ME 513 Auto Body Structure

Mini Group Project

December 10th, 2014

Prepared by Team 2

Yuwei Li

Jie Ma

Yuhao Pan

Fangzhou Xia

Undergraduate Engineers, University of Michigan College of Engineering

Prepared For

Dr. Donald Malen

ME 513 Instructor Department of Mechanical Engineering

University of Michigan College of Engineering

Table of Contents

1 Project Objective and Scope

The objective of this project is to design the structure of a 5 passenger automobile, which is target to users that travels for long distance every now and then. In particular, the voice of the customer is summarized as the following.

Voice of Customer (VOC): Retired couple with secure income wants comfortable vehicle for travel between primary home in Michigan and winter home in Florida. Target price; $30,000. Looking for a 5 passenger, mid-size, transverse front drive vehicle.

The scope of the project is to lay out the internal load supporting structure of the vehicle that meets the user requirement. A general lay out of the appearance and size of the vehicle was given at the beginning of the design so that the structure elements also need to fit into the given geometry. Special consideration need to be taken for packaging as well. The model utilized in all analysis is based on the first order models presented in class.

2 Requirement and Specifications

To allow analytical design of the automobile structure that can meet the user requirement, engineering specifications were derived before detailed design. The corresponding interpretation for VOC to engineering specifications can be found in Table 1.

Category	**User Requirement**	**Engineering Specification**	**Rationale**
Degree of Safety	high	crush efficiency > 70%	resist high speed impact on highway
Vibration Solidness	vehicle should feel solid	primary vehicle frequencies: 22-25Hz; torsional stiffness: 12000-15000 Nm/deg; hole vehicle body bending stiffness > 8300N/mm	comfortable, solid feeling for long distance traveling
Durability	vehicle should be durable	resist twist ditch torque, front and rear towing bending moment, no permanent deformation in bending for F = 4169.25N	long distance between Michigan and Florida
Cost Efficient	the vehicle should not be too expensive	price < $30,000	price as specified by the voice of customer

Table 1: User Requirement and Engineering Specification

With the expected long distance travelling on highway required by the user, durability and safety are considered very important for the vehicle. Vibration solidness is also included primarily for consideration of offering the user smooth trips. With the budget of $30,000, the cost efficiency of the design should be considered but does not drive the design that much for the relatively big enough budget.

3 Design Process

A list of steps taken during the design of body structure is shown in this section.

1. Translate voice of customer to engineering specifications
2. Evaluate dimensions of the given sketch for the general layout.
3. Develop general lay out of the structure
4. Estimate mass of a nominal vehicle
5. Adjust the nominal mass of the vehicle according to the user requirement
6. Calculate static, dynamic, front and rear towing bending moments with the H point bending test
7. Calculate twist ditch torque required and the force on each side frame
8. Calculate average crush force and side impact force
9. Size the structure of the element and size.
10. Calculate section property considering both yield and buckle condition
11. Resize section for several iterations to minimize mass and satisfy the strength or stiffness requirement
12. Consider packaging issue and resize
13. Estimate the structure mass
14. Update concept drawing with structure elements
15. Report design and analysis result

All calculations were conducted using the first order model as presented in class with the help of software in evaluating section properties. The section sizing process went through several iterations majorly for side impact loading resistance. Due to the limited crush space available for side impact, the B pillar section needs to be enlarged to produce large enough load resistance capacity during side impact.

4 Structure Design Concept

Based on the given layout of the vehicle, structure element design were carried out first by evaluating the geometry of the frame. After detailed analysis following the procedure as described in the previous section, the vehicle concept lay out is shown in Figure 1 and Figure A-1.

From the sizing of the vehicle, the structure element dimensions are obtained as the following:

1. Vehicle total length: 4.7 m
2. Vehicle total width: 1.77 m
3. Top view area: 8.319 m^2

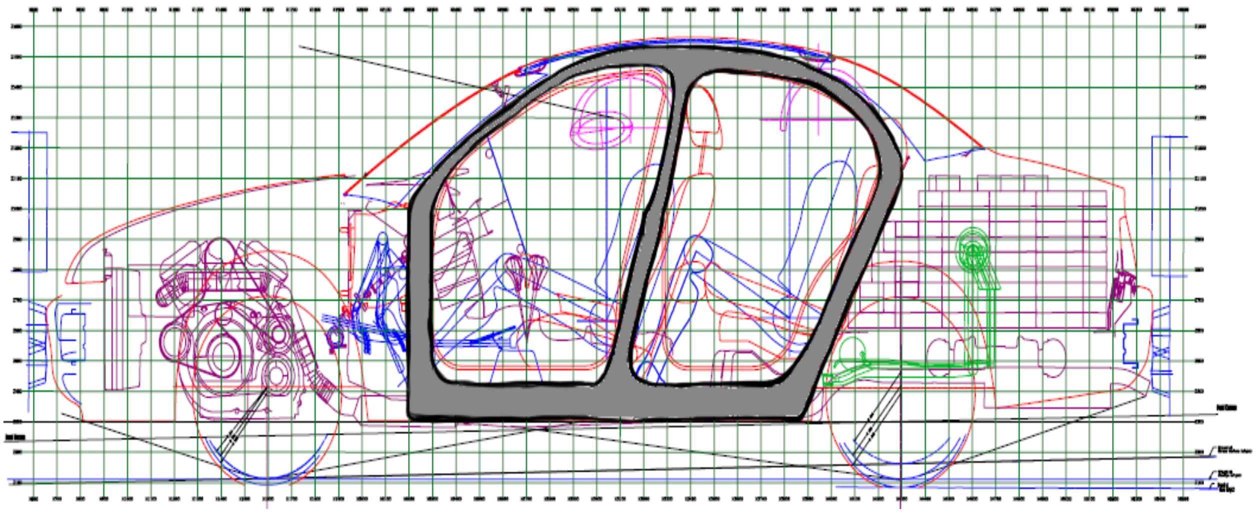


Figure 1: Vehicle Side Frame Structure

5 Analysis for Loading Conditions

5.1 Mass Estimation

With the dimension measured from the layout of the vehicle, an estimation on nominal vehicle mass was conducted. The additional mass utilized in this case include:

1. Cargo mass: 125 kg
2. Passenger number: 2

With detailed analysis shown in Figure B-1, the vehicle mass estimation result for 2 passenger case was obtained:

1. Curb mass: 1411.82 kg
2. Gross vehicle mass: 1676.82 kg

5.2 Mass Adjustment with Customer Requirement

As the targeted customers are retired couple with secure income and will travel long distance using the vehicle very likely with luggage, the estimated mass would increase for the . If luxurious trim level is needed an additional 50kg of content is added to the interior trim in the body. With the help of software as shown in Figure B-2, the vehicle mass is adjusted to be:

1. Curb mass: 1503.04 kg
2. Gross vehicle mass: 1768.04 kg

5.3 Bending Moment

To obtain the bending moment diagram, the assumed evenly distributed weight is calculated as the following:

	x (mm)	load (kg)
front of vehicle	0	
front engine mount	500	269.66/2 = 134.84
front suspension	900	71.66
rear engine mount	1100	269.66/2 = 134.84
2 occupants	2400	2*70 = 140
fuel	3200	62.01
rear suspension	3600	64.64
cargo	4100	125
end of vehicle	4700	

Table 2: Vehicle Mass Components and Coordinates

Assume Weight
= Total curb mass - Fuel - Engine - Front suspension - Rear suspension)
= 1503.04 - 62.01 - 269.66 - 71.66 - 64.64
= 1035.07 kg

For evenly distributed weight, the uniform loading is calculated as:

W = 1035.07kg/4700mm = 0.22kg/mm

The maximum bending moment is calculated to be 1.42×106 Nmm at the x -2400 mm location.

5.4 Bending Strength Load for H Point Bending

By using the software as shown in Figure C-1 and Figure C-2, the following results were obtained for the H point bending test.

