Conceptual Design and Analysis of an All-Terrain Vehicle Roll Cage

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Abstract

Roll cage is a significant structure of an All-terrain Vehicle (ATV) for safety, ergonomics and aesthetic appearance. Roll cage functions as a frame for supporting the body and diverse subsystems of the ATV. Roll cage of the ATV should endure the shock, twist, load, vibration and other stresses during competing. The main make of this effort is to design a roll cage based on definite rules of SAE BAJA to accommodate driver securely, ergonomically design, appropriate material selection with well balance high strength to weight ratio, least possible number of roll cage member and also to achieve an adequate factor of safety. To attain all the above said factors optimal design, analysis and material selection is mandatory. The prime objective of proposed work is, conceptual design and analysis of ATV roll cage is done. It is very vital to check all failure modes of roll cage. Various designed roll cage is taken for analysis for front impact, rear impact and side impact, to get optimal design based on the analysis for the stress, deformation and factor of safety values. The following objective of the proposed work is appropriate material selection, by changing the various suitable low density material in roll cage, yields weight reduction, which leads to better performance of the ATV. For the proposed four various design, analysis were done for front impact, rear impact and side impact. From this four models, Model 4 is an optimal roll cage based on stress, deformation and factor of safety values. Then, for this optimal model different material grades have been incorporated and analysis have been done. From this different analysis of various material grades, ASTM 181 material grade is suitable for ATV roll cage because of better in weight to strength ratio and cost factor.

Key words — *ATV, Roll cage, Analysis, Stress, Deformation, Factor of safety*

I. INTODUCTION

An all-terrain vehicle (ATV), is well-defined by the American Standard National Institute (ANSI) as an automobile which travels on low-pressure tires, with a seat that is straddled by the operator, along with handlebars for steering control. As the name implies, ATV is designed to handle a diversity of terrain than most other vehicles. Although it is a street legal vehicle in some countries, it is not street-legal within most states and provinces of Australia, the United States or Canada [1].

ATV's are used in a variety of industries for their manoeuvrability and off-roading ability. These include construction, emergency medical services, land management, military, mineral exploration, oil exploration and wild land fire control [2].

In today's engineering world, thus an ATV is helpful in some cause. Before fabricating any component, design and analysis should be carried out to meet out the requirements, because it saves time and money. Without any proper design and analysis of the product it cannot be fabricated and used. For this proposed study, for modelling the roll cage Solid works has been used and for analysis Ansys software have been used. By designing a roll cage and analysing it in the Ansys software we can rectify the pros and cons of our component, then slight alteration in design and material can be done and then fabrication the roll cage can be done [3].

Design of any component encompasses of three foremost principles they are Optimization, Safety and Comfort. The primary objective of the roll cage is to provide an envelope around the driver which acts as a 3 dimensional protected space that will keep the driver safe. Secondly it is used to provide reliable mounting locations for components, be appealing, low in cost and weight [4].

Base is designed by taking a horizontal plane as reference plane, the length and width of the base area are designed by taking ninety fifth percentile of man as a constrain. Then, the firewall can be inclined up to 20° on the either side of the base plane. In our case, firewall is inclined to 9° away from the base plane. Primary function of the firewall is to separate cockpit form the engine and gear box assembly unit. A suitable material is used to cover the firewall which can withstand the heat produced from the engine while running. Also it provides area for mounting the seat belts and fire extinguisher which is needed as per SAE BAJA rule book constrain. Then further cockpit is developed based upon the driver requirement, suspension mount points, steering assembly and ease of manufacturing [5].

Finite Element Analysis (FEA) is a systematic mathematical approach for finding an approximate solutions and the behaviour of objects virtually [6]. It is a method for anticipating how an object or a model behaves to real world scenario. It prepares a mathematical model to find approximate solution to boundary value problems by using partial differential equations. Finite element analysis shows whether a product will break, wear out, or work the way it was designed [4-6].

While analysis we can obtain the stress, deformation and factor of safety values based upon the given impact load and boundary conditions given. If the obtained value were not satisfactory then the design can be slightly changed and then tested till we get better factor of safety value. Also if the design too much safe i.e. having very high factor of safety, then some members can be reduced and then tested for the impacts. Thus automatically the weight of the roll cage will be reduced and will be the optimal roll cage for the ATV [7].

For reducing the weight, besides eliminating the members, we can go for the change in material with higher bending strength and stiffness higher than the base material suggested by SAE BAJA rule book, provided that material should have 0.18% carbon content. If we go for material with such factors, we can use pipe with minimum thickness of 1.57mm rather than using pipe of 3mm thickness, which will reduce the weight of roll cage significantly. Also we can choose light density material also so that we can reduce the weight of the roll cage [5-8].

There are lot of materials available in the market. In this case, we should consider the cost of the material too as it is one of the most important factor for deciding the material selection. Based on the cost and the strength the material for the roll cage should be decided. The material which met out SAE BAJA rules and our calculations are ASTM 1018, ASTM 106 B, ASTM 108, AISI 148, AISI 182, AISI 335, AISI 4340, AISI A 36, AISI 205 [8].

In the previous year's selective driver was taken and roll cage measurements were done and designed. This year based on severe literature survey, SAE INDIA BAJA rule book constrain and commercial requirement we have designed roll cage for the 95th percentile of the man. In the material selection, if the material with high strength with low density, the cost of the material will be significantly higher. On other hand, if the material is of lesser cost, the properties of the materials will be lower than the previous case. In this case, material which is cost effective and good in strength should be selected. It is the fact that, the material will have higher strength while bended rather than the welding. In this case, proposed roll cage has been incorporated with much bending than the previous year which reduced welding cost also. Also while bending the roll cage meshing of the pipe will be finer than welding [9]. In this proposed study four different types of roll cage with slight modification in the design have been analysed. In this having an advantage of lower weight of the roll cage, it will also lead to less number of the welded members in the roll cage. Due to this cost and weight of the roll cage will be reduced.

II. DESIGN AND ANALYSIS OF ROLL CAGE

A. Calculation for Impact Force and Strength

For analysis of the roll cage, force impact values should be calculated. Also Bending Strength for the different grade materials should be calculated and the value should be greater than the reference material bending strength as suggested by SAE BAJA rule book.

1) Force calculation for front and rear impact

Front impact is in which there is possibility of hitting another vehicle which affects vehicle front part. The deceleration value for the front impact is 4g. The load is applied on the frontal members of the roll cage while the rear suspension mount points are made fixed.

Rear Impact is in which there is possibility of hitting our vehicle by another from the rear side which affects rear part. The deceleration value for rear impact is 4G. The load is applied on the rear members of the roll cage while the front suspension mount points are fixed.

Assuming the weight of the ATV with driver as 330kg, the impact force was calculated based on G load of 4.

$F = ma$

$=330*9.81*4$

$=12,949.2N$

So approximately frontal and rear impact load was taken as 13,000N and the analysis is carried out is given below.

2) *Force calculation for side impact*

Side Impact analysis is done due to possibility of hitting our vehicle from the either of direction. In this case deceleration value is 2G. In this case, load is applied on the side impact members, while the other side of the suspension mount points are fixed.

Using the assumed weight of the vehicle with driver 330kg, the impact force was calculated based on G load of 2

F = ma

= 330*9.81*2

= 6,477.6N

So approximately side impact load was taken as 6,500N and analysis is carried out is given below.

Analysis is done in Ansys Workbench 14.5, in which fine mesh with zero relevance is chosen. Meshing size is default meshing which is program controlled by software.

