Design and Static Analysis of Roll Cage for The Off-Road Vehicle

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Abstract- *A roll cage is a skeleton of an Off-Road Vehicle or the All-Terrain Vehicle. The roll cage not only forms the structural base but also a 3-D shell surrounding the driver which protects the driver in case of roll over incidents and all other impact conditions. The roll cage is acting as the main frame of the off-road vehicle which contains the other components like Engine assembly, Steering mechanism, Transmission assembly and the Driver. Also, the roll cage is the main aesthetics of the off-road vehicle. This paper outlines the Design & Modelling with Static analysis of roll cage for the off-Road vehicle. The roll cage model is designed and modelled in the CAD software SolidWorks and Static analysis is carried out with the help of CAE software ANSYS Static Structural. In the static analysis the different impact tests are carried out for determining the optimum Factor of safety for roll cage. This paper is aimed to study every point of roll cage to improve the performance of vehicle as well as safety of driver without failure of roll cage.*

Keywords- roll cage, off-road, static analysis, solid works, ANSYS, static structural

I. INTRODUCTION

The paper is examining the study of various aspects of roll cage design for off-road vehicle, with an emphasis on application to a four-wheeled, a single seated driver vehicle, is used in SAE Mini-Baja competition. This competition is sponsored by the Society of Automotive Engineers and Mahindra & Mahindra.

Roll Cage is the skeleton of an off-road vehicle, besides its function being seating the driver, providing safety and incorporating other sub-systems of the vehicle, the main function is to form the frame or so called vehicle chassis. We were designed the roll cage keeping in mind the view of driver's point of view the safety and aesthetics of vehicle. These are the two factors which matters us the most, therefore they are given utmost consideration. This paper outlines the design of roll cage for an off-road vehicle and various impact loading conditions like front impact, rear impact, side impact and top impact tests have been conducted on the roll cage with the help of finite element analysis method. This research discusses about static analysis of all possible impact conditions during event site. The static analysis is done using analytical calculation for impact forces by assuming impact time, the optimum mesh size is taken for all impact conditions in this paper study. The optimum factor of safety is find out for the roll cage by static analysis. The roll cage model is designed and developed in CAD software SolidWorks, the static analysis is then carried out with the help of CAE software ANSYS.

II. DESIGN METHODOLOGY

The design of any component is contains the three major principles optimization, safety and comfort. The primary function of the roll cage is to provide a 3-D protected space around the driver that will keep the driver safe. Its secondary function is to provide reliable mounting locations for components, be appealing, low in cost and weight. These functions were achieved by choosing the optimum material for roll cage which has good strength and also has less weight which giving us an advantage in weight reduction. The low cost roll cage was achieved through material selection and incorporating more continuous members with bends rather than a collection of members welded together to reduce manufacturing costs. The modelling of the roll cage structure was done by using CAD software SolidWorks in weldments tool. Then design is checked by Finite Element Analysis. The static analysis is carried out by using ANSYS Static Structural.

A. Roll Cage design and Material Selection

A chassis at its most basic, acts as the skeleton for the entire vehicle. It provides a rigid connection between the front and rear suspension, creates structural support for the other necessary systems and provides protection for the driver. There are a variety of different frame designs to choose from; however, a tubular space frame is most commonly used due to its inherent structural properties, and ease of fabrication and modification. This style of chassis consists of a series of tubes connected together in different ways to form a coherent structure.

To start the initial design of the roll cage, there are some design procedures were required to be set. The procedures included intended transmission system, steering mechanism and suspension systems and placement of it on roll cage, mounting of seat, aesthetics of design and methods of manufacturing. It is also required to keep a minimum clearance of 3 inches between the driver and the roll cage members as described in rule book for SAE Mini-Baja. It is also most required to keep the weight of roll cage as low as possible to achieve better acceleration. The centre of gravity of the vehicle is also required to keep as low as possible to avoid roll over of vehicle. The heavier mounting components like engine, driver seat etc. are placed directly on the roll cage is one way of achieving low centre of gravity.