1. Bending load at H point: 1420389N
2. Bending load at 3600mm: 1918065N
3. Maximum bending moment at rear towing: Happens at 3000mm, 5.56×106Nmm
4. Equivalent load: 850 kg. (8338.5N)

5.5 Twist Ditch Torque

From body bending diagram, the maximum load from the front and rear wheels is estimated to be 8714 N. With the measured track length of 1560mm, the twist ditch torque is obtained by both hand calculation and software calculation:

Twist ditch torque = 8714N × 1560mm/2 = 6796920 Nmm

5.6 Bending Stiffness

The bending stiffness for the structure element is calculated based on vehicle dimension and mass with total length of 4700 mm and wheel distance 2700 mm. The calculation result is summarized in Table 3 with software usage demonstrated in Figure C-4. The average bending stiffness for the entire vehicle is taken as 8300 N/mm for body structure sizing.

601.216 Rigidly Attached Mass (kg)		901.824 Rigidly Attached Mass (kg)	
Frequency (Hz)	Bending Stiffness (N/mm)	Frequency (Hz)	Bending Stiffness (N/mm)
22	5796	22	8694
25	7485	25	11227

Table 3: Bending Stiffness Requirement

5.7 Torsion Stiffness

As torsional stiffness required for solid feeling is dominant for passenger cars, the target range is 12000-15000Nm/degree with calculation demonstrated in Figure C-5.

5.8 Front Crush Analysis

From the given dimension as shown in Figure 2 , the available crush space is calculated as

Estimated front crush space available: Δ = (100+150+150+250) mm= 650mm

With the assumed impact speed of V = 30 mph = 13.3 m/s, the crush efficiency is calculated as

$$\eta = \frac{V^2}{2\Delta a_{max}} = \frac{V^2}{2\Delta \times 20g} = 75\%$$

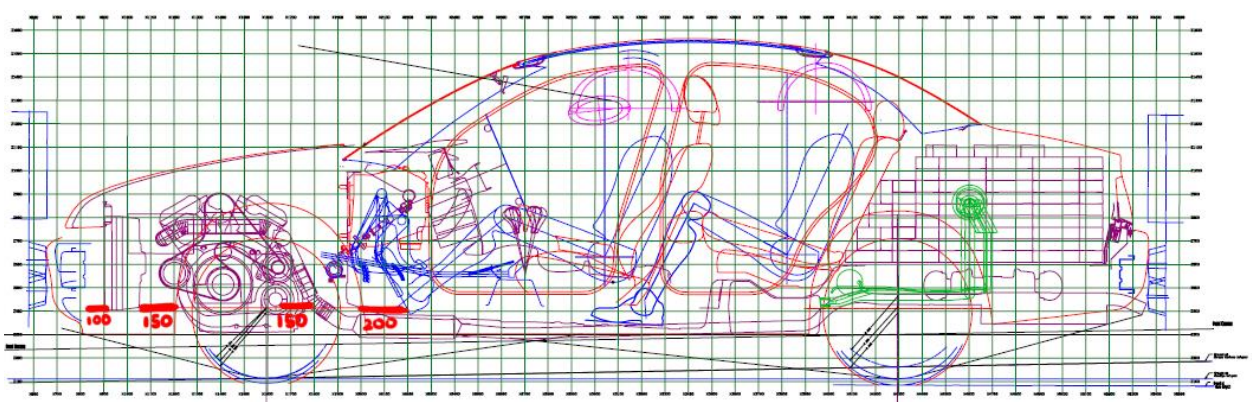


Figure 2: Vehicle Crush Space Determination

With the help of software as shown in Figure C-6, the average barrier crush force requirement is calculated as:

$$F_{avg} = \eta \times F_{max} = \eta \times m \times 20g = 0.75 \times \frac{196.2m}{s^2} \times 1768kg = 259902\ N$$

6 Vehicle Structure Layout

6.1 General Dimension for Bending and Torsion Analysis

The general dimension for bending and torsion analysis are identical as estimated from the given vehicle as shown in Figure 3. Internal loads for the structure is obtained from the software for section sizing purpose later.

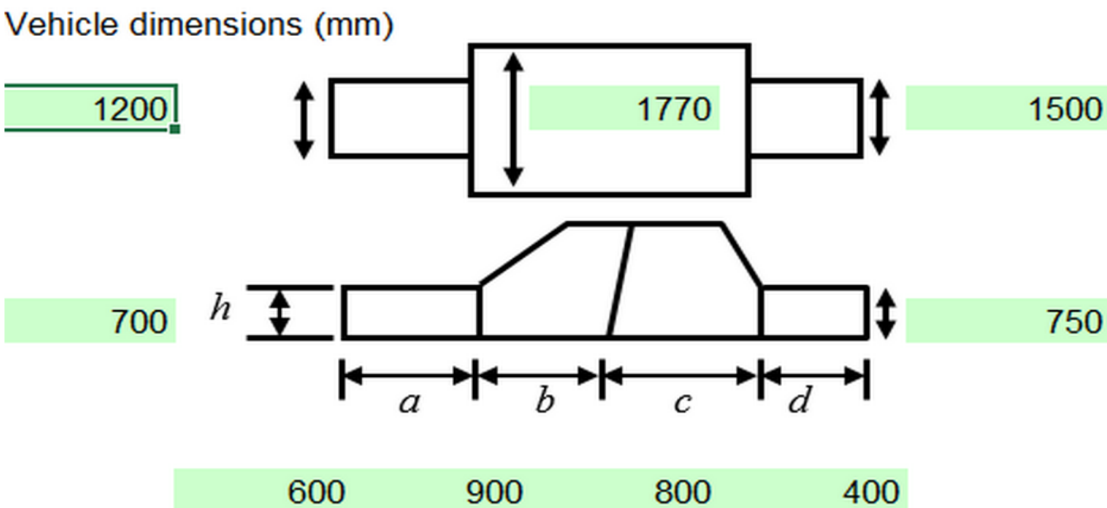


Figure 3: First Order Model Structure Dimension

6.2 Material Selection

To perform further sizing of the structure elements, the material needs to be determined in advance. Possibly due to the difference in structure for aluminum and steel for section sizing, the software calculation for first order model yields higher mass for aluminum than steel to achieve similar stiffness, which needs careful adjustment of the model that is beyond the scope of this project. For this reason and the potential cost increase by using aluminum, the selected material for all following section sizing analysis is Steel-Hot Stamped with properties shown in Table 4.

Material	E N/mm^2	G N/mm^2	Yield N/mm^2	Tensile N/mm^2	Density kg/m^3	Cost \$/kg	Selection Status
Steel-Hot Stamped	207000	79300	1030	1200	7860	1	Yes
Aluminum Cast	67000	26000	150	290	2710	2.8	No

Table 4: Material Property

6.3 Side Frame Sizing

To satisfy the bending stiffness requirement, several design iterations were performed to achieve the required bending stiffness 8300 N/mm for the entire vehicle (4150 N/mm for the side frame). With the assumption that all joints acts as rigid joints, he section sizing result for bending stiffness requirement is shown in Figure D-1.

After preliminary sizing, the torsion frame requirement is considered for all sections. With the specified dimension, the buckle stress is calculated using the software for each section. The result is then compared with the load on each section as obtained from the cabin shear loads under torsion calculation shown in Figure D-2. The section size obtained from the step is shown in Table 5. As the buckle stress for each section is significantly larger than that of the required stress due to torsion, no adjustment to the section size were performed.

		H (mm)	W (mm)	T (mm)	Buckle Stress (N/mm^2)	Force(N)	Area (mm^2)	Required Stress (N/mm^2)
Q2	Hinge pillar	100	50	1	299.04	3852.2	300	12.84067
Q3	A pillar	35	35	1	610.28	2106.83	140	15.04879
Q4	Roof rail	50	80	3	1030	1811.9	780	2.322949
Q5	C-Upper	75	25	1	1030	1657.41	200	8.28705
Q6	C_Lower	50	50	1	299.04	3722.78	200	18.6139
Q7	Rocker	120	55	2.5	1030	4400.34	875	5.02896

Table 5: Side Frame Section Size

6.4 Structure Panel Sizing

Considering the fact that window on the windshield and roof is usually small due to the thin structure, the effective shear rigidity Gt is taken as 320 N/mm for these two components as an estimation. In addition, due to the possible need of carrying luggage, the seat back should be able to fold down to enlarge the trunk space for luggage placing and thereby reducing the effective shear rigidity of the seat back, which is taken as 320 N/mm as an estimation here. To meet the stiffness in torsion requirement of 12000 to 15000 Nm/deg and considering the three components with lower effective stiffness, all other panels should have an effective shear rigidity Gt of a value at around 80000 N/mm as shown in Figure D-3. Given the shear rigidity of hot stamped steel as 79000 N/mm2, the thickness of the panels need to be greater than 1.02 mm.