3) *Strength calculation for roll cage material*

Property	Value
Density	7500 kg/m3
Poisson Ratio	0.3
Yield strength	377.8Mpa
Modulus of elasticity	205Gpa
Cost per metre	165Rs

Table 1: Mild Steel ASTM 106B properties

The material selected for this process is Mild Steel (MS) ASTM 106 B. The bending strength for MS ASTM 106 B material was calculated as follows:

Bending Strength = (Sy*I)/C

Bending Stiffness = Ex*Ix

Where,

Sy = Yield Strength;

I = Second moment of inertia for the structural cross member;

C = Distance from neutral axis to extreme fibre;

Ex = Modulus of elasticity (205Gpa)

Moment of Inertia = (3.14/64)*(D^^{4} - d^^{4})

= (3.14/64)*(25.4^^{4} - 19.4^^{4})

= 13,478.6mm^^{4}

= 1.34786 * 10^$^{-8}$ m^^{4}

Yield Strength Sy = 377.8Mpa

Bending Strength = (377.8*10^^{6}*1.347*10^$^{-8}$) / (0.0127)

= 400.70 Nm

Hence the bending Strength obtained for this material is greater than the reference material AISI 1018 (387Nm) in SAE BAJA rule book, this material is used for our analysis.

The following assumptions were made for design and analysis they are**;** material used for roll cage is assumed to be homogenous and all the welded joints are assumed to be perfect joints.

B. *Computational Design and Analysis of roll cage Model 1*

Initially a roll cage is modelled by using solid works and the model was given below.

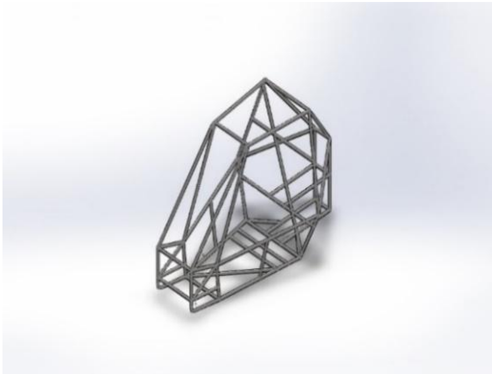
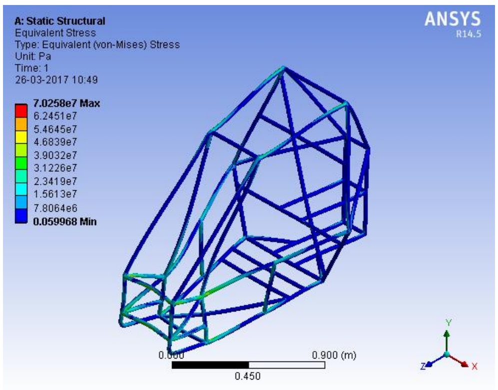


Figure1: Modelled roll cage (Model 1)

Analysis of model 1 roll cage for front impact, rear impact and side impact were done and the results are shown.

1) *Front Impact for Model1*

Front Impact analysis for Model 1 has been done and Stress, deformation and factor of safety results were shown in figure.



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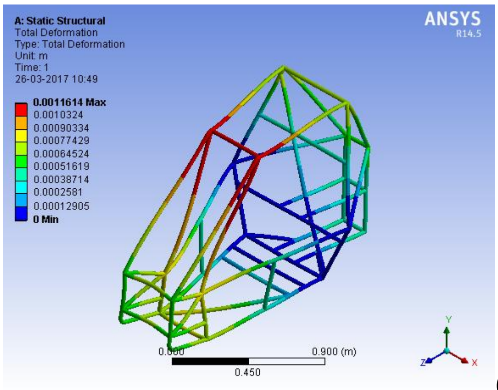

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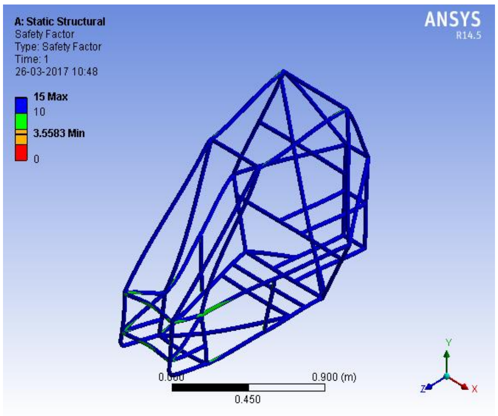

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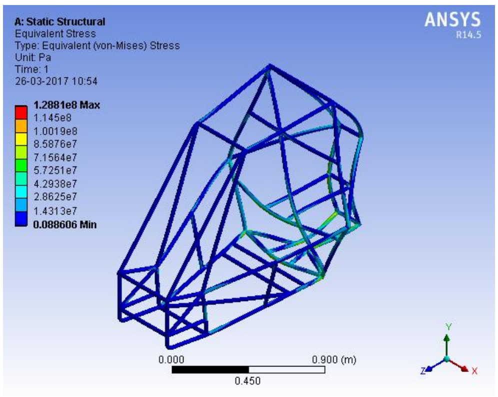
Figure 2: Model 1 front impact (i) stress (ii) deformation and (iii) factor of safety

2) Rear Impact for Model1

Rear Impact analysis for Model 1 has been done and Stress, deformation and factor of safety results were shown in figure.



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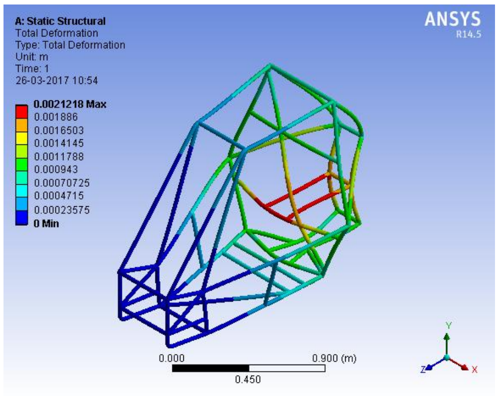

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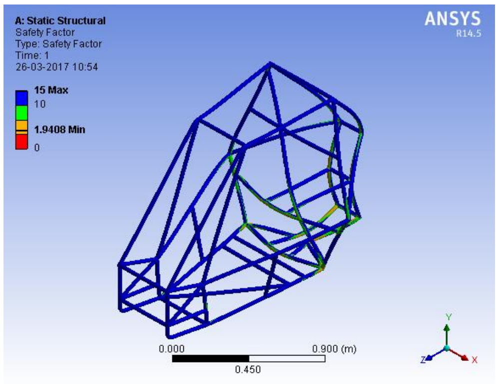

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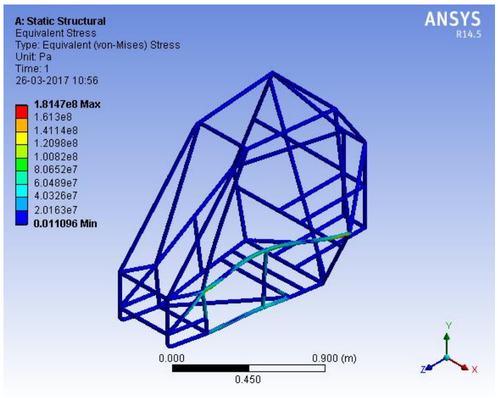
Figure 3: Model 1 rear impact (i) stress (ii) deformation and (iii) factor of safety

3) Side Impact for Model1

Side Impact analysis for Model 1 has been done and Stress, deformation and factor of safety results were shown in figure.