The constraints are given in the rulebook; the roll cage material must have at least 0.18% carbon content with minimum 25.4mm outer diameter and 1.57mm wall thickness for primary and 0.89mm wall thickness for secondary. After deep market survey on various factors like weight of pipe with respect to cross section, cost and availability, strength the AISI 1018 and AISI 4130 steel materials are shortlisted. A comparative study of these shortlisted materials is done on the factors like strength, availability and cost. The shortlisted materials and comparison between them are given as follows.

Table 1. Material Properties

Class	AISI 1018	AISI 4130
Density	7.86 g/cm^3	7.86 g/cm^3
Ultimate Tensile Strength	470 MPa	750 MPa
Yield Tensile Stress	365 MPa	700 MPa
Bulk Modulus	140 GPa	140 GPa
Shear Modulus	80 GPa	80 GPa
Brinell Hardness	126	217
Poisson's Ratio	0.29	0.27-0.30
Elongation	15%	25.5%

B. Frame Cross Section Determination Calculation

- For Material (AISI 1018 of 25.4mm outer diameter and 3mm wall thickness)
  Syt = 365 MPa, Sut = 470 MPa, Carbon % = 0.18%
- Bending Strength = Sy I / C
  = 387.37 Nm
- Bending Stiffness = E I
  = 2763.12 Nm2
- Weight of pipe per meter = 1.6614 kg/meter

- For Material (AISI 4130 of 31.75mm outer diameter and 1.6mm wall thickness)
  Sut = 750 MPa, Syt = 700 MPa, Carbon % = 0.3%

- Bending Strength = Sy I / C
  = 761.4236 Nm
- Bending Stiffness = E I
  = 3539.94 Nm2
- Weight of pipe per meter = 1.1927 kg/meter

Now, from above calculation for material AISI4130 has the weight of one meter of pipe is less than the material AISI1018, with having the more Bending strength as well as stiffness and also since AISI 4130 material has 700MPa Yield Tensile Strength and 750MPa Ultimate Tensile Strength. So from all aspects and design considerations for the material AISI 4130 will be more suitable material for roll cage design. The CAD model of roll cage developed in the SolidWorks software is given below.

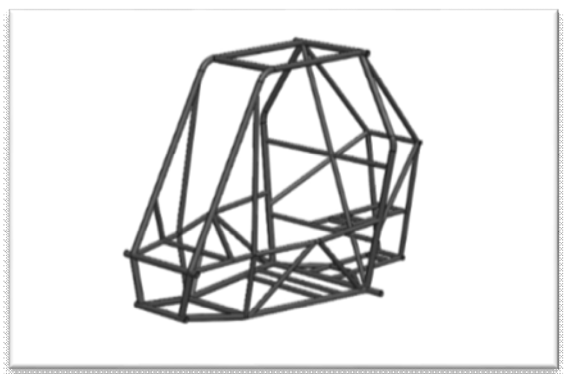

Figure 1. SolidWorks CAD Model

III. FINITE ELEMENT ANALYSIS

After finalizing the frame along with its material and cross section, it is very essential to test the rigidity and strength of the frame under severe conditions. The frame should be able to withstand the impact, torsion, roll over conditions and provide utmost safety to the driver without undergoing much deformation. So, to check this factors the static analysis is carried out. When we use the term analysis in this context, its mean to analyze the stress and deflection within the members of the chassis, under reponse to varoius structural loads. To do this, we used a CAE software ANSYS. This is a finite element analysis software that allows the user to analyze the object virtually any complex geometry. The mesh model generted in ANSYS software is given below.

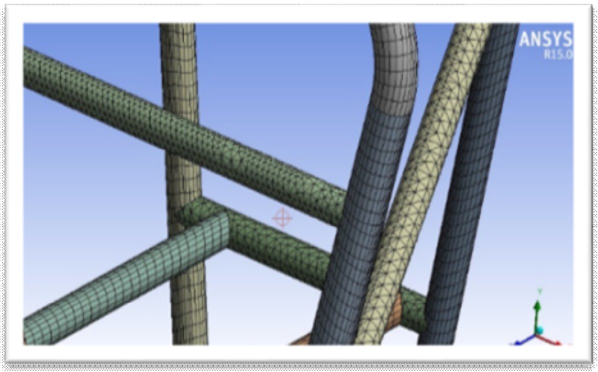

Figure 2. ANSYS Mesh Model

Finite element analysis is a computerized method for predicting how a product reacts to real-world forces, vibration, and other physical effects. It shows whether a product will break, wear out, or work the way it was designed. Here we divide the roll cage into small sizes known as element and collective elements on the model form a mesh. The computer analyses the elements and shows us a collective result. The computer solves by the computational method provided. The Following tests were performed on the roll cage.