6.5 Front Crush Barrier Sizing

With two front crush barrier and taking $P_m = 0.5\ P_{max}$ for convenience, the required mean crush load to withstand by the front barrier is obtained:

$$P_m = 259902 / 4 \text{ N} = 64975.5 \text{ N}$$

With the yield stress of 1030 N/mm^2 for hot stamped steel, the geometry of the front crush barrier is obtained as shown in Figure D-4 with results summarized below:

1. Geometry: Octagon
2. Thickness: 1.25 mm
3. Width: 81 mm
4. Flange Position: Middle
5. Load Capacity: 65039 N

The plastic hinge capacity to withstand the load need to be 6,000,000 Nmm to withstand the load with the geometry as shown in Figure *4*.

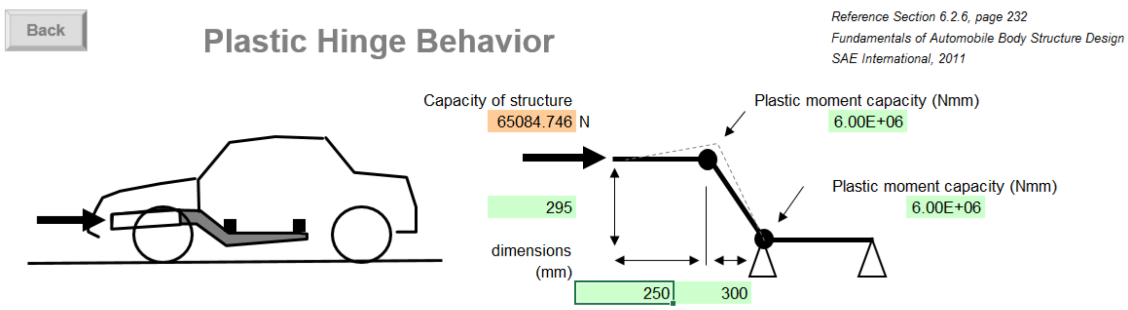


Figure 4: Plastic Hinge Requirement

6.6 B Pillar Resizing for Side Impact

With a limited side crush space of 0.28 m available, the side moment needed to be relatively large to allow an acceleration smaller than 55 g during side impact. The required force is 170,000 N acting 0.3 m above the lower joint of the B-pillar. The B-pillar needs to be resized to have a thickness of 6 mm instead of 1 mm. This resulted in an addition of weight from the original 27.98 kg to 35.32 kg for the side frame structure.

6.7 Roof Panel Sizing

To allow the vehicle to withstand special weather condition like hail storm, the roof panel needs special consideration in terms of its sizing. The hail stone is assumed to have a mass of 0.005 kg, a terminal velocity of 28.53 m/s and thereby a kinetic energy of 20350 Nmm. With the size of the roof panel with 1100 mm in width and 1000 mm in length, the double crowned panel is selected to have a height of 50 mm to have large safety range to avoid surface being dented. The analysis is shown in Figure D-5.

6.8 Packaging Concerns

Apart from considering the sizing of the structure elements based on the given geometry, the blind angle caused by A pillar and B pillar that are on the close side of the driver is calculated and compared against the 6 degree bench mark. The result is summarized in Table 6.

Component	Distance to Driver (mm)	Maximum Size (mm)	Angle (deg)	Benchmark
A pillar	860	49.50	3.31	Satisfied
B pillar	583	55.90	5.49	Satisfied

Table 6: Vision Obstruction Angle Calculation

6.9 Structure Mass Estimation

By adding up the side frame, crush barrier and structure panels, structure mass add up to 111.3925 kg for all the components considered. This mass of structure is relative low compared to typical mass percentage of structure elements out of the total mass of a nominal vehicle. This may due to the fact that the model did not consider the mass added at joints and other supporting structure such as fixture for motors and etc. In addition, there is no additional safety factor included in the calculation.

6.10 Joint Details

To improve structure stiffness other than resizing the sections, the geometry of joints need to be carefully considered. Several design technics can be applied on the design of the joint to improve joint efficiency and reduce joint buckling. A simple sketch of Rocker/B-Pillar joint that adopts beads, fillet, and shear walls to potentially increase stiffness is included in Figure 5 to demonstrate the design practice of joints.

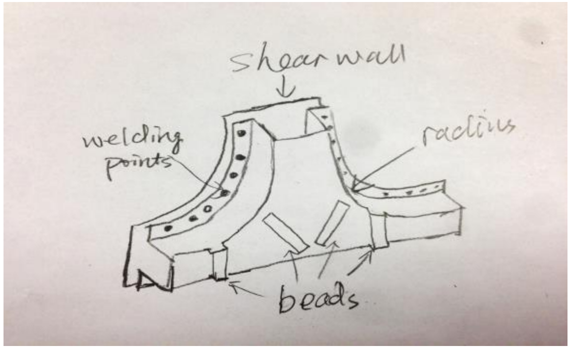


Figure 5: Joint Concept Drawing

6.11 Section Geometry Redesign

To make full use of the high strength of the hot stamp steel. The sections need to be redesign for buckling with beads added as shown in Figure 6.

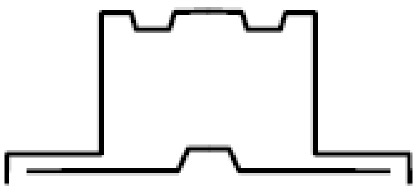


Figure 6: Adding Beads to Sections

6.12 Pinch Point Consideration

Besides blind angle, the given geometry, and styling requirements, the pinch points on the vehicle body structure design are also considered. To tackle the constraints of pinch points, the vehicle body structure is optimize by making use of as much as internal space as possible. For example, as you can see in Figure 1Figure *3* the side frame is designed right at the external roof line. The C-lower pillar is sloped forward to accommodate the wheel interference, but is designed as close to the wheel as possible to reduce slope angle. Also as shown in Figure 2, despite the limited rooms in the engine cabin ate constrained by styling, all of the "spare spaces" between the engine and the exterior are utilized to increase crash space.

7 Design Critic and Future Work

7.1 Design Analysis

During the structure sizing procedure, all engineering specifications derived from the user requirement was carefully considered and evaluated. The structure sizing was conducted using the software and reiterated for side impact improvement.

Due to the assumption of rigid joints, the flexibility issue at joints were not considered too full extent during the analysis. The structure may needs to increase its size to meet the stiffness requirement when the joint stiffness is considered. Moreover, the joints need to be carefully designed to increase its stiffness to avoid significant increase of the structure size which will result in the increase of structure mass.

7.2 Future Work

Due to the limited crush space available for side impact, the load requirement for the B pillar is relatively large and can be reduced significantly by adding some crush space such as 5 cm to reduce the structure load requirement as well as the acceleration.

In the next stage of design, joint efficiency should be included into the model for detailed analysis. Structure size and orientation, which will be very different from the first order simplified model, needs to be determined after the preliminary analysis. Finite element analysis for critical part locations such as B pillar joint and other structure elements need to be conducted to allow careful design and adjustment of the structure geometry.

