

“Design and Simulation of Roll Cage of an All-Terrain Vehicle”

Ketha Jaya Sandeep

Department of Mechanical Engineering, Indian Institute of Technology, Bhilai, Chhattisgarh, India

Abstract - A roll cage is a specially engineered and constructed frame built in the passenger compartment of a vehicle to protect its occupants from being injured or killed in an accident, particularly in the event of a rollover. This paper is based on the static analysis and optimization of a Roll cage of a single seated vehicle in off-road conditions using a constant pipe cross-section. The objective of this work is to design an efficient roll cage to be installed on an All-Terrain Vehicle for the competitions Enduro Student India and Mega ATV Championship, by keeping the frame weight low and having enhanced ergonomics that is comfortable and safe with adequate structural strength and stiffness along with other subsystems compatibility. Three dimensional solid models of a roll cage are created using SOLIDWORKS 2018 software. Analysis of roll cage is performed on Ansys 16.2 Detailed description of material is provided, finite element meshing is done, the load condition is worked out, and the boundary conditions are clearly mentioned. The responses of the Roll cage, which includes the stress distribution and the displacement under various loading conditions, are described.

Key Words: ANSYS 16.2, SolidWorks, RollCage, Total Displacement, Minimum Combined Stress, Force, Factor of Safety.

1. INTRODUCTION

A roll cage is a frame that is used to protect the rider when the vehicle rolls over. It is generally made of thin pipes welded together to make a structure called a cage. A roll cage is generally employed in car racing for additional protection of the driver. There are many different roll cage designs depending on the application; hence different racing organizations have different specifications and regulations, although most of these organizations harmonize their regulations with those of the FIA.

Roll cages help to stiffen the chassis, which is desirable in racing applications. Racing cages are typically either bolt-in or welded-in, with the former being easier and cheaper to fit while the latter is stronger.

When the car flips upside down, roll cage prevents the rider from getting stuck inside the crushed metal. Roll cage provides additional strength to the car body frame and provides better safety.

2. ROLL CAGE DESIGN

For designing the roll cage of the ATV, various software is available, and it is up to the user which software to select for designing. In this paper, I used Solidworks 2018. The design and development process of the roll cage involves various

factors, namely material selection, pipe size selection, Welding process, frames design, and finite element analysis. The details of each step are given below.

2.1 Material Selection

Material for the roll cage is selected such that it keeps the weight of the vehicle low and without compromising necessary strength. The selection of material for chassis is made by a detailed study of properties of material considering their strength and cost; results found that two materials AISI 1018 and AISI 4130 which are having similar properties

Table No.1: Mechanical Properties of Material

Property	AISI 1018	AISI 4130
Yield Tensile Strength	365 Mpa	600 Mpa
Ultimate Tensile Strength	440 Mpa	700Mpa
Modulus of Elasticity	205 Gpa	205 Gpa
Poisson's Ratio	0.290	0.290

2.2 Cross-section Determination

For cross-section determination, the resulting member's mass should be less at the same time possess high strength.

Table No.2: Determination of Cross-Section

Material (AISI)	Outer Diameter (mm)	Thickness (mm)	Mass/length (g/cm)	Bending Stiffness (Gpa mm ⁴)	Bending Strength (Gpa mm ³)
1018	25	3	16.3098	2.618e+06	1.864e+05
4130	25.4	2	11.5357	2.077e+06	2.592e+05
4130	25.4	2.5000	14.1116	2.445e+06	3.051e+05
4130	25.4	3	16.5641	2.761e+06	3.447e+05
4130	29.2	1.6500	11.2048	2.786e+06	3.025e+05
4130	31.7	1.6500	12.2216	3.613e+06	3.614e+05

Therefore, as the table suggests, pipe with OD 29.2mm and ID 25.9mm of AISI 4130 was considered best amongst pipes given in the table and selected as the primary member of the roll cage. Because AISI 4130 has higher yield strength and high strength to weight ratio over AISI 1018. Moreover, the material AISI-4130 is selected in the chassis design because of its good weldability, relatively soft and strengthens as well as good manufacturability. A good strength material is important in a roll cage because the roll cage needs to absorb as much energy as possible to prevent the roll cage material from fracturing at the time of high impact.

2.3 Design Consideration

Typical capabilities on the basis of which these vehicles are judged are hill-climbing, pulling, acceleration and maneuverability on land as well as shallow waters. The Centre of Gravity was tried to keep in the middle of the vehicle & closest to the ground for optimum stability. The length of the vehicle was kept small so as to reduce weight and maintain a desired center of gravity, while the width of the vehicle was to keep the most to maintain stability in turns.