- Front impact test
- Rear Impact Test
- Top Impact Test
- Side Impact Test

IV. STATIC ANALYSIS

In the static condition analysis, the vehicle is considered to be in static state and maximum possible force is applied on the vehicle or roll cage with suitable constraints as per various impact conditions described above. As per earlier studies impact time of roll cage in case of impact with rigid body like wall, floor, etc. is taken as 0.13 sec, while that in case of impact with the deformable object like another vehicle, the impact time is taken to be 0.30 sec.

A. Front Impact

As the front impact happens, the vehicle may hit a tree, another vehicle or a wall. Time of impact will be more for the deformable bodies as compare to the rigid bodies so the impact force in the case of wall will be more than that in case of another vehicle or tree. The impact time in case of impact with wall is taken as 0.13 seconds. For analysis, vehicle is considered to be in static state and force corresponding to velocity 60 km/h with impact time 0.13 seconds was applied to front part of the roll cage keeping rear suspension members fixed.

Calculations

We assume following factors for analytical calculations are,
Weight of the ATV, M =300 kg
Initial velocity before impact, $V_{initial}$ = 16.67 m/s
Final velocity after impact, V_{final} will be zero.
Impact time = 0.13 seconds
As we know,
Work done = change in kinetic energies

$$W = (0.5 \times M \times V_{final} - 0.5 \times M \times V_{initial})$$
$$|W| = |-0.5 \times M \times V_{initial}|$$
$$= |-0.5 \times 300 \times 16.672|$$
$$= 41666.67 \text{ Nm}$$

Now,
Work done = force × displacement= F × s

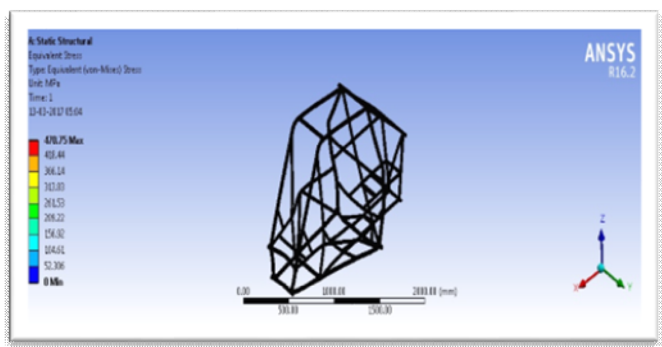

Figure 3. Von Misses stress distribution for front Impact

As, s = impact time × $V_{maximum}$

$$= 0.13 \times 16.67$$
$$= 2.1671 \text{ m}$$

So, $F = W/ s$

$$= 41666.67 / 2.1671$$
$$= 19{,}226.925 \approx 20{,}000 \text{ N}$$

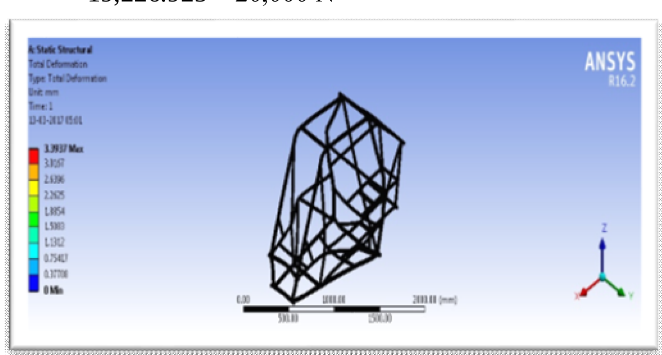

Figure 4. Deformation for Front Impact

B. Rear impact

In actual condition during rear impact, another ATV is going to hit ATV on its rear part. As the ATV is a deformable body so the impact time is taken as 0.30 seconds. For analysis, ATV is considered to be in static state and force corresponding to velocity 60 km/h with impact time 0.30 seconds is applied to rear part of the roll cage of ATV keeping front suspension members fixed.