Appendix A Vehicle Concept Layout

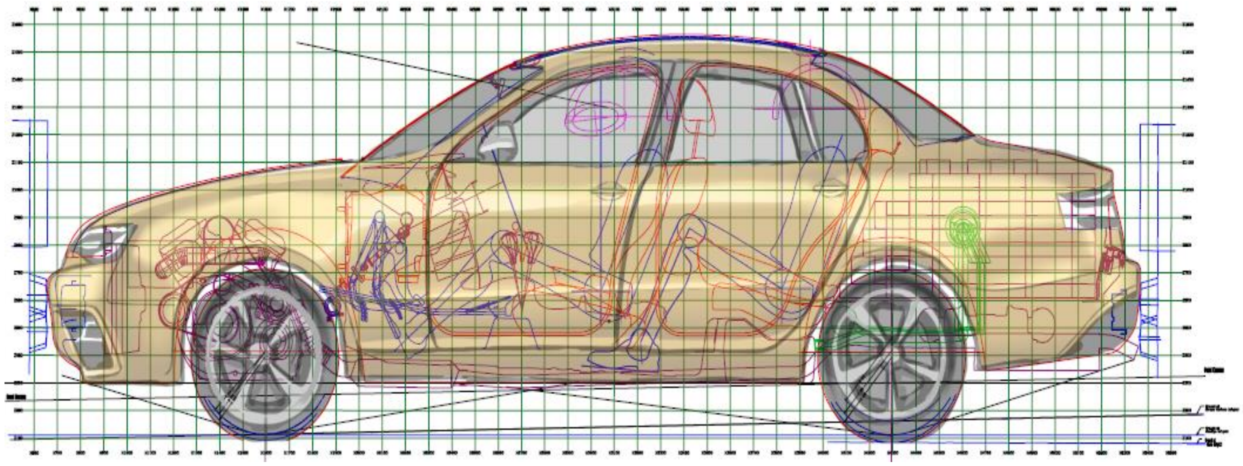
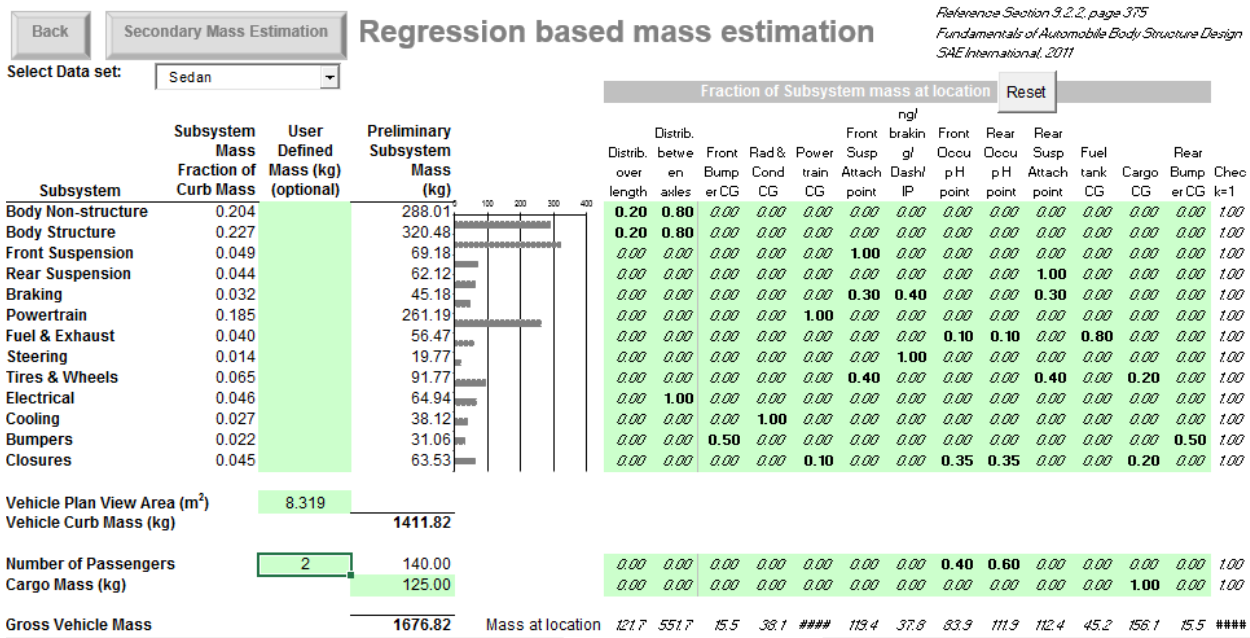


Figure A-1: Vehicle Concept Dimension Overlapping

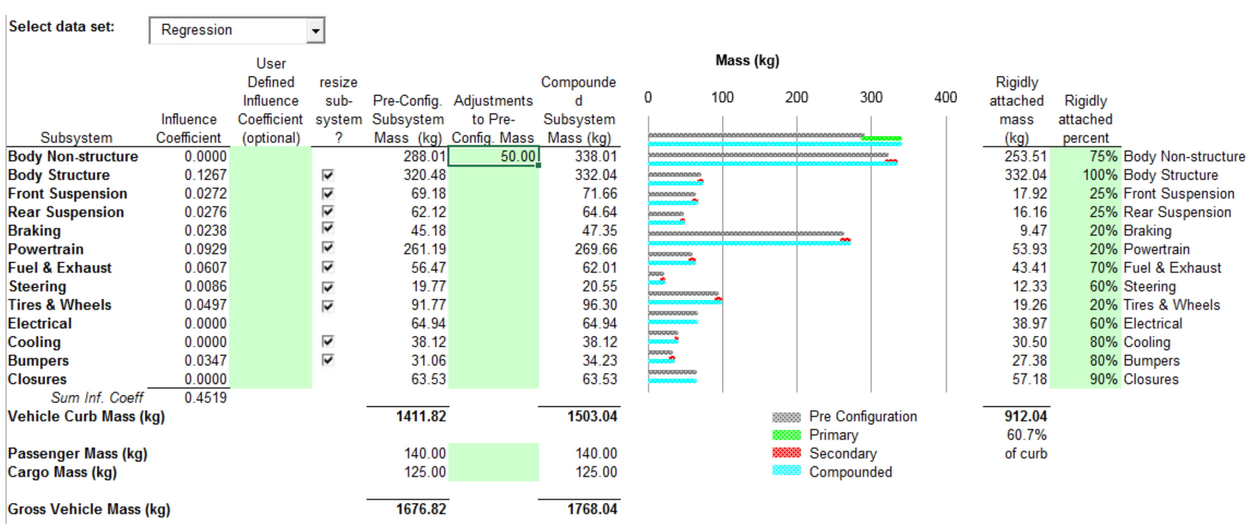
Appendix B Vehicle Mass Estimation



Subsystem	Subsystem Mass Fraction of Curb Mass	User Defined Mass (kg) (optional)	Preliminary Subsystem Mass (kg)
Body Non-structure	0.204		288.01
Body Structure	0.227		320.48
Front Suspension	0.049		69.18
Rear Suspension	0.044		62.12
Braking	0.032		45.18
Powertrain	0.185		261.19
Fuel & Exhaust	0.040		56.47
Steering	0.014		19.77
Tires & Wheels	0.065		91.77
Electrical	0.046		64.94
Cooling	0.027		38.12
Bumpers	0.022		31.06
Closures	0.045		63.53
Vehicle Plan View Area (m^2)		8.319	
Vehicle Curb Mass (kg)			1411.82
Number of Passengers		2	140.00
Cargo Mass (kg)			125.00
Gross Vehicle Mass			1676.82

Subsystem	Distrib. over length	Distrib. between axles	Front Bumper CG	Rad & Cond CG	Power train CG	Front Susp Attach point	ng/ braking/ Dash/ IP	Front Occup H point	Rear Occup H point	Rear Susp Attach point	Fuel tank CG	Cargo CG	Rear Bumper CG	Check=1
Body Non-structure	0.20	0.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Body Structure	0.20	0.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Front Suspension	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Rear Suspension	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	1.00
Braking	0.00	0.00	0.00	0.00	0.00	0.30	0.40	0.00	0.00	0.30	0.00	0.00	0.00	1.00
Powertrain	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Fuel & Exhaust	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.10	0.00	0.80	0.00	0.00	1.00
Steering	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Tires & Wheels	0.00	0.00	0.00	0.00	0.00	0.40	0.00	0.00	0.00	0.40	0.00	0.20	0.00	1.00
Electrical	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Cooling	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Bumpers	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	1.00
Closures	0.00	0.00	0.00	0.00	0.10	0.00	0.00	0.35	0.35	0.00	0.00	0.20	0.00	1.00
Number of Passengers	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.40	0.60	0.00	0.00	0.00	0.00	1.00
Cargo Mass (kg)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	1.00
Mass at location	121.7	551.7	15.5	38.1	####	119.4	37.8	83.9	111.9	112.4	45.2	156.1	15.5	####