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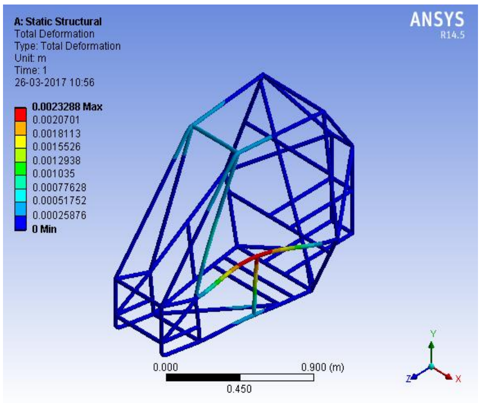

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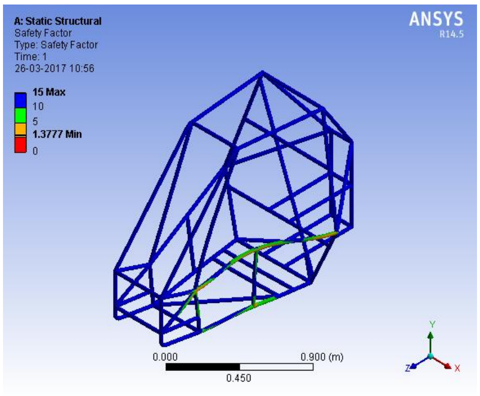

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Figure 4: Model 1 side impact (i) stress (ii) deformation and (iii) factor of safety

Description	Stress (MPa)	Deformation (mm)	Factor of Safety
Front impact	70.25	1.16	3.55
Rear impact	128.88	2.12	1.94
Side impact	181.47	2.33	1.37

Table 2: Impact analysis value for Model 1

Thus impact value for the roll cage model 1 was tabulated above.

C. Computational Design and Analysis of roll cage Model 2

Thus the factor of safety obtained for the three impact analysis was very safe. But, while fabricating this design might lead to more members in the roll cage and increases the weight of the ATV. So from this design some members were removed which also satisfy rulebook norms and then analysis were done. After redesigning the roll cage, analysis for roll cage (Model 2) have been done. Model 2 roll cage is shown in the figure below

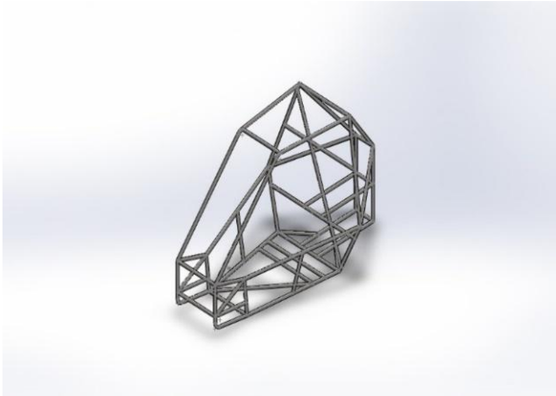
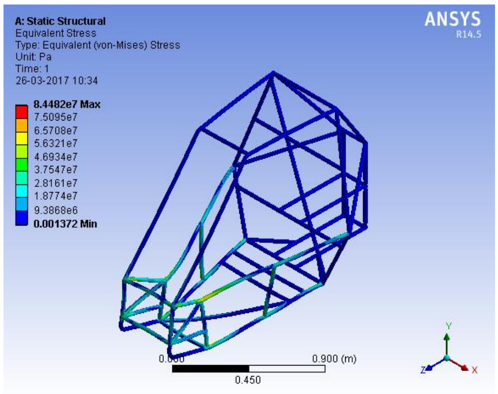


Figure 5: Modelled Roll cage (Model 2)

Analysis of model 2 roll cage for front impact, rear impact and side impact were done and the results are given below.

1) Front Impact Model2

Front Impact analysis for Model 2 has been done and Stress, deformation and factor of safety results were shown in figure.



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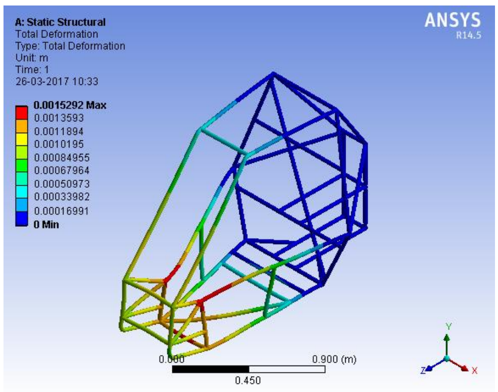

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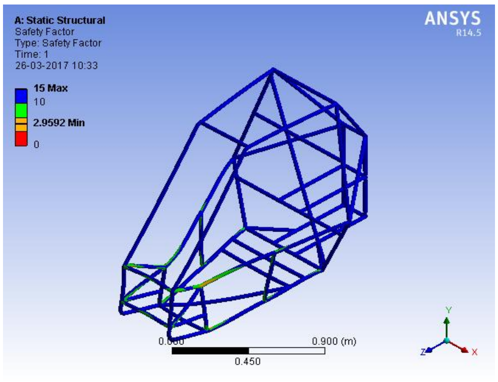

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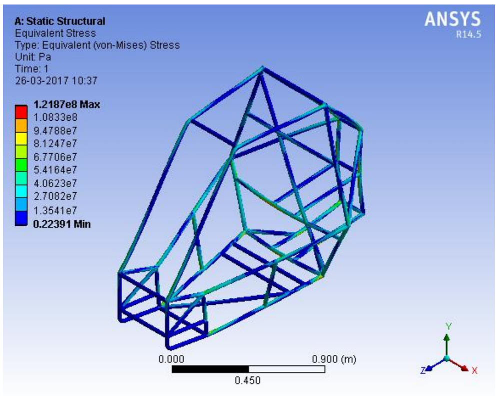
Figure 6: Model 2 front impact (i) stress (ii) deformation and (iii) factor of safety

2) Rear Impact Model2

Rear Impact analysis for Model 2 has been done and Stress, deformation and factor of safety results were shown in the figure.



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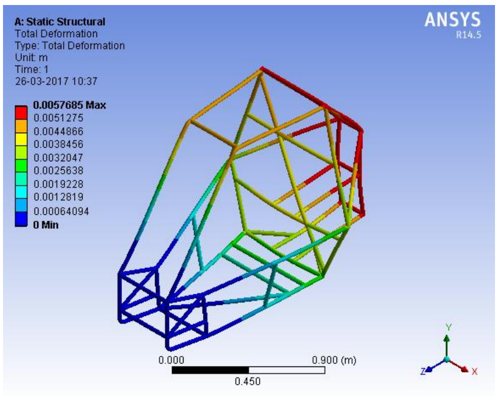

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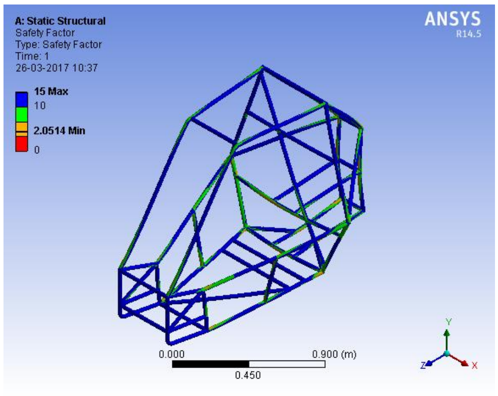

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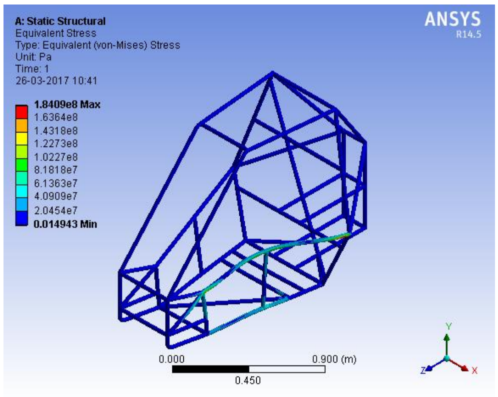
Figure 7: Model 2 rear impact (i) stress (ii) deformation and (iii) factor of safety

3) Side Impact Model2

Side Impact analysis for Model 2 has been done and Stress, deformation and factor of safety results were shown in figure.