Following are some of the factors which are taken into account while designing the Roll Cage:

1. **Driver Ergonomics:** High Priority is provided.
2. **Manufacturability:** Essential importance is provided.

Table No.3: Design Considerations

CONSIDERATIONS	TARGET	ACHIEVED
Weight	28 to 35 Kg	33.675 Kg
Maximum vehicle width (inches)	30 to 40	33
Maximum vehicle length (inches)	65 to 80	66.8

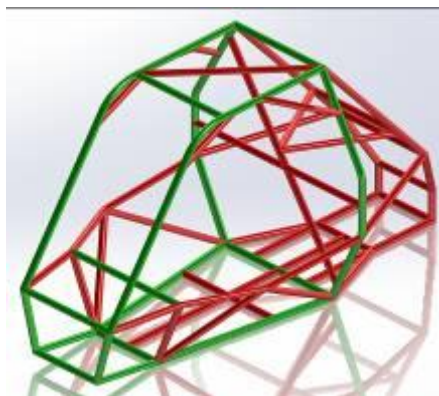


FIGURE.1: Isometric View

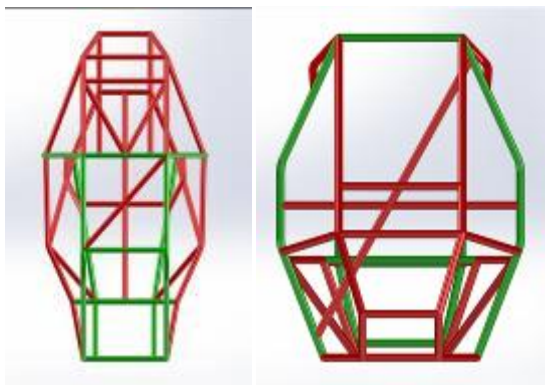


FIGURE.2: Top View **FIGURE.3:** Rear View

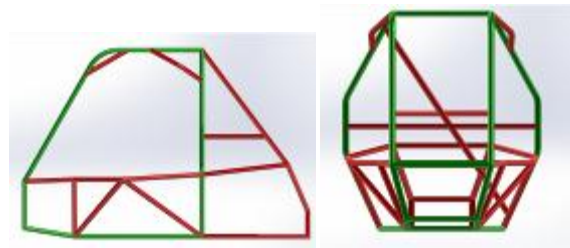


FIGURE.4: Side View **FIGURE.5:** Front View

2.4 Ergonomics

Ergonomics is the process of designing or arranging things so that people can use them safely and comfortably. This frame is designed in the way to absorb the kinetic energy during impacts reducing the risk of injuries for drivers and navigators. The roll cage is designed to carry a person height 180cm (70.8 in) tall, weighing 70kg (154.3 lbs) &, along with that, incorporate all the vehicle sub-systems. A 3-D software model is prepared in Solid works 2018 using the weldments option majorly. Rula Analysis is performed to check the ergonomics of the roll cage. Since the chassis weight consideration is the main part of an automotive, it should be strong and lightweight. Thus, the chassis design becomes very important.



FIGURE.6: Rula Analysis

3. ANALYSIS METHODOLOGY

Design is tested against all modes of failure by conducting various simulations and stress analysis with the help of ANSYS 16.2. Based on the result obtained from these tests, the design is modified accordingly. The 1-D analysis is chosen for the purpose of Finite element analysis. 1D elements are used generally when

1. The structure is too long when compared to cross-section ($L/r > 20$).
2. Useful when bending is the root cause of failure.
3. When the assumption of change in material properties along the cross-section is negligible is considered.

4. FINITE ELEMENT METHOD ANALYSIS

Static analysis is carried out for all cases along with modal analysis. We incorporate the work-energy principle and impulse-momentum equation to find out the forces which are used as input parameters in static analysis with all suitable constraints and variable conditions for validation of analysis. The frame should be able to withstand the impact, torsion, rollover conditions, and provide utmost safety to the driver without undergoing much deformation.

Following tests were performed on the roll cage:

- (1) Front Impact, (2) Rear Impact, (3) Side-Impact,
- (5) Front rollover, (5) Front Bump, (6) Torsional Rigidity and (7) Modal Analysis

4.1 Meshing

The result of any FEA software depends mainly on the kind and the quality of the mesh. Mesh size is calculated by checking the mesh independency. Mesh size has been calculated by plotting the mesh convergence curve. Mid side node has been used for better accuracy. In the analysis, our roll cage, the optimum size of the mesh, was found out to be 0.5mm by trial and error method because after 0.5mm mesh size didn't affect the result as it was doing from 10mm to 0.5mm mesh size.