Figure B-1: Nominal Vehicle Mass Estimation



Subsystem	Influence Coefficient	User Defined Influence Coefficient (optional)	resize sub-system ?	Pre-Config. Subsystem Mass (kg)	Adjustments to Pre-Config. Mass	Compounded Subsystem Mass (kg)	Rigidly attached mass (kg)	Rigidly attached percent	
Body Non-structure	0.0000			288.01	50.00	338.01	253.51	75%	Body Non-structure
Body Structure	0.1267		☑	320.48		332.04	332.04	100%	Body Structure
Front Suspension	0.0272		☑	69.18		71.66	17.92	25%	Front Suspension
Rear Suspension	0.0276		☑	62.12		64.64	16.16	25%	Rear Suspension
Braking	0.0238		☑	45.18		47.35	9.47	20%	Braking
Powertrain	0.0929		☑	261.19		269.66	53.93	20%	Powertrain
Fuel & Exhaust	0.0607		☑	56.47		62.01	43.41	70%	Fuel & Exhaust
Steering	0.0086		☑	19.77		20.55	12.33	60%	Steering
Tires & Wheels	0.0497		☑	91.77		96.30	19.26	20%	Tires & Wheels
Electrical	0.0000			64.94		64.94	38.97	60%	Electrical
Cooling	0.0000		☑	38.12		38.12	30.50	80%	Cooling
Bumpers	0.0347		☑	31.06		34.23	27.38	80%	Bumpers
Closures	0.0000			63.53		63.53	57.18	90%	Closures
Sum Inf. Coeff	0.4519								
Vehicle Curb Mass (kg)				1411.82		1503.04	912.04 60.7% of curb		
Passenger Mass (kg)				140.00		140.00			
Cargo Mass (kg)				125.00		125.00			
Gross Vehicle Mass (kg)				1676.82		1768.04			