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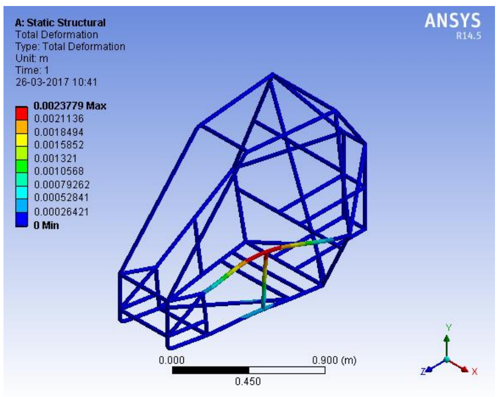

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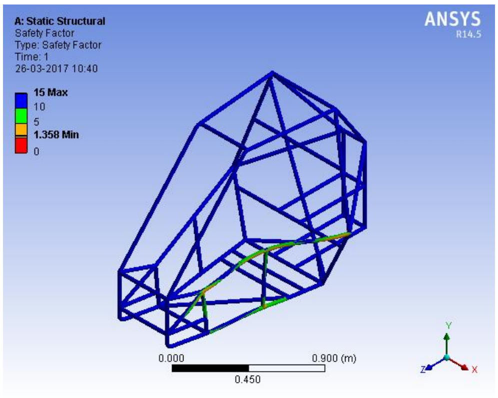

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Figure 8: Model 2 side impact (i) stress (ii) deformation and (iii) factor of safety

Description	Stress (Mpa)	Deformation (mm)	Factor Of Safety
Front Impact	84.48	1.52	2.95
Rear Impact	121	5.67	2.05
Side Impact	184	2.37	1.358

Table 3: Impact analysis value for Model2

Thus impact value for the roll cage model 2 was tabulated above.

D. Computational Design and Analysis of roll cage Model 3

Thus the factor of safety, deformation ad stress values obtained for the model 2 are safe and within permissible limits. From model 2 some members have been removed and then analysis have been done for the model 3. Model 3 roll cage is shown in the figure below

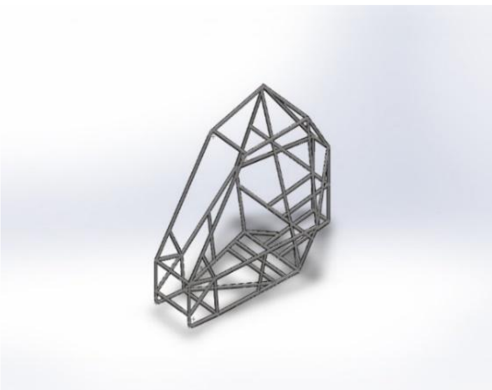
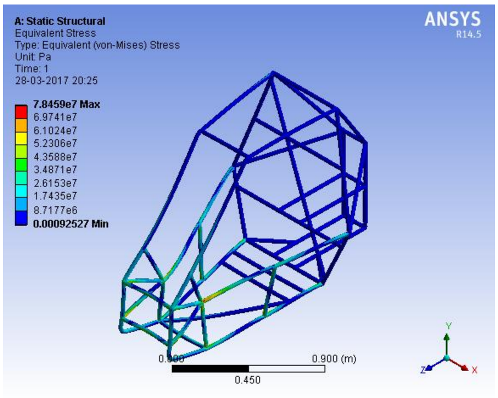


Figure 9: Modelled Roll cage (Model 3)

Analysis of model 3 roll cage for front impact, rear impact and side impact were done and the results are given below

1) Front Impact for Model 3

Front Impact analysis for Model 3 has been done and Stress, deformation and factor of safety results were shown in figure.



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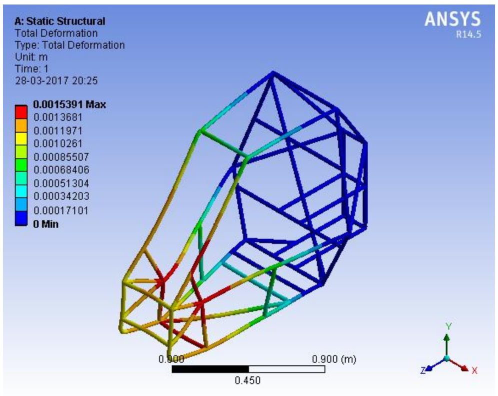

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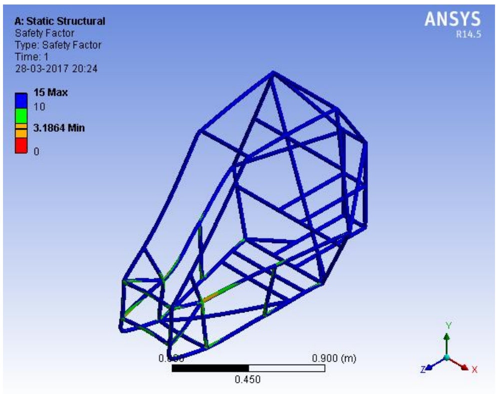

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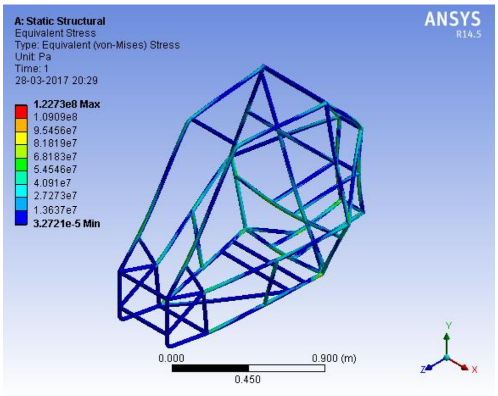
Figure 10: Model 3 front impact (i) stress (ii) deformation and (iii) factor of safety

2) Rear Impact for Model3

Rear Impact analysis for Model 3 has been done and Stress, deformation and factor of safety results were shown in figure.



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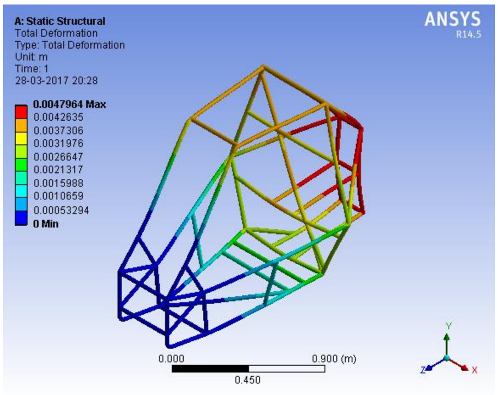

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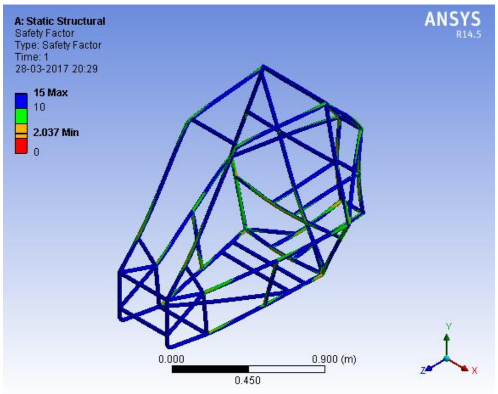
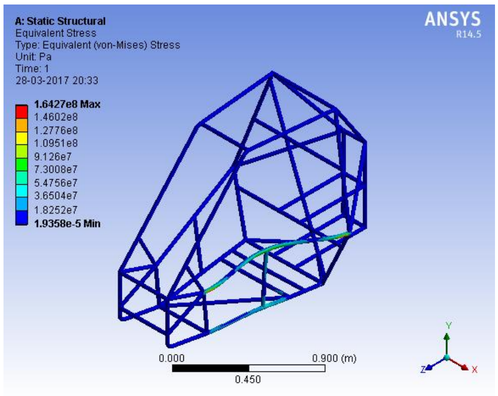


(iii)

Figure 11: Model 3 rear impact (i) stress (ii) deformation and (iii) factor of safety

3) Side Impact for Model3

Side Impact analysis for Model 3 has been done and Stress, deformation and factor of safety results were shown in figure.