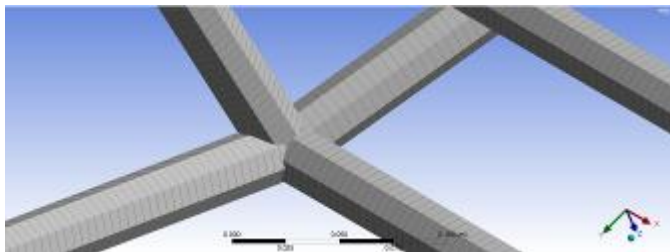


FIGURE.7: Meshing

The following data has been found after the meshing of chassis:

Table No.4: Number Of Nodes Found.

Statistics	
Nodes	12073
Elements	6055
Mesh Metric	None

4.2 Front Impact Analysis

During the front impact, the ATV may hit another ATV or a tree at the event site. Usually, the impact duration is of the range of 0.15 to 0.2 s. So, now assuming time of impact as 0.18 s. As the ATV is the deformable-body; hence, the impact time is assumed to be 0.18 seconds. For analysis, ATV is considered to be in static state and force corresponding to velocity 60 Km/hr. With the impact time, 0.18 seconds is

applied to the front part of the roll cage of ATV, keeping RRH to be fixed.

Calculations:

Weight of the ATV (m) = 260 kg

Initial velocity (v) = 16.67m/s (60 Km/hr.)

Final Velocity (u) = 0 m/s.

Impact time (t) = 0.18 seconds.