Figure B-2: Regression Vehicle Mass Adjustment Based on User Requirement

Appendix C Structure Load Analysis

Appendix C.1 Bending Moment Analysis

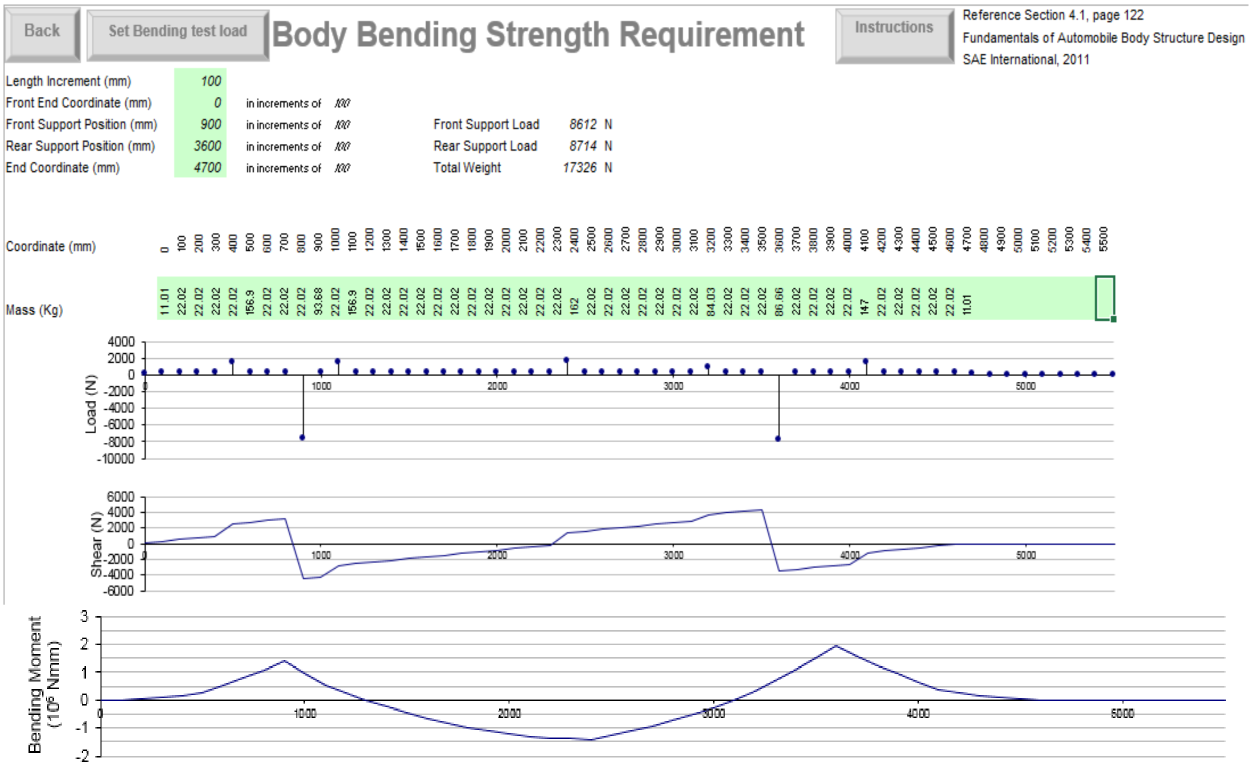


Figure C-1: Bending Moment Diagram

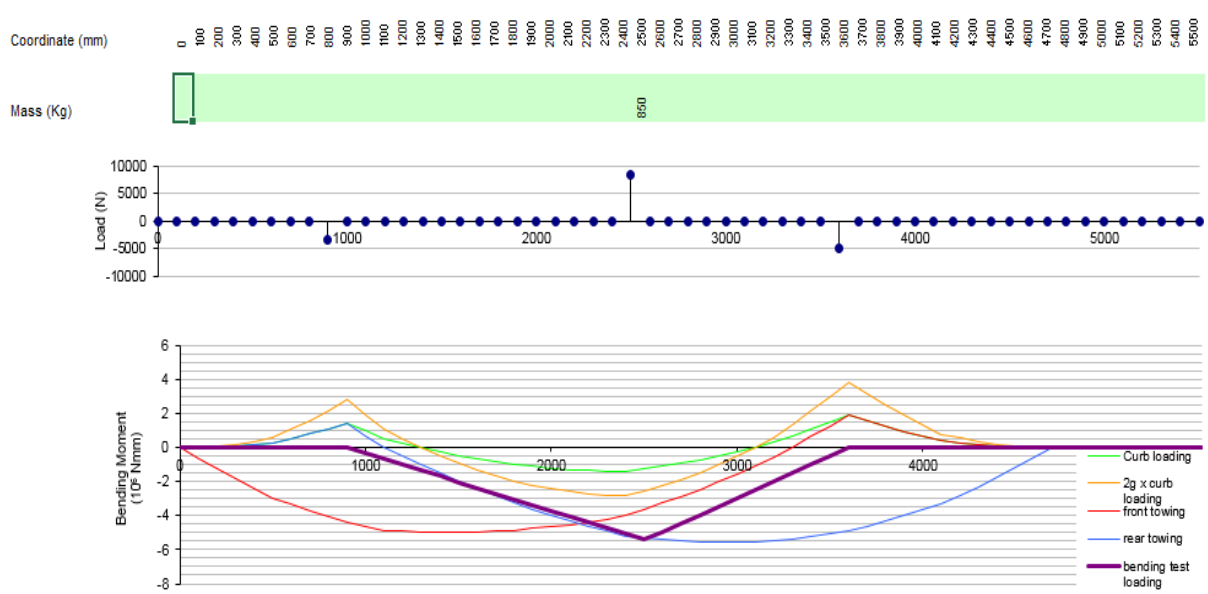


Figure C-2: Bending Strength Load for H Point Bending Test

Appendix C.2 Tiwst Ditch Torque

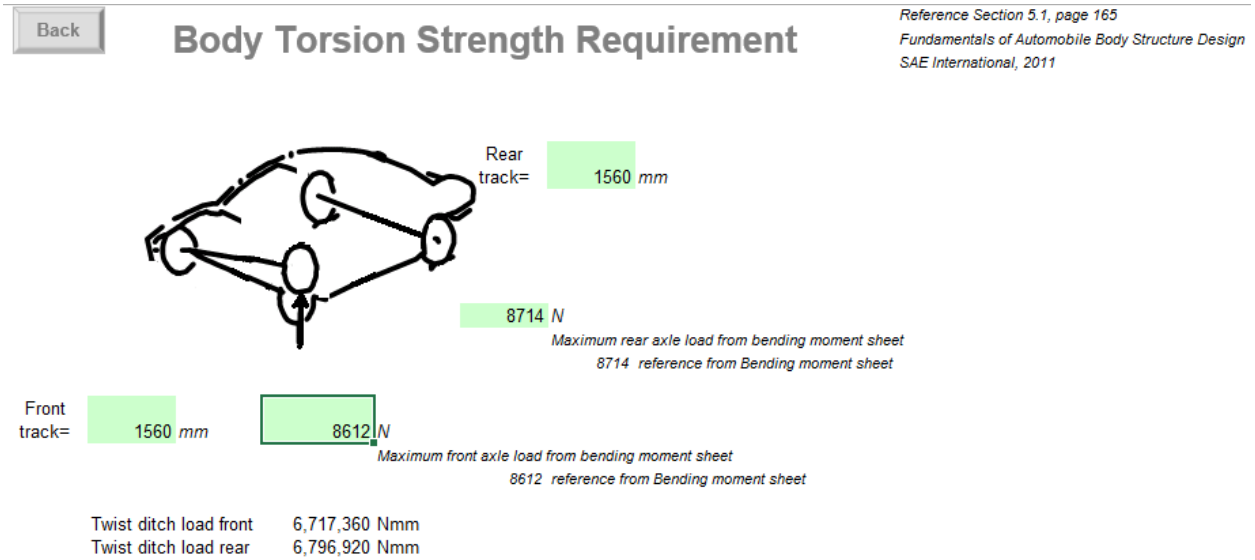


Figure C-3: Twist Ditch Torque Calculation

Appendix C.3 Bending Stiffness

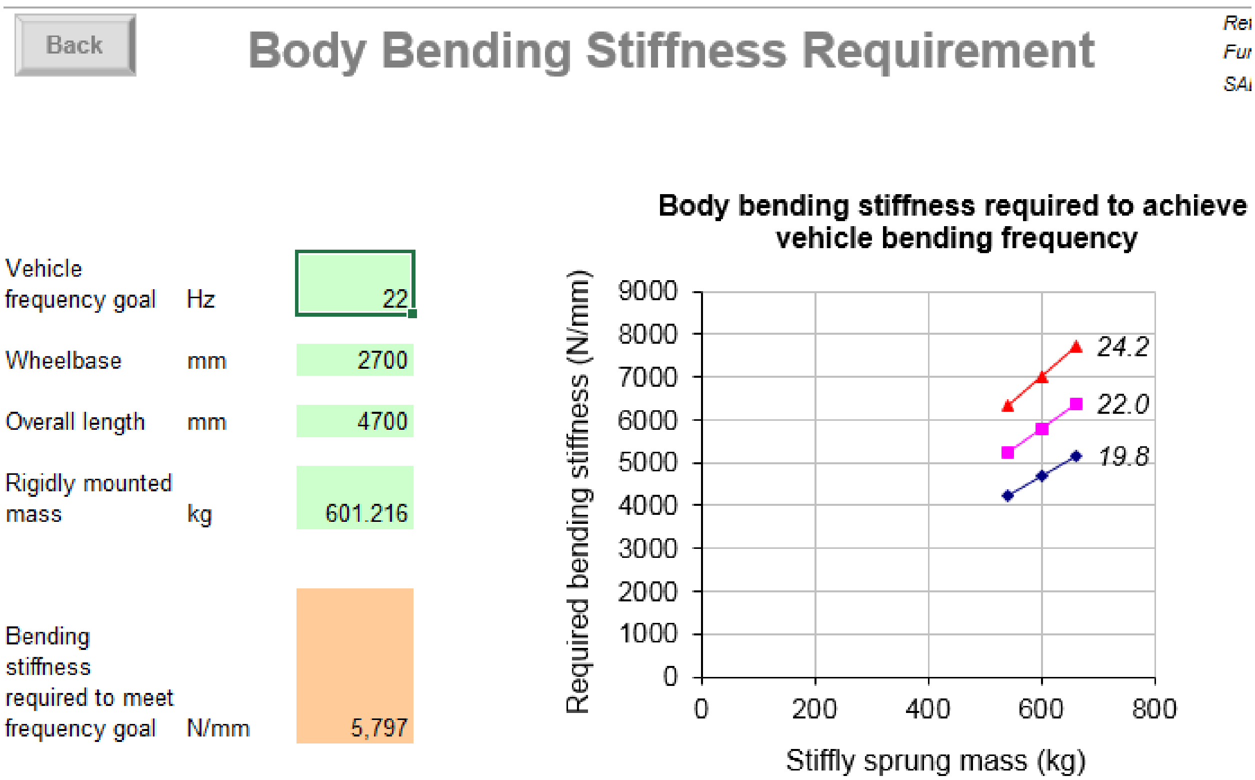


Figure C-4: Bending Stiffness Calculation

Appendix C.4 Torsion Stiffness

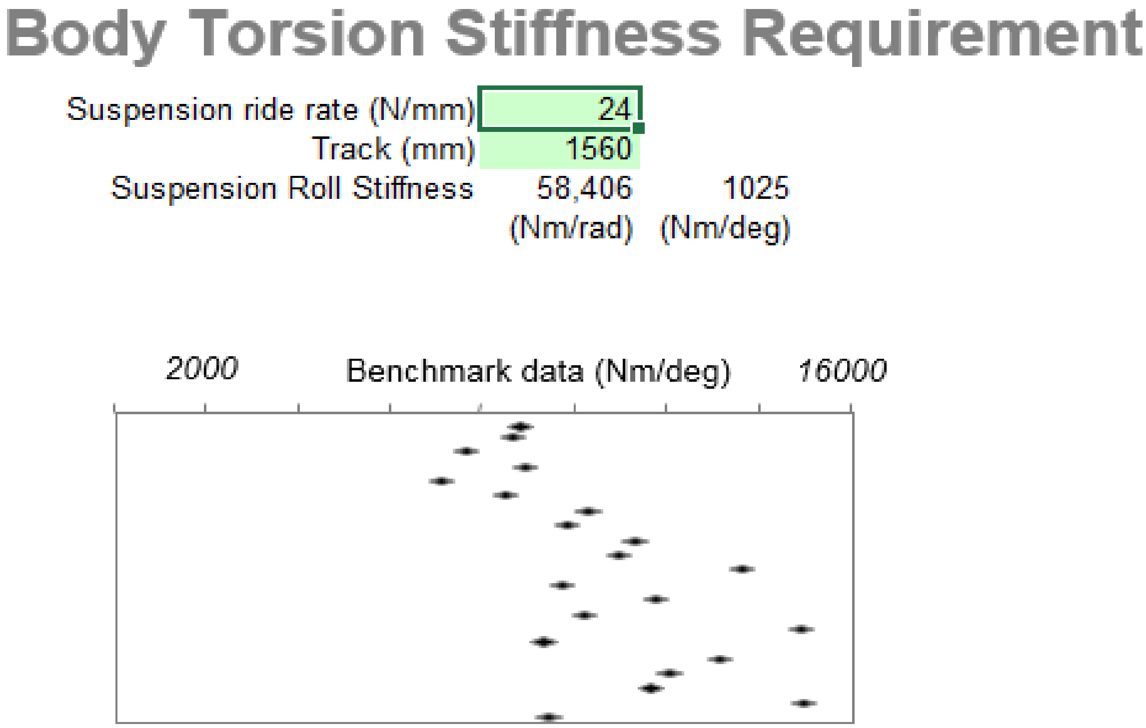
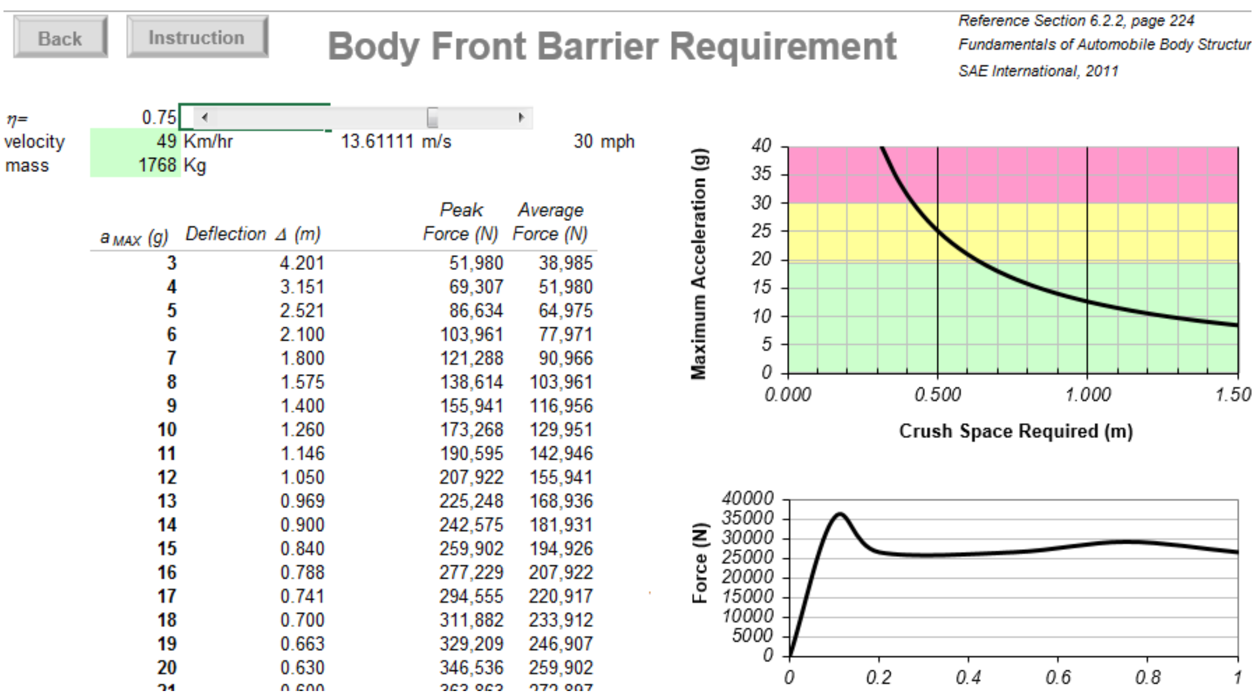


Figure C-5: Torsion Stiffness Calculation

