}{ds} \\ ds &= \rho d\theta \\ ds' &= (\rho - y) d\theta \\ \therefore \\ \epsilon &= \frac{[(\rho - y)d\theta - \rho d\theta]}{\rho d\theta} \\ &\rightarrow \\ \frac{1}{\rho} &= -\frac{\epsilon}{y} \\ \sigma &= -\frac{My}{I} \\ \epsilon &= \frac{\sigma}{E} \\ \therefore \\ \frac{1}{\rho} &= -\frac{\sigma}{Ey} = \frac{My}{Ely} = \frac{M}{EI} \end{aligned}$$

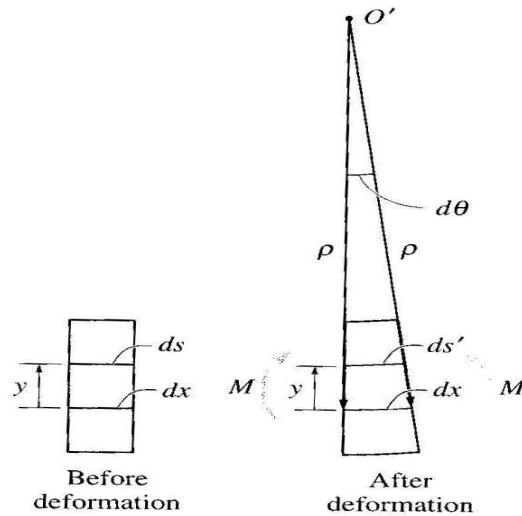


Figure 37: Cross-sectional element of beam. [3]

## APPENDIX L: FINITE ELEMENT ANALYSIS

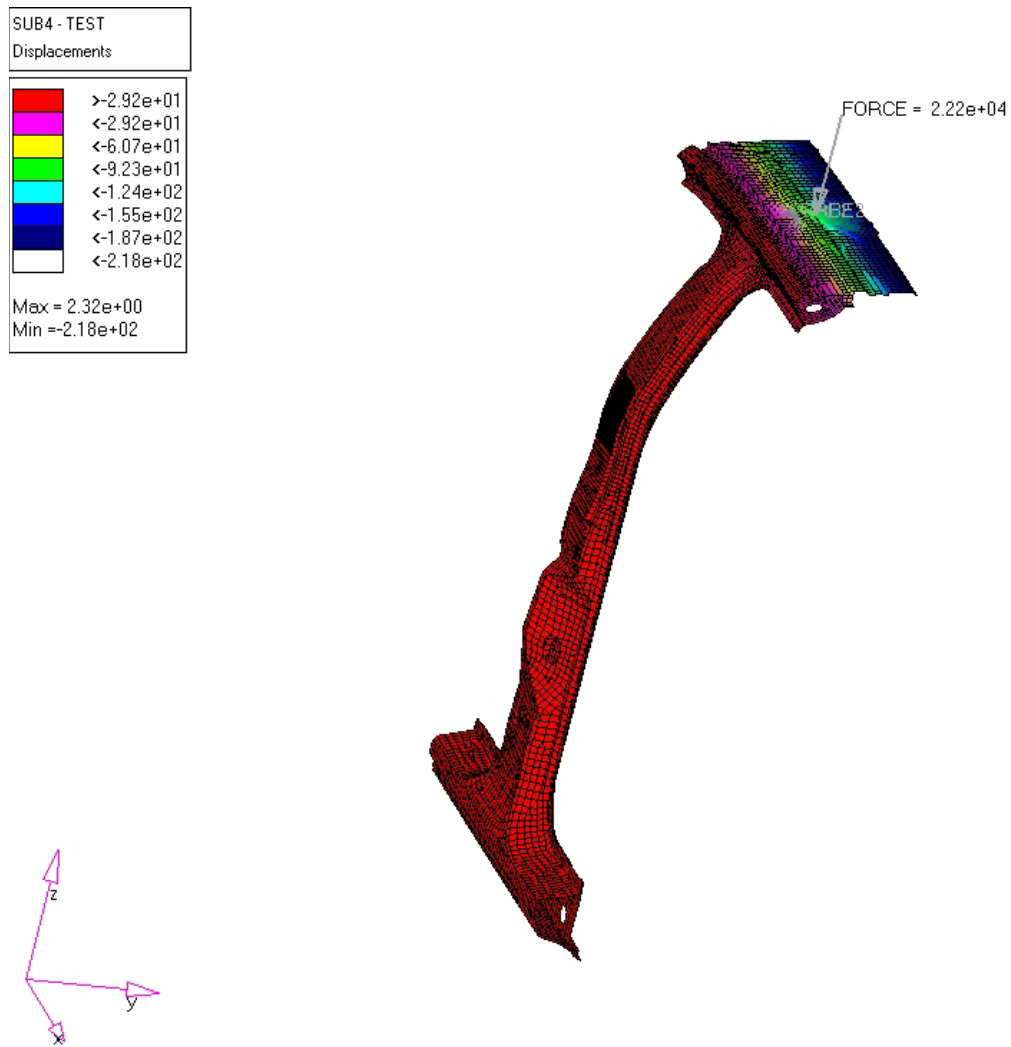
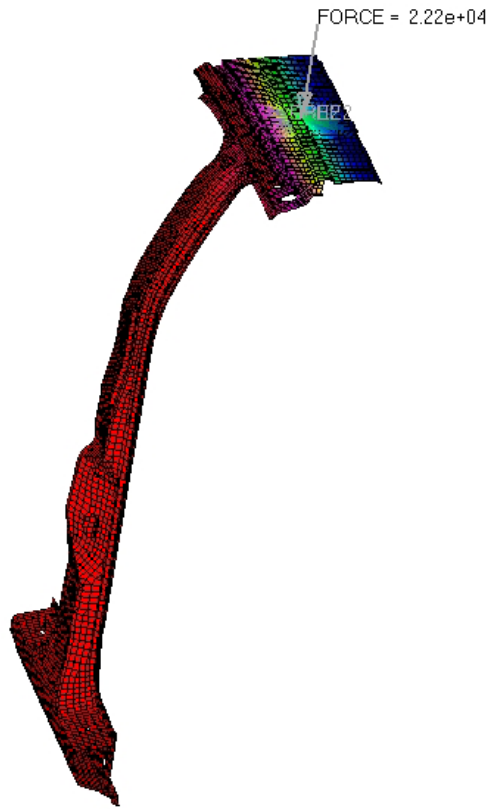
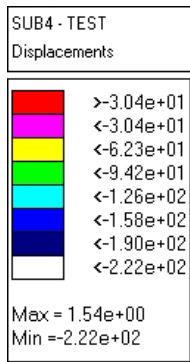


Figure 38: B-Pillar without reinforcement showing deformation data





**Figure 39: B-Pillar with reinforcement showing deformation data**