By applying Newton's 2nd law,

F = change in momentum/time

$$F = (m \cdot (v - u)) / t$$

$$F = (260 \cdot (16.67 - 0)) / 0.18$$

$$F = 24079N$$

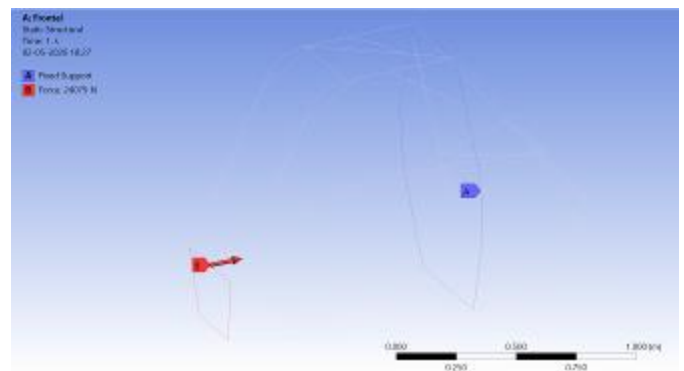


Figure.8: Analysis Condition

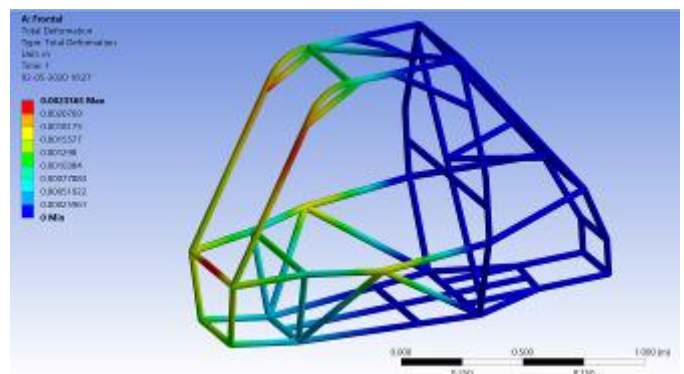


Figure.9: Total Deformation

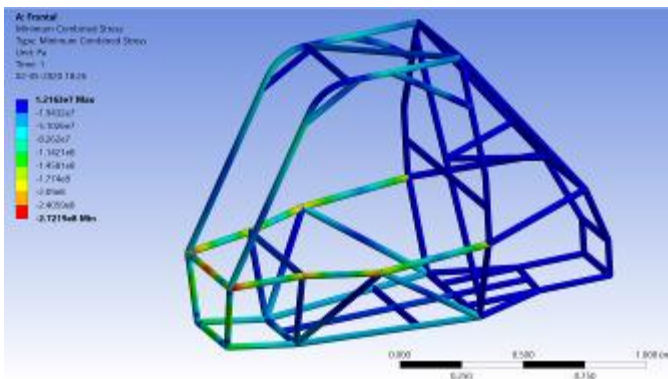


FIGURE.10: Minimum Combined Stress

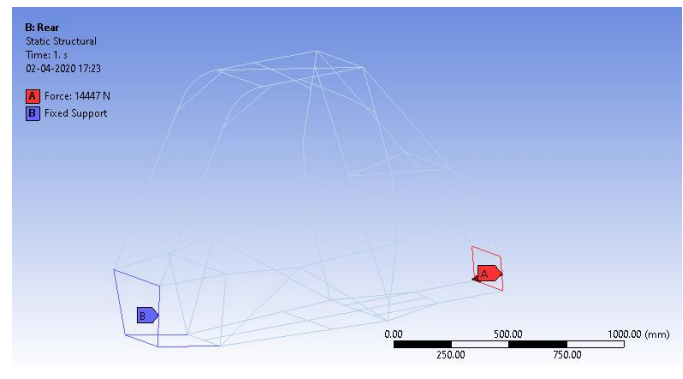


FIGURE.11: Analysis Condition

Result discussion- The minimum combined stress-induced is 272.19MPa. Hence FOS =2.204 with maximum deformation of 2.3365mm, which is within the permissible limit.

4.3 Rear Impact Analysis

This analysis is done to simulate those conditions when another ATV is going to hit ATV on its rear part. Under such conditions, the amount of forces generated reacts at the rearmost portion of the vehicle. The boundary conditions for the rear impact test, the roll cage is to be fixed from the front side, and the rear portion of the roll cage will come across the applied load. Now, assuming time of impact as 0.30 s because the collision is in between two deforming bodies, therefore impact time will be more than that of a frontal impact.

Calculations:

Weight of the ATV (m) = 260 kg

Initial velocity (v) = 16.67m/s (60 Km/hr.)

Final Velocity (u) = 0 m/s.

Impact time (t) = 0.30 seconds.

By applying Newton’s 2nd law,

F = change in momentum/time

$$F = (m*(v-u))/t$$

$$F = (260*(0-16.67))/0.30$$

$$F = 14447.34N$$

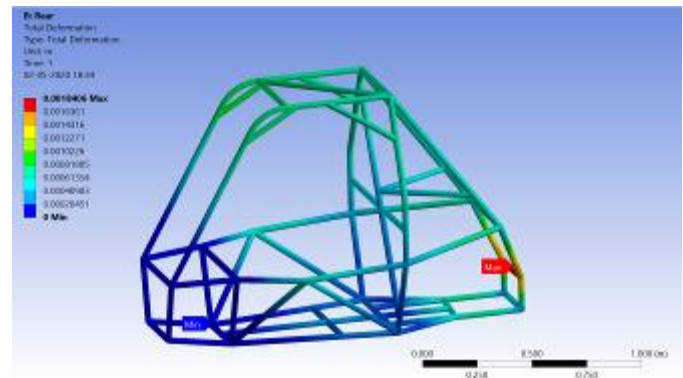


FIGURE.12: Total Deformation

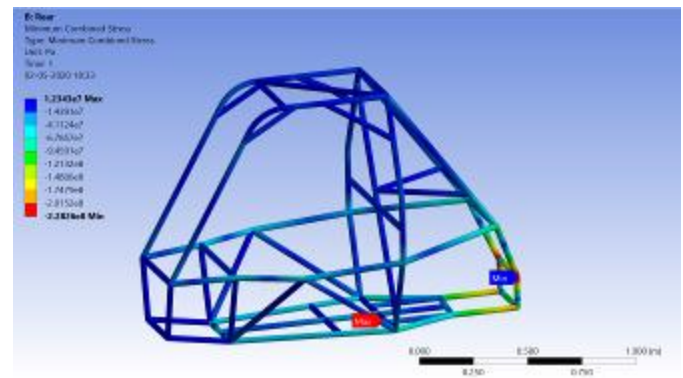


FIGURE.13: Minimum Combined Stress

Result discussion- Maximum combined stress-induced is 228.26MPa. Hence FOS =2.629 with maximum deformation of 1.8406mm, which is within the permissible limit.

4.4 Side Impact Analysis

This analysis is done to simulate those conditions when another ATV hits ATV on the side. Under such conditions, the amount of forces generated reacts at the side most portion of the vehicle. The collision is assumed to be perfectly plastic i.e.; vehicle comes to rest after the collision.

Calculations:

Weight of the ATV (m) = 260 kg

Initial velocity (v) = 16.67m/s (60 Km/hr.)

Final Velocity (u) = 0 m/s.

Impact time (t) = 0.30 seconds.