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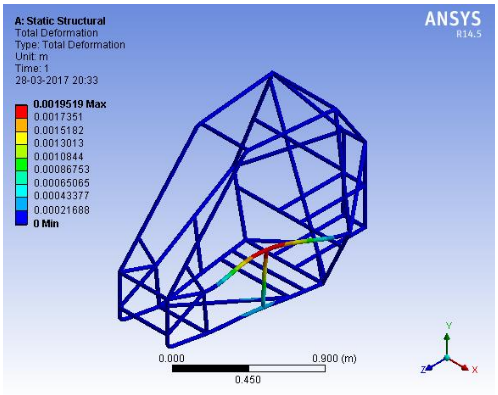

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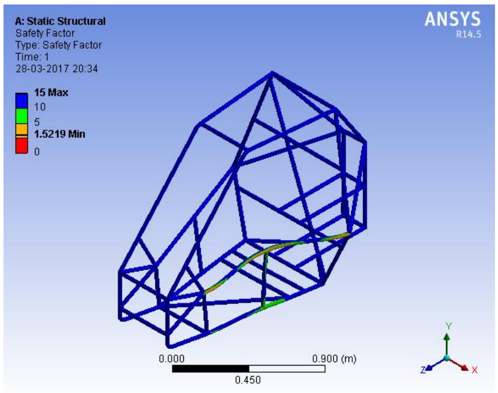

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Figure 12: Model 3 side impact (i) stress (ii) deformation and (iii) factor of safety

Description	Stress (Mpa)	Deformation (mm)	Factor Of Safety
Front Impact	78.4	1.539	3.186
Rear Impact	122.73	4.769	2.031
Side Impact	164	1.951	1.522

Table 4: Impact analysis value for model 3

Thus impact value for the roll cage model 3 was tabulated above.

E. Computational Design and Analysis of roll cage Model 4

From this model analysis, the roll cage design is safer. But some members can also be removed from this model and then a new design can be obtained with reduction in members. Then analysis for new model is done. Model 4 roll cage is shown in figure below.

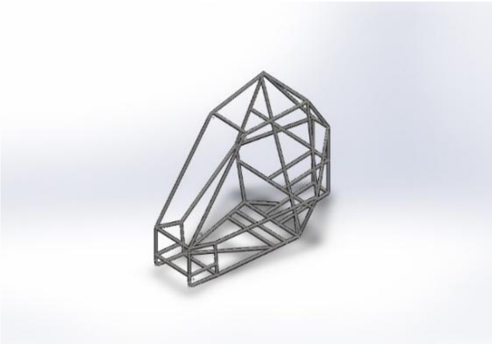
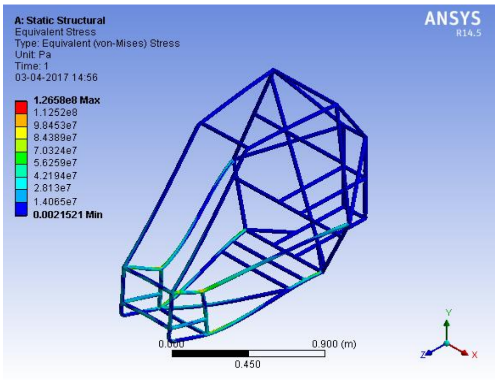


Figure 13: Modelled Roll cage (Model 4)

Analysis of model 4 roll cage for front impact, rear impact and side impact were done and the results are given below.

1) Front Impact for Model 4

Front Impact analysis for Model 4 has been done and Stress, deformation and factor of safety results were shown in figure.



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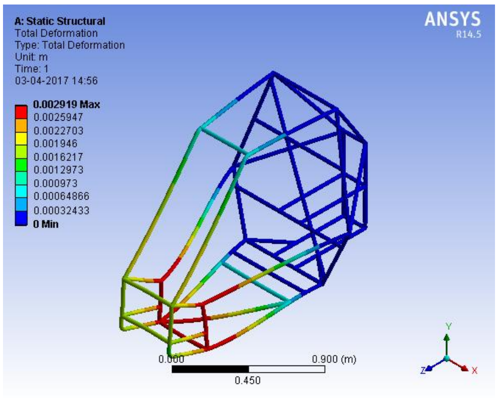

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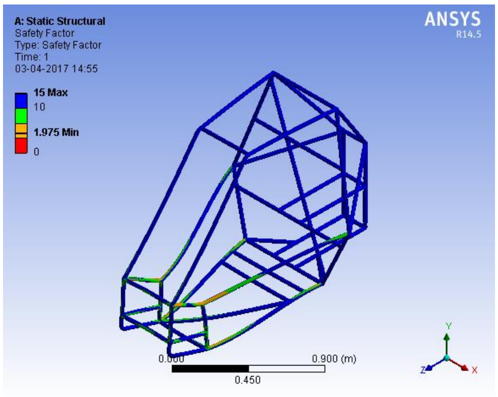

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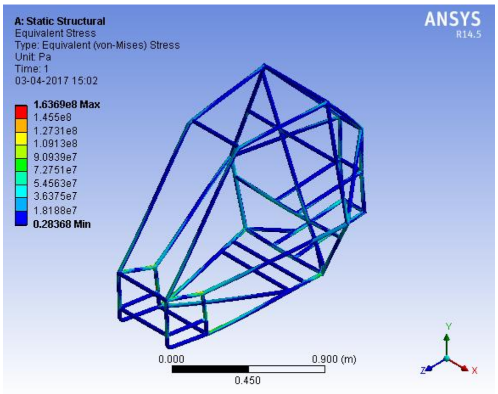
Figure 14: Model 4 front impact (i) stress (ii) deformation and (iii) factor of safety

2) Rear Impact for Model4

Rear Impact analysis for Model 4 has been done and Stress, deformation and factor of safety results were shown in figure.



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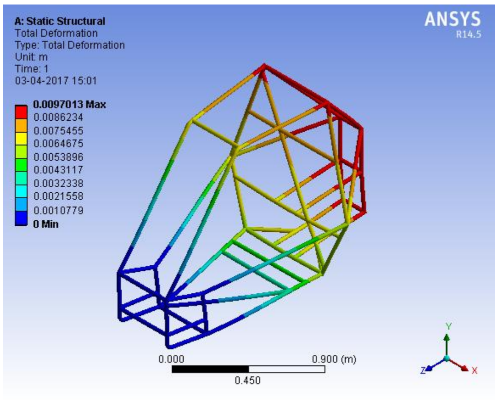

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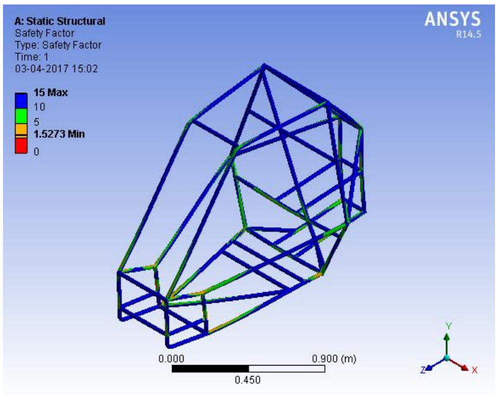