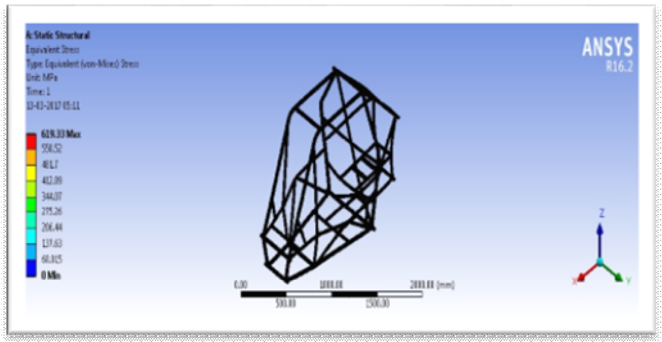

Figure 5. Stress Distribution for Rear Impact

Calculations

From work energy principal,

Work done = change in kinetic energies

$W = (0.5 \times M \times V_{final} - 0.5 \times M \times V_{initial})$

$|W| = |-0.5 \times M \times V_{initial}| = -0.5*300*16.672$

$= 41666.67$ Nm

Now, Work done = force × displacement

$= F \times s$

As, s = impact time × Vmaximum

$= 0.30 \times 16.67$

$= 5.001$ m

So, F = W/ s

$= 41666.67 / 5.001$

$= 8331.67 \approx 9{,}000$ N

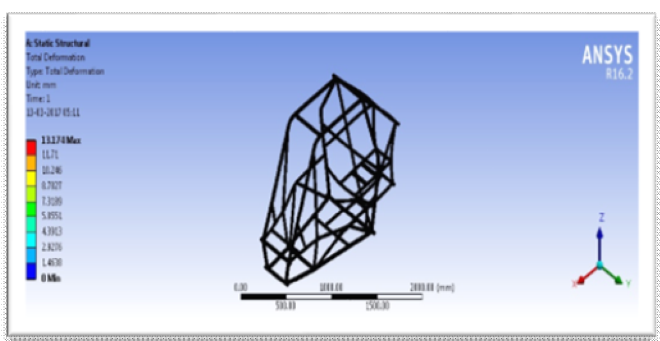

Figure 6. Deformation for Rear Impact

C. Top Impact

In top impact, the vehicle is considered to be dropped on its roof on road or ground from a height of 10 feet. The 10 feet for the drop height was selected because it is sufficiently more than anything expected at the event site. We know road and ground are non-deformable bodies, the impact time will be selected as 0.13 seconds. For top impact analysis, vehicle is considered to be in static state and force corresponding to the calculated velocity 27.83 km/h for 10 feet with impact time 0.13 seconds is applied to top of the roll cage of vehicle keeping the bottom members of roll cage will be fixed.

Calculations

Impact time = 0.13 s

During the fall, the whole potential changes into kinetic energy,

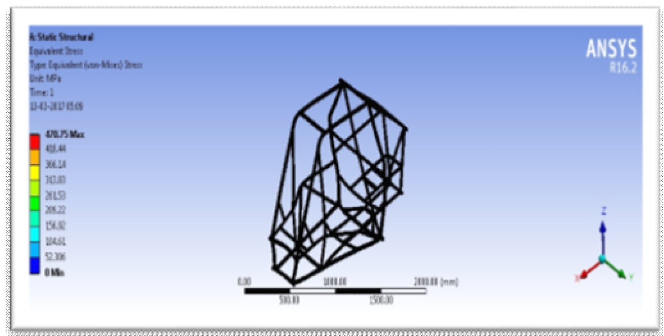

Figure 7. Stress Distribution for Top Impact

So we know,

$M \times g \times h = 0.5 \times M \times V2$

$V = \sqrt{(2 \times g \times h)}$

$= \sqrt{(2 \times 9.81 \times 3.048)}$

= 7.73 m/sec (or 27.83 km/h)