By applying Newton's 2nd law,

F = change in momentum/time

$$F = (m \cdot (v - u)) / t$$

$$F = (260 \cdot (0 - 16.67)) / 0.30$$

$$F = 14447.34N$$

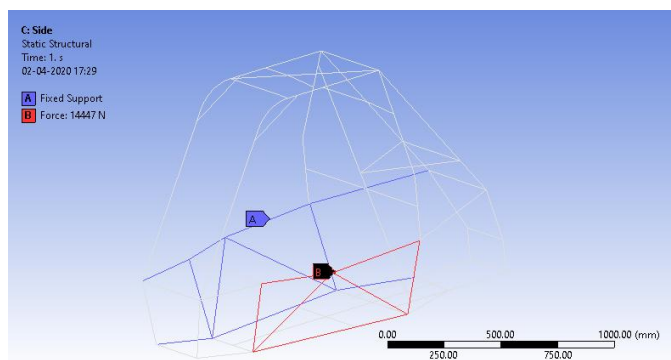


FIGURE.14: Analysis Condition

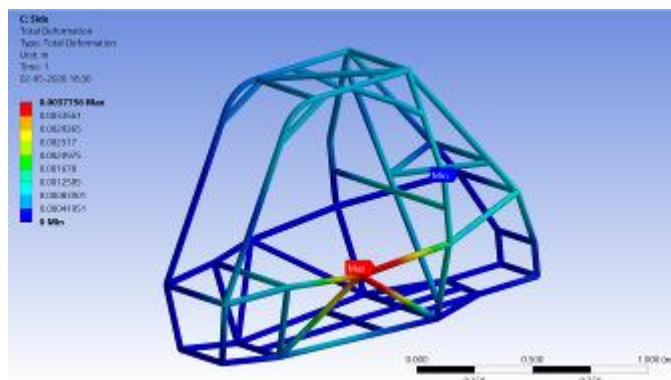


FIGURE.15: Total Deformation

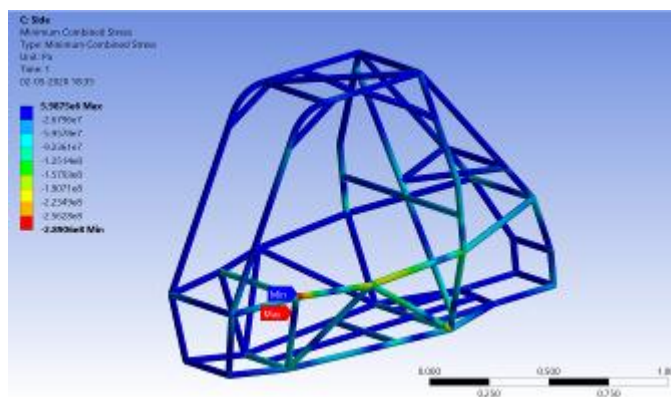


FIGURE.16: Minimum Combined Stress

Result discussion- The maximum combined stress-induced is 289.06MPa. Hence FOS=2.076 with maximum deformation of 3.7756mm, which is within the permissible limit.

4.5 Front Roll Analysis

The impact test or crash test is performed, assuming the vehicle hits the ground after dropping from a height of 10 ft (3.05m). The collision is assumed to be perfectly plastic i.e.; the vehicle comes to rest after the collision. In case of Rollover or topples impact, the ATV is going to roll on the track at an angle of 45 during the race. In this impact, the upper and rear members of the vehicle will bear the force. The boundary conditions for the Rollover test, the roll cage members are fixed from the bottom side, and the upper portion of ATV comes across the applied load.

Calculations:

Weight of the ATV (m) = 260 kg

Initial velocity u=0 m/s

$$\text{Final velocity } v = \sqrt{2gh} \text{ m/s} = 7.736 \text{ m/s}$$

Usually, the impact is of the range 0.15 to 0.2 s. Now, assuming time of impact as 0.18 s.