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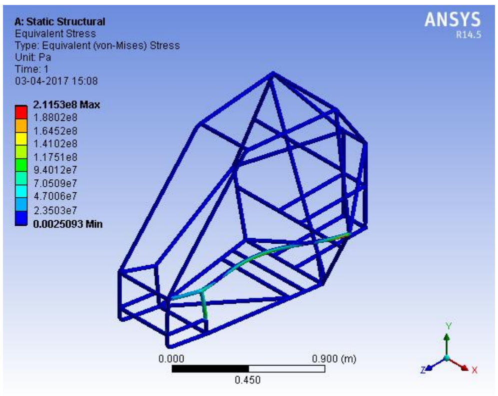
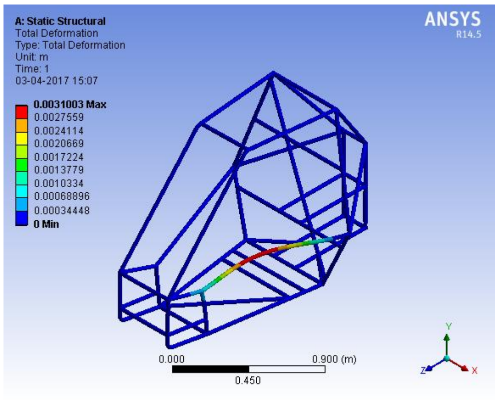
Figure 15: Model 4 rear impact (i) stress (ii) deformation and (iii) factor of safety

3) Side Impact for Model4

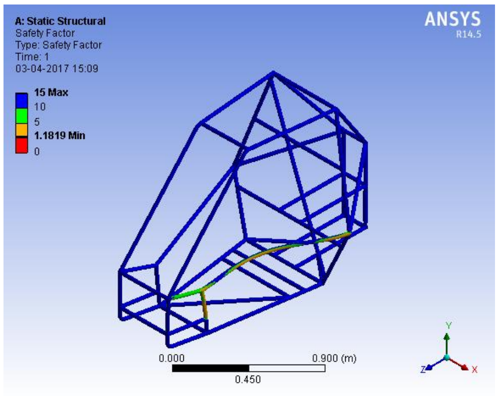
Side Impact analysis for Model 4 has been done and Stress, deformation and factor of safety results were plotted in figure.



(i)



(ii)



(iii)

Figure 16: Model 4 side impact (i) stress (ii) deformation and (iii) factor of safety

Description	Stress (Mpa)	Deformation (mm)	Factor Of Safety
Front Impact	126.5	2.919	1.975
Rear Impact	163.7	9.71	1.527
Side Impact	211.18	3.127	1.184

Table 5: Impact analysis value for model 4

Thus impact value for the roll cage model 4 was tabulated above.

F. Computational Design and Analysis of Optimized Roll cage

Thus the factor of safety obtained in this model are satisfactory and Model 4 will be the optimized roll cage, which follows all the rule book constrain and driver can accommodate into this roll cage without any discrepancy. The below model shows Optimal design for roll cage taken for further analysis.

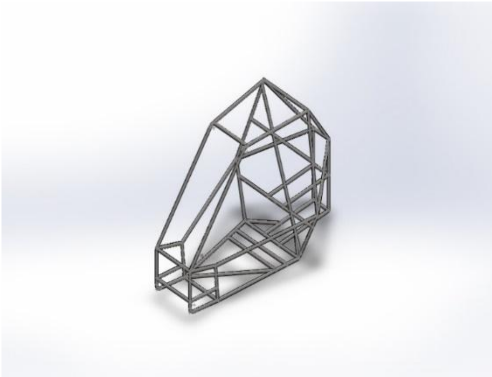


Figure 17: Optimized Roll cage

Based upon market survey, there are lot of materials available rather than MS ASTM 106B. So with this optimized roll cage, analysis is will be done for the different materials and their factor of safety, stress, deformation were analysed. Then at last, comparing all different materials analysis value and cost factor, a roll cage material is chosen, which is effective both in cost and strength. Based on the market survey, cost factors and strength to weight ratio, nearly equivalent grates to be taken & by varying different roll cage materials for further analysis. The various grades are ASTM 181 & AISI 4340.

G. Strength calculation for roll cage material ASTM 181

Property	Value
Density	7800 kg/m3
Poisson Ratio	0.29
Yield strength	497.3Mpa
Modulus of elasticity	205Gpa
Cost per metre	325Rs

Table 6:ASTM 181 material properties

The material selected for this process is ASTM 181. The bending strength for ASTM 181 material was calculated as follows:

Bending Strength = (Sy*I)/C

Bending Stiffness = Ex*Ix

Where,

Sy = Yield Strength;

I = Second moment of inertia for the structural cross member;

C = Distance from neutral axis to extreme fibre;

Ex = Modulus of elasticity (205Gpa)

Moment of Inertia = $(3.14/64)*(D^{\wedge 4} - d^{\wedge 4})$

$= (3.14/64)*(25.4^{\wedge 4} - 21.4^{\wedge 4})$

$= 10136.74mm^{\wedge 4}$

$= 10136.74 * 10^{\wedge -12}\ m^{\wedge 4}$

Yield Strength Sy = 497.3Mpa

Bending Strength = $(497.3*10^{\wedge 6}*10136.74*10^{\wedge -12})/(0.0127)$

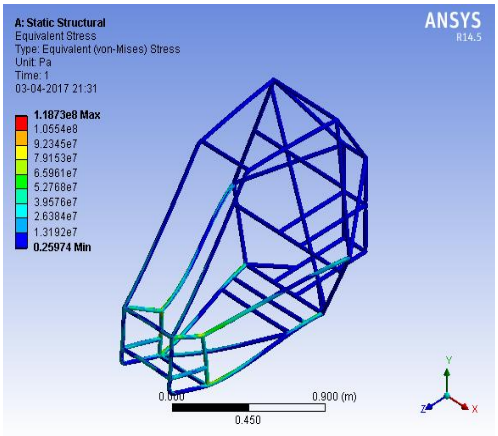
= 396.929 Nm

Hence the bending Strength obtained for this material is greater than the reference material AISI 1018 (387Nm) in SAE BAJA rule book, this material is used for analysis.

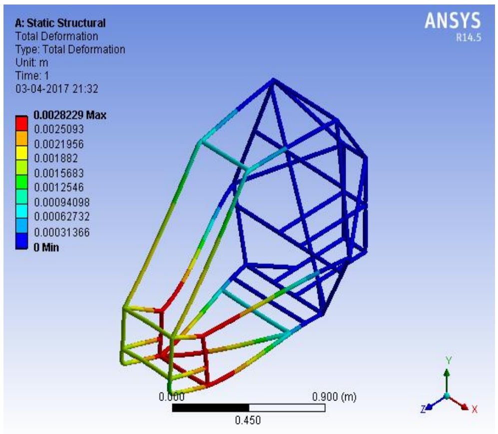
Analysis of optimized roll cage for front impact, rear impact and side impact were done with material grade ASTM 181 with 1" OD and 2mm thickness and the results are given below.

1) Front Impact for ASTM 181

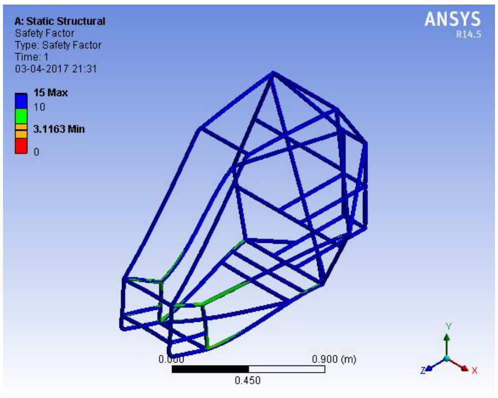
Front Impact analysis for optimized roll cage with ASTM 181 has been done and Stress, deformation and factor of safety results were shown in figure.