Now from work energy principal,

Work done = change in kinetic energies

$|W| = |-0.5 \times M \times V_{initial}|$

$= |-0.5 \times 300 \times 7.732|$

$= 8962.935$ Nm

Now, Work done = force × displacement

$= F \times s$

As, s = impact time × Vmaximum

$= 0.13 \times 7.73$

$= 1.0049$ m

So, F = W/ s

$= 8962.935 / 1.0049$

$= 8919.2307 \approx 9{,}000$ N

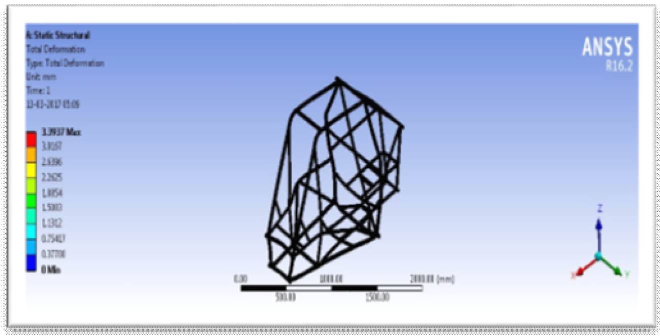

Figure 8. Deformation for Top Impact

D. Side Impact

During the side impact another vehicle will hit our vehicle on side and as vehicle is deformable body, so we will take impact time as 0.30 seconds. For side impact analysis, vehicle is considered to be in static state and force corresponding to velocity 60 km/h with impact time 0.30 seconds is applied to side of the roll cage of vehicle keeping the suspension members of vehicle of other side fixed.

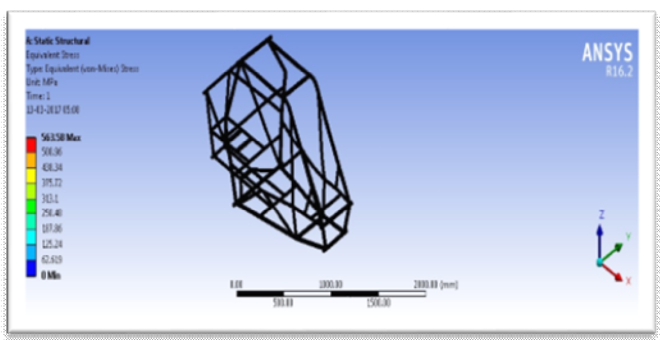

Figure 9. Stress Distribution for Side Impact

Calculations

From work energy principal,

Work done = change in kinetic energies

$$W = (0.5 \times M \times V_{final} - 0.5 \times M \times V_{initial})$$

$$|W| = |-0.5 \times M \times V_{initial}|$$

$$= |-0.5 \times 300 \times 16.67^2|$$

$$= 41666.67 \text{ Nm}$$

Now, Work done = force × displacement

$$= F \times s$$

As, s = impact time × Vmaximum

$$= 0.30 \times 16.67$$

$$= 5.001 \text{ m}$$

So, $F = W / s = 41666.67 / 5.001$

$$= 8331.67 \approx 9{,}000 \text{ N}$$

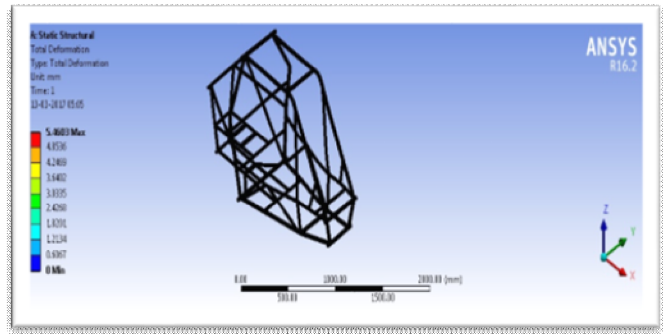

Figure 10. Deformation for Side Impact

The summary from all the static impact tests result is given below in table. From this impact analysis we conclude that the roll cage is safe in all impact conditions as described above and our roll cage design is safe.

Table 2. Result Summary

Impact Condition	Force Applied (N)	Maximum Stress (MPa)	Maximum Deformation(mm)	Factor of Safety
Front	20000	470.75	3.3937	1.48
Rear	9000	619.33	13.174	1.13
Top	9000	448.71	2.8604	1.56
Side	9000	563.50	5.4603	1.24

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