By applying Newton's 2nd law,

F = change in momentum/time

$$F = (m \cdot (v - u)) / t$$

$$F = (260 \cdot (7.736 - 0)) / 0.18$$

$$F = 11174.22N$$

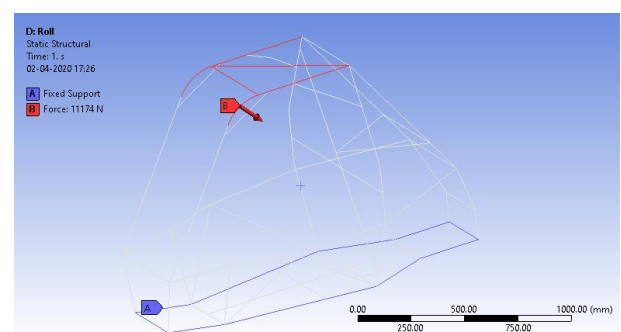


FIGURE.17: Analysis Condition

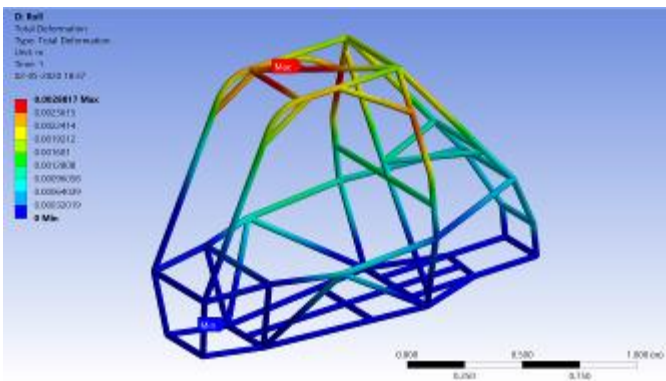


FIGURE.18: Total Deformation

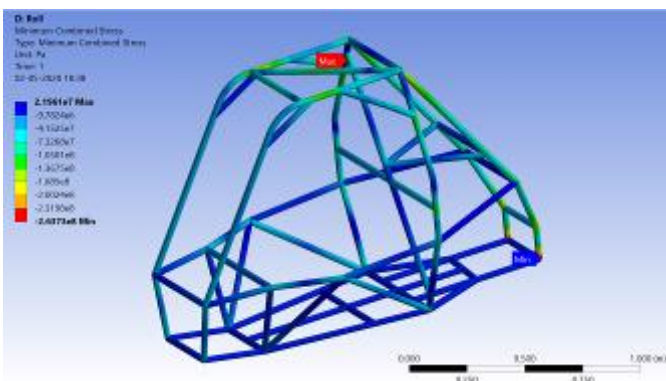


FIGURE.19: Minimum Combined Stress

Result discussion- The maximum combined stress-induced is 263.73MPa. Hence FOS=2.275 with maximum deformation of 2.8817mm, which is within the permissible limit.

4.6 Torsional rigidity

Torsional analysis of the roll cage was done to find the torsional stiffness of the roll cage during cross bumps at the front and rear. The main aim of this analysis is to have a greater roll cage stiffness to sustain dynamic suspension loads. This was ensured by adding members at suitable locations on the roll cage after the analysis was done.

A couple is created by four force in upward direction & four downward directions.

Calculations:

The weight distribution of our ATV is 60:40 (Rear: Front). So, the force transfer from rear to the front after applying the brake at the bump 60% of the total weight of the ATV. Weight on front axle = 0.6 x 260 x 9.81 = 1530.36 N

A couple is generated which tries to twist the roll cage, so the force 1530.36 N is applied on the four mounting points of the suspension and fixing the rear suspension mounting, in case of front torsional analysis.

Couple are acting on the mean of nose Length (in inch). i.e. 17.28 + 12.62 = 14.95 inches (379.73 mm)