(i)

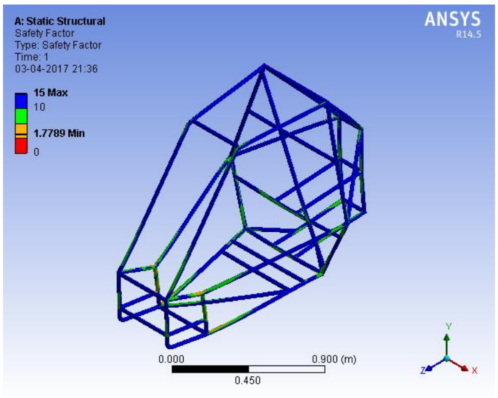


(ii)



(iii)

Figure 18: ASTM 181 front impact (i) stress (ii) deformation and (iii) factor of safety

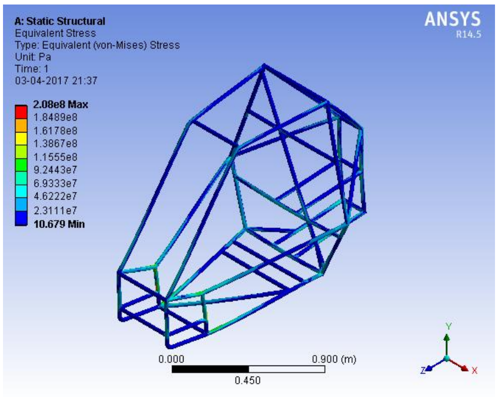


(iii)

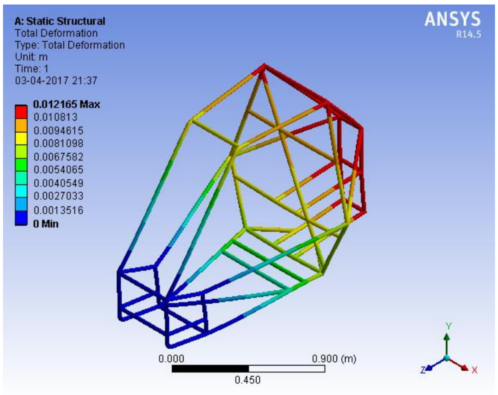
Figure 19: ASTM 181 rear impact (i) stress (ii) deformation and (iii) factor of safety

2) Rear Impact for ASTM 181

Rear Impact analysis for optimized roll cage with ASTM 181 has been done and Stress, deformation and factor of safety results were shown in figure.



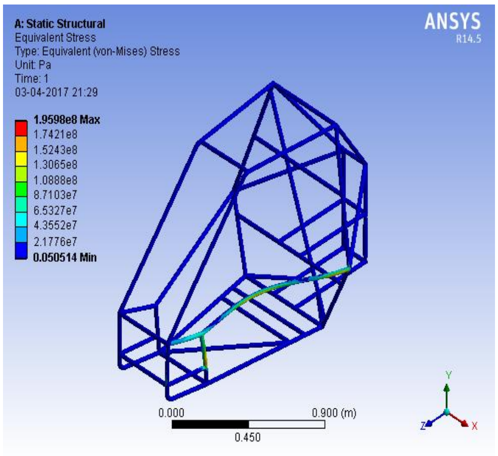
(i)



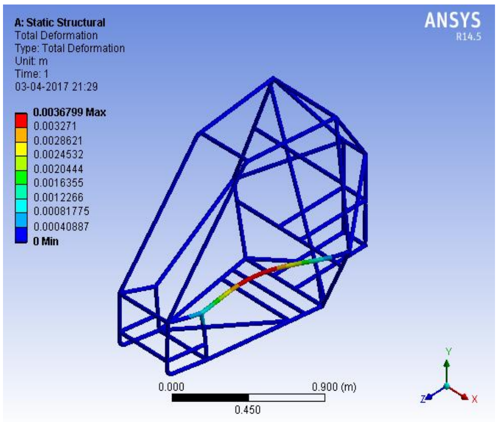
(ii)

3) Side Impact for ASTM 181

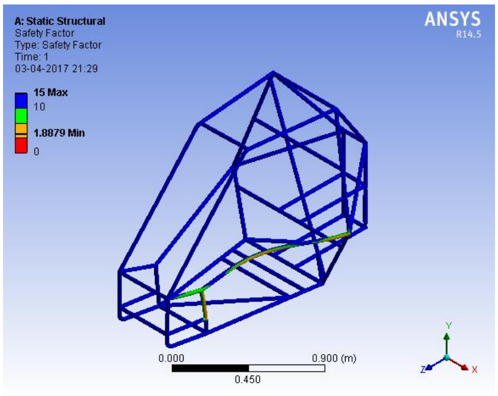
Side Impact analysis for optimized roll cage with ASTM 181 has been done and Stress, deformation and factor of safety results were shown in figure.



(i)



(ii)



(iii)

Figure 20: ASTM 181 side impact (i) stress (ii) deformation and (iii) factor of safety

Description	STRESS (MPa)	DEFORMATION (mm)	FACTOR OF SAFTEY
Front Impact	118.73	2.8229	3.1163
Rear Impact	208	12.165	1.7789
Side Impact	195.98	3.6799	1.8879

Table 7: Impact analysis value for optimized roll cage with ASTM 181

Thus impact value for the optimal roll cage model with ASTM 181 material was tabulated above.

Next, for the optimized roll cage, AISI 4130 material is selected and bending strength of the material is calculated as below.

H. Strength calculation for roll cage material AISI 4130

Property	Value
Density	7850 kg/m3
Poisson Ratio	0.29
Yield strength	591.12Mpa
Modulus of elasticity	205Gpa
Cost per metre	635Rs

Table 8: AISI 4130 material properties

The material selected for this process is AISI 4130. The bending strength for AISI 4130 material was calculated as follows:

Bending Strength = (Sy*I)/C

Bending Stiffness = Ex*Ix

Where,

Sy = Yield Strength;

I = Second moment of inertia for the structural cross member;

C = Distance from neutral axis to extreme fibre;

Ey = Modulus of elasticity (205Gpa)

As per market survey, AISI 4130 pipe with 1.75mm thickness and 1" OD is the minimum availability. So we are going for that thickness pipe.

Moment of Inertia = $(3.14/64)*(D^{\wedge 4} - d^{\wedge 4})$

$=(3.14/64)*(25.4^{\wedge 4}–21.9^{\wedge 4})$

$= 9140.35 mm^{\wedge 4}$

$= 9140.35 * 10^{\wedge -12}\ m^{\wedge 4}$

Yield Strength Sy = 591.12Mpa

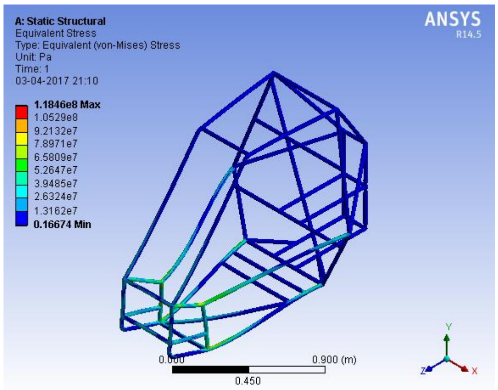
Bending Strength = $(591.22*10^{\wedge 6}*9140.35*10^{\wedge -12})$ / (0.0127)

= 425.50Nm

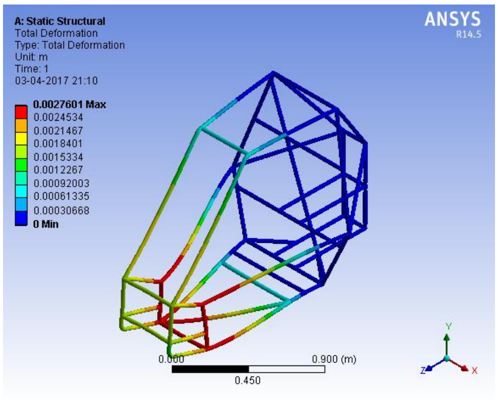
Hence the bending Strength obtained for this material is greater than the reference material AISI 1018 (387Nm) in SAE BAJA rule book, this material is used for analysis.