Appendix C.5 Front Barrier Requirement



a_{MAX} (g)	Deflection Δ (m)	Peak Force (N)	Average Force (N)
3	4.201	51,980	38,985
4	3.151	69,307	51,980
5	2.521	86,634	64,975
6	2.100	103,961	77,971
7	1.800	121,288	90,966
8	1.575	138,614	103,961
9	1.400	155,941	116,956
10	1.260	173,268	129,951
11	1.146	190,595	142,946
12	1.050	207,922	155,941
13	0.969	225,248	168,936
14	0.900	242,575	181,931
15	0.840	259,902	194,926
16	0.788	277,229	207,922
17	0.741	294,555	220,917
18	0.700	311,882	233,912
19	0.663	329,209	246,907
20	0.630	346,536	259,902

Figure C-6: Front Barrier Requirement Calculation

Appendix D Section Sizing

Appendix D.1 Side Frame Sizing

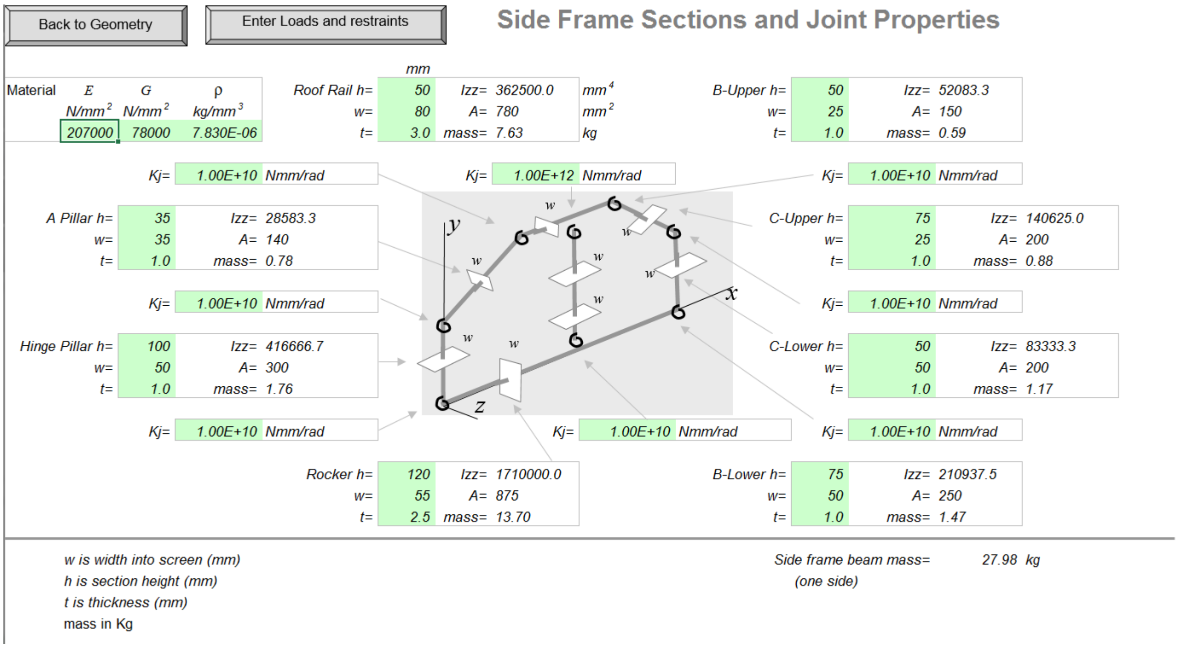
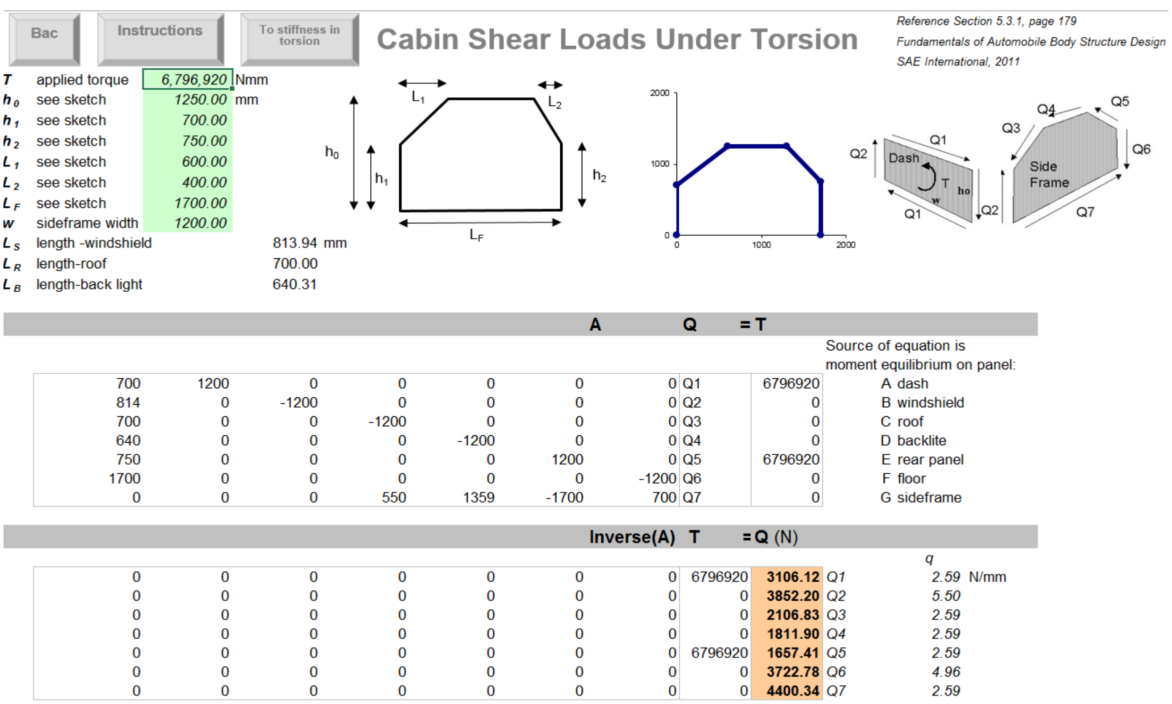