$$K=T/\theta$$

$$\tan \theta = D/L$$

$$\tan \theta = \text{Deflection} / (1/2 \times (\text{mean of nose length}))$$

Assuming maximum deflection as 4mm

$$\tan \theta = 2 \times 4 / 379.73$$

$$\theta = \tan^{-1} 8 / 379.73$$

$$\theta = \tan^{-1} 0.021 \text{ and hence } \theta = 1.207$$

Now, for torque Our Front track width is 121.92 cm

So, applied torque on front section of our rollcage is

$$T = F \times 1/2 (\text{track width})$$

$$T = 1530.36 \text{ N} \times 0.6096 \text{ m} = 932.9074 \text{ N-m}$$

So, the torsional stiffness of our roll cage is $K = T / \theta$

$$K = 932.9074 / \theta \text{ N-m} = 974.3 / 1.207 = 772.91 \text{ N-m}$$

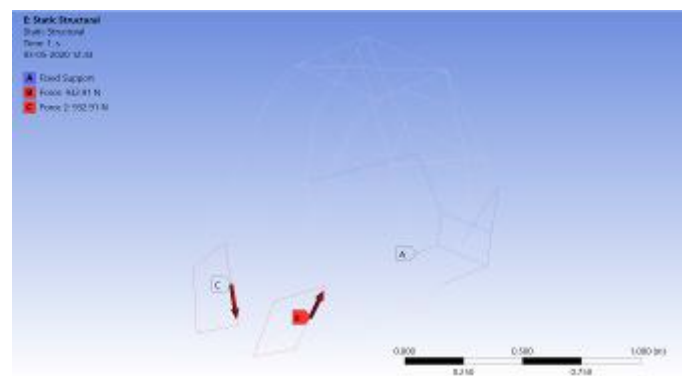


FIGURE.20: Analysis Condition

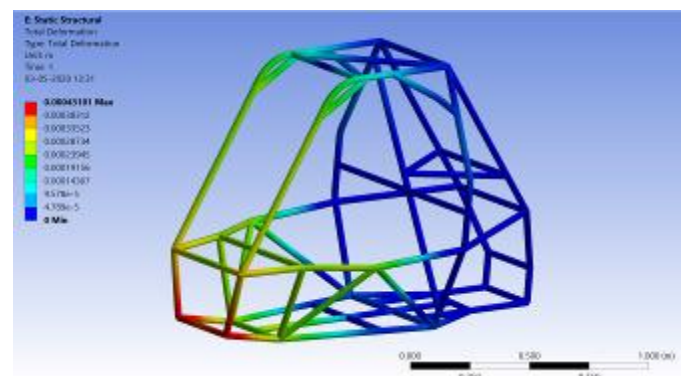


FIGURE.21: Total Deformation

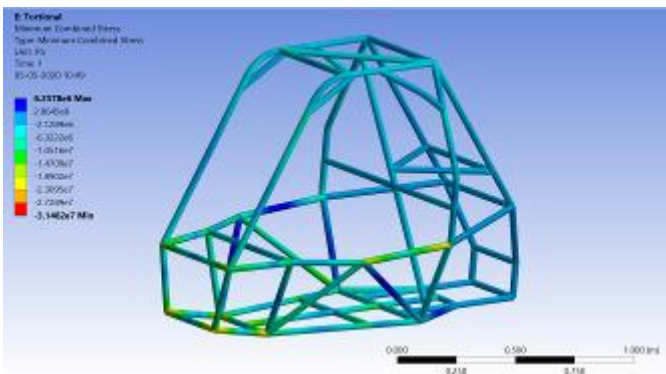


FIGURE.22: Minimum Combined Stress

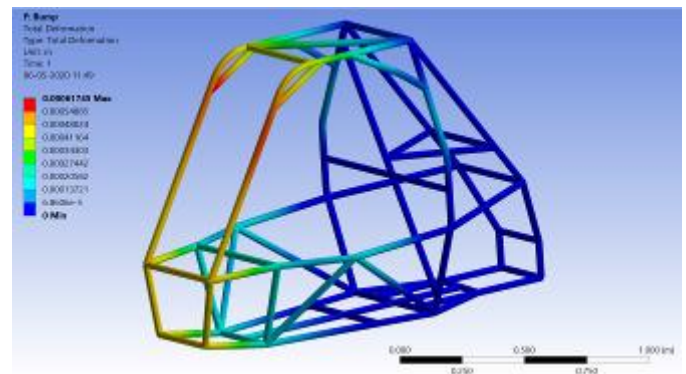


FIGURE.24: Total Deformation

Result discussion- Maximum combined stress-induced is 31.482MPa. Hence FOS=19.05 with maximum deformation of 0.4310mm which is within the permissible limit.

4.7 Bump Impact

During bump analysis, let us consider an ATV undergoes a bump. According to the Indian Road Congress code suggested that speed breaker is formed basically by providing a rounded radius of 17-meter, a hump of 3.7-meter width, and 0.10-meter height for the preferred crossing speed of 25 Km/hr. 40% of the vehicle weight (1020.24 N) is equally distributed to the front suspension mounting member. Rear suspension mounting member of the roll cage is fixed.

Calculations:

Radius = 17 m

Hump Width = 3.7 m

Height = 0.1 m

Speed = 25 Km/hr. = 6.94 m/s

Mass on front = mf = 104 kg

Bump Force (F) = $(m \times v^2) / r + mg$

$F = (104 \times 6.942) / 17 + 104 \times 9.81 = 1062.708N \approx 1070 N$

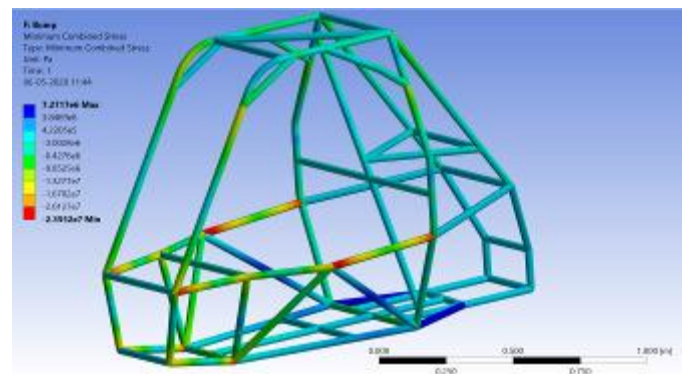


FIGURE.25: Minimum Combined Stress

Result discussion- Maximum combined stress-induced is 23.552MPa. Hence FOS=25.4 with maximum deformation of 0.6174mm, which is within the permissible limit.