1) 2.8.1 Front Impact for AISI 4130

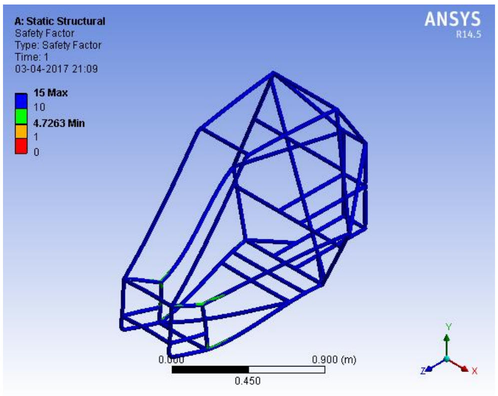
Front Impact analysis for optimized roll cage with AISI 4130 has been done and Stress, deformation and factor of safety results were shown in figure.



(i)



(ii)

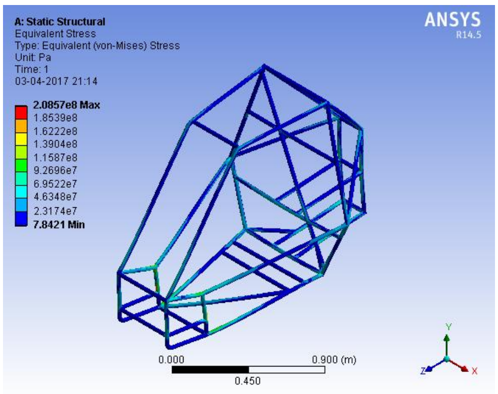


(iii)

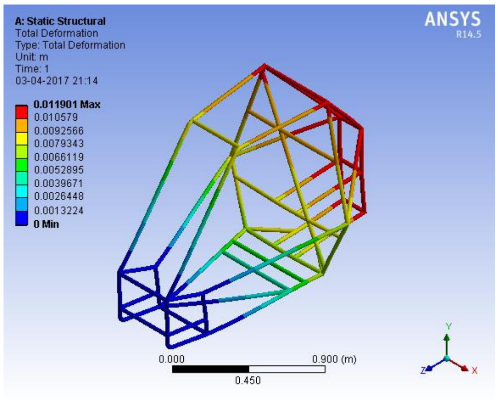
Figure 21: AISI 4130 front impact (i) stress (ii) deformation and (iii) factor of safety

1) Rear Impact for AISI 4130

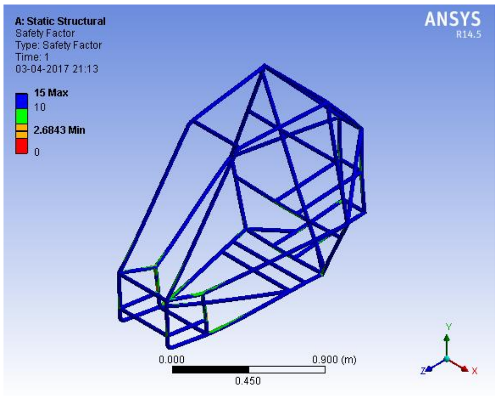
Rear Impact analysis for optimized roll cage with AISI 4130 has been done and Stress, deformation and factor of safety results were shown in figure.



(i)



(ii)

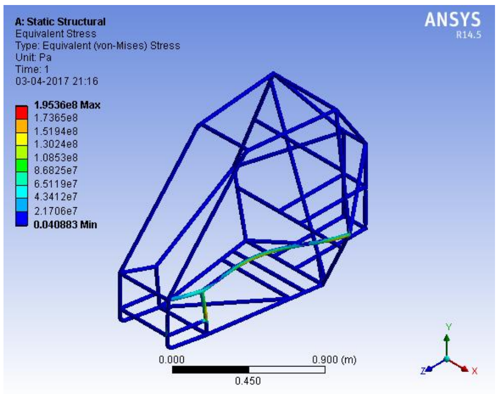


(iii)

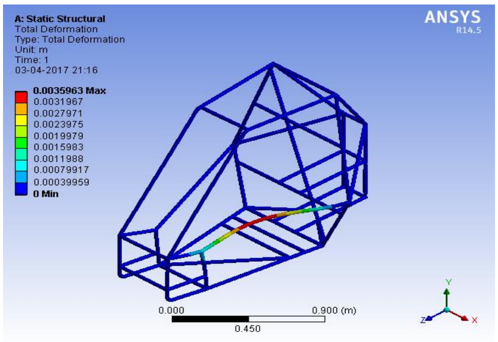
Figure 22: AISI 4130 rear impact (i) stress (ii) deformation and (iii) factor of safety

2) Side Impact for AISI 4130

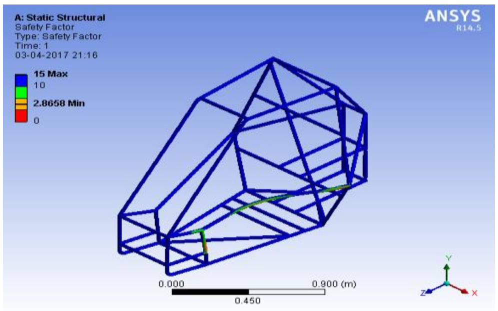
Side Impact analysis for optimized roll cage with AISI 4130 has been done and Stress, deformation and factor of safety results were shown in figure.



(i)



(ii)



(iii)

Figure 23: AISI 4130 side impact (i) stress (ii) deformation and (iii) factor of safety

Description	Stress (Mpa)	Deformation (mm)	Factor Of Safety
Front Impact	118.46	2.7601	4.726
Rear Impact	208.57	11.901	2.6843
Side Impact	195.36	3.5693	2.8658

Table 9: Impact analysis value for optimized roll cage with AISI 4130

Thus impact value for this roll cage model was tabulated above.

Thus, based upon this analysis values for AISI 4130 and ASTM 181, AISI 4130 yields good strength value than the AISI 181. But Based upon the economic fact AISI 4130 is twice costly than ASTM 181. Since ASTM 181 strength is only slightly lesser than AISI 4130 and cost economic, ASTM 181 is considered for further process.

III. CONCLUSION

Thus in this work, roll cage model is designed and then analysed by taking Mild steel ASTM 106 B as roll cage material, then some modification have been done in the roll cage and then analysed with various designed models yields optimal model. This lead to reduction in weight of roll cage and welding cost.

From the first design to final design, gradually members and the weight of roll cage have been reduced. Totally eight members were removed from the initial design and optimal design is obtained and then used for further process.

From the optimal design, based upon market survey, commercially used different material grades have been incorporated and analysed and the values were reported. In which ASTM 181, was better in both economic fact and strength.

Initial design of roll cage with Mild steel ASTM 106 B weights 40.2kg while the optimal design with Mild Steel ASTM 106 B yields 36.8kg. But when we incorporate ASTM 181 material for the optimal roll cage it weight 27.5kg.Thus 12.7kg have been reduced in the roll cage model by changing the design and integrating the optimal roll cage material, which will helps in better performance of the ATV.The optimal design roll cage is of 55” wheel base and 51” track width.

Thus the optimal design with optimal material of ASTM 181 yields sufficient factor of safety of 3.1163, 1.7789, 1.8879 for front impact, rear impact and side impact analysis respectively. Also deformation for the same model is 2.8229mm, 12.165mm, 3.6799mm for front impact, rear impact and side impact analysis respectively. Thus the factor of safety, deformation values obtained for the optimized roll cage with ASTM 181 grade material is adequate, the same model with ASTM 181 material is used for the further process.

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