Figure D-1: First Order Model Structure Dimension

Appendix D.2 Torsion Load Analysis



700	1200	0	0	0	0	0	Q1	6796920	A dash
814	0	-1200	0	0	0	0	Q2	0	B windshield
700	0	0	-1200	0	0	0	Q3	0	C roof
640	0	0	0	-1200	0	0	Q4	0	D backlite
750	0	0	0	0	1200	0	Q5	6796920	E rear panel
1700	0	0	0	0	0	-1200	Q6	0	F floor
0	0	0	550	1359	-1700	700	Q7	0	G sideframe

0	0	0	0	0	0	0	6796920	3106.12	Q1	2.59 N/mm
0	0	0	0	0	0	0	0	3852.20	Q2	5.50
0	0	0	0	0	0	0	0	2106.83	Q3	2.59
0	0	0	0	0	0	0	0	1811.90	Q4	2.59
0	0	0	0	0	0	0	6796920	1657.41	Q5	2.59
0	0	0	0	0	0	0	0	3722.78	Q6	4.96
0	0	0	0	0	0	0	0	4400.34	Q7	2.59

Figure D-2: Torsion Load Calculation

Appendix D.3 Panel Shear Rigidity for Torsion Stiffness

Back | Back to Cabin shear loads under torsion

Stiffness in Torsion

Uses cabin dimensions and applied torque input on ***Cabin Shear Loads Under Torsion (sheet: Shear Flow)***

Panel	Area of Panel (mm^2)	Effective Shear Rigidity *Gt* (N/mm)	Shear Flexibility Contribution (mm^3/N)	Pecent Contribution to Shear Flexibility
Dash	*840,000*	*80,000*	*10.5*	*0.1%*
Winshield	*976,729*	*320*	*3052.3*	*35.6%*
Roof	*840,000*	*320*	*2625.0*	*30.6%*
Back Light	*768,375*	*80,000*	*9.6*	*0.1%*
Seat Back	*900,000*	*320*	*2812.5*	*32.8%*
Floor	*########*	*80,000*	*25.5*	*0.3%*
Side Frame-Left	*########*	*80,000*	*23.3*	*0.3%*
Side Frame-Right	*########*	*80,000*	*23.3*	*0.3%*
		sum	*8581.9*	*100.0%*

angle of twist (rad)	*8.46E-03*	rad	*under T=*	*6,796,920 Nmm*
torsional stiffness	*8.03E+08*	Nmm/rad		
torsional stiffness	*14,022*	Nm/deg		

Figure D-3: Panel Shear Rigidity

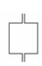
Appendix D.4 Front Barrier Sizing

Back | Instructions

Beam Sizing for Energy Absorption

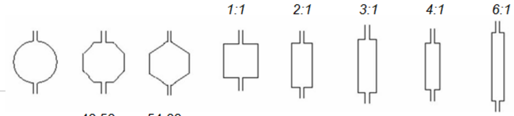
Reference Section 6.2.3, page 226
Fundamentals of Automobile Body Structure Design
SAE International, 2011

Square section



thickness	1.25	mm
width, b	81	mm
yield stress	1030	N/mm^2
material density	7.830E-06	kg/mm^3
perimeter	324	mm
Mean Crush Force	56409	N
Peak unadjusted force	161893	N
Secondary peak force	80100	N
Mass (kg)=	3.171	*kg*
for 1000mm length		

valid for: 38< b <95mm, 62.5< b/t
current b/t= 64.8
current b= 81.0



				1:1	*2:1*	*3:1*	*4:1*	*6:1*
flat (mm)=		40.50	54.00					
width (mm)=	103.13	97.77	108.00	81.00	54.00	40.50	32.40	23.14
height (mm)=	103.13	97.77	93.53	81.00	108.00	121.50	129.60	138.86
perimiter (mm)=	324.00	324.00	324.00	324.00	324.00	324.00	324.00	324.00
Mean Crush Force (N)=	64080	65039	60639	56409	48793	39035	32661	17035

(mass for these sections is same as square section)

Courtesy of the American Iron and Steel Institute, Automotive Steel Design Manual)

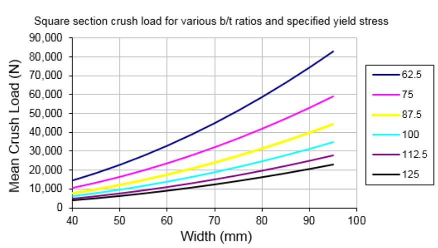


Figure D-4: Front Barrier Sizing Calculation

Appendix D.5 Roof Sizing

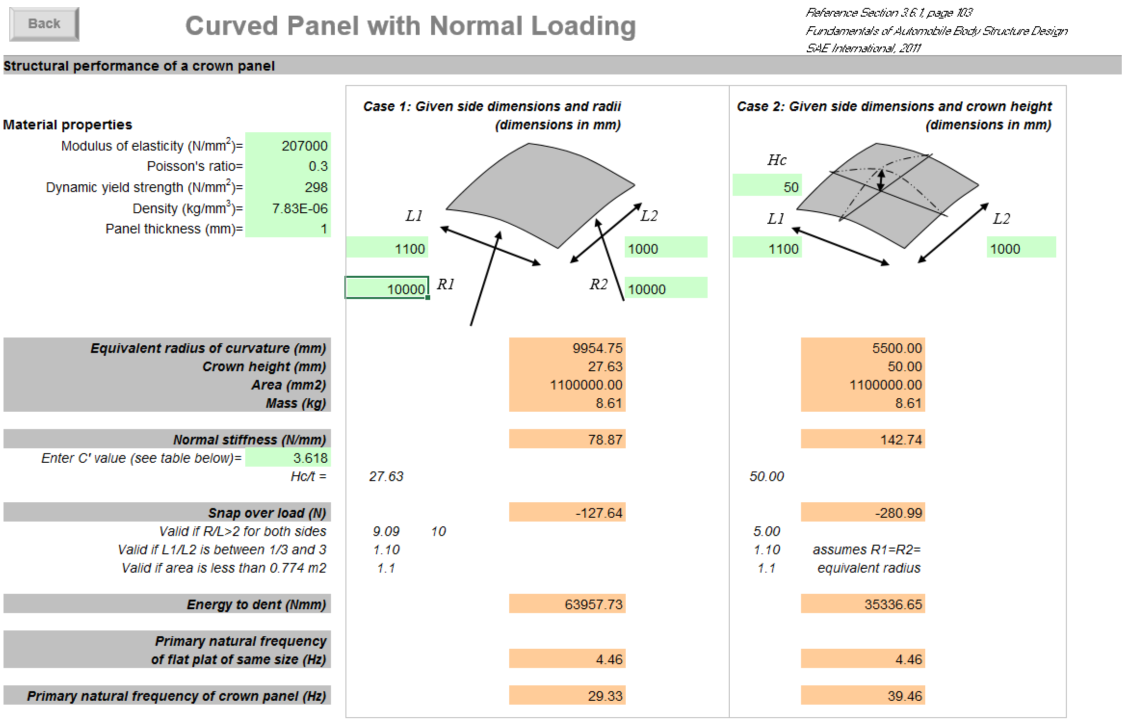


Figure D-5: Roof Denting Energy Calculation