4.7 Modal Analysis

The Baja ATV, being an off-road racing vehicle, experiences severe uneven loading. When the natural frequency of vibration of frame equals the excitation frequency of forced vibrations, there occurs a phenomenon of resonance that causes a large deflection of the structure. This excessive vibration and resonance result in failure of the frame of ATV due to harsh conditions in which the vehicle is driven. Therefore, finding the natural frequency of ATV roll cage using modal analysis in order to avoid such a harsh situation of resonance is necessary. The natural frequency of an ATV roll cage can be calculated using the following equation:

$$W_n = \sqrt{(k/m)} \text{ where}$$

k = stiffness of the roll cage

m = mass of the roll cage

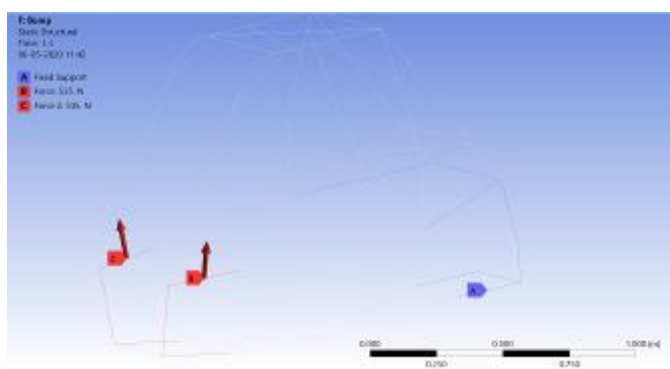


FIGURE.23: Analysis Condition

Vibrations can also be induced due to the bumps or road, but as their intensity would be low, it is not considered. Although the bumps and vibration due to the reciprocating engine could add up to a greater value but it would be less than the calculated frequency of the first mode of vibration which is 63.839 Hz

Boundary Conditions:

The chassis frame is fixed at the suspension points in order to know about the various mode shapes of the upper body structure. Fixed supports are given at suspension points since the wheels and suspension are mounted to the axle, thereby restricting the degree of freedom of lower base to zero.

Various mode shape values are tabulated below:

Sr. No	Frequencies	Values (Hz)
1.	Frequency 1	63.839
2.	Frequency 2	125.7
3.	Frequency 3	128.24
4.	Frequency 4	142.25
5.	Frequency 5	145.32
6.	Frequency 6	153.09

Result discussion - The min and maximum frequencies of which will be faced are 15-35 Hz and as the first mode frequency if 63.839 Hz the vehicle is safe for the operations.

5. RESULTS

Results of all the analysis are tabulated below:

Test	Forces (N)	Stress (MPa)	Deformation (mm)	Factor of Safety
Front Impact	24079	272.19	2.3365	2.204
Rear Impact	14447.34	228.26	1.8406	2.629
Side Impact	14447.34	289.06	3.7756	2.076
Roll Over	11174.22	263.73MPa	2.8817	2.275
Tortional Impact	932.91	31.482	0.4310	19.05
Bump Impact	1070	23.552	0.6174	25.4

6. CONCLUSION

The safety of the driver is the first and foremost priority. Therefore, a considerable factory of safety is applied to the roll cage of an ATV to reduce the risk of failures and possible injuries. Larger factory of safety implies the large ability of an ATV to withstand all kinds of loads and capable of moving on various terrains. This paper has illustrated the entire design methodology of the roll cage and understanding the critical aspects of the design, also static analysis in finite element analysis along with modal analysis to avoid the phenomenon of resonance.

REFERENCES

- BAJA SAEINDIA rule book 2020.
- http://www.engineeringtoolbox.com/torsion_shafts_d_947.html
- Thomas D. Gillespie. Fundamentals of Vehicle Dynamics. Society of Automotive Engineers, Inc.
- Prof. Dipl.-Ing.Jornsen Reimpell. The automotive chassis: engineering principles (2001). ButterworthHeinemann.
- Properties of Carbon steel AISI 1018 & 4130 <http://www.efunda.com/materials/alloys/carbon>

BIOGRAPHIES



Ketha Jaya Sandeep is currently in 2nd year of Mechanical Engineering Program at IIT Bhilai, Chhattisgarh, India. Sandeep is a member of SAEINDIA COLLEGIATE CLUB.