International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 10 Issue: 08 | Aug 2023 www.irjet.net p-ISSN: 2395-0072

Design optimization and analysis of ATV Roll Cage

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Abstract - *The purpose of this paper is to design a roll cage. Here we will be going through the step-by-step procedure involved in designing a roll cage, including material selection, geometric design, and analysis. We will also be taking a look at all the calculations involved in the design and optimization of the roll cage.*

1. INTRODUCTION

The design of the roll cage heavily influences the ergonomics and appearance of the entire vehicle. The weight reduction in the chassis is crucial to having a dynamically stable vehicle with a low center of gravity while considering all mechanical design and safety considerations. The roll cage needed to be constructed with many factors in mind because it plays such a significant role. The roll cage must have the best possible design that balances its weight and strength. The All-Terrain Vehicle (ATV) Roll cage design under investigation in this research is based on SAE Standards. The document also includes elaborate 3D sketching and weldments design.

2. Design Overview

The roll cage of an ATV is the main outer structure that provides protection to the driver during any crash or rollover. The roll cage also acts as the vehicle's main frame, providing mountings for components like the suspension system, drive system (engine, front differential, gearbox), steering system, etc. The design of the roll cage has been carried out in SOLIDWORKS 2021, with the ergonomics check being done in Catia V5.

First, some initial constraints of the vehicle were fixed, which included track width, wheelbase, ground clearance, wheel radius steering rack length, rack position, etc., which helped us finalize the suspension points using Lotus Shark software. This was done following an iterative process trying different combinations to obtain the best possible dynamic results for the vehicle; the finalized suspension geometry can be seen in Fig [1].

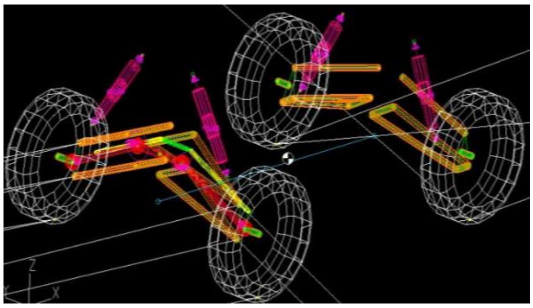

Fig. 1

The roll cage has to be designed considering the following goals and requirements.

1. BAJA SAE rules
2. Driver safety
3. Driver ergonomics
4. Proper weight biasing
5. Proper orientation & installation of subassemblies.
6. Ease of manufacturing

3. Design and optimization

The design process of the roll cage can mainly be divided into three steps which are

1. Material selection
2. Structure design
3. Analysis

This is an iterative process wherein if we are not satisfied with the results, we repeat the process.

3.1 Material Selection

The selected material must satisfy the requirements of the BAJA SAE Rule book. According to the rule book, the roll cage must consist of 2 different types of members, i.e., Primary and secondary members.

For primary members, the rules are
• Circular steel tubing with an outside diameter of 25 mm (1.0 in) and a wall thickness of 3 mm (0.120 in.) and carbon content of at least 0.18%.

- A steel shape with bending stiffness and bending strength exceeding that of circular steel tubing with an outside diameter of 25 mm (1.0 in.) and a wall thickness of 3 mm (0.120 in.). The wall thickness must be at least 1.57 mm (0.062 in.), and the carbon content must be at least 0.18%, regardless of material or section size. The bending stiffness and bending strength must be calculated about a neutral axis that gives the minimum values.

For Secondary members, the rules are

- Secondary members must be steel tubes having a minimum wall thickness of 0.89 mm (0.035 in) and a minimum outside diameter of 25.4 mm (1.0 in) or rectangular steel tubes having a minimum wall thickness of 0.89mm (0.035 in) and a minimum outside dimension of 25.4 mm (1.0 in).

Based on the requirements, necessary calculations were performed, and a survey was conducted on the metal pipes that could be used for the vehicle. The main substitutes found for AISI1018 (BAJA recommended) were AISI4130 and DUPLEX 2205, out of which AISI4130 was chosen for its high weight-to-strength ratio.

Properties	AISI4130	AISI1018	DUPLEX
Yield strength	734MPa	370MPa	448MPa
Ultimate Tensile Strength	860MPa	440MPa	661MPa
Density	7.8g/cm3	7.8g/cm3	7.8g/cm3
Poisson's ratio	0.3	0.3	0.29
Shear Modulus	80GPa	80GPa	80GPA

Table -1: Material Properties

After checking the market availability for different sizes, the following sizes were finalized, and all the necessary calculations are noted below

Primary pipe= 29.21x1.65mm

Secondary pipe= 25.4x1.5mm

Bending Stiffness Calculations:

definitions,

E= modulus of elasticity (in GPa)

I= second moment of area for structural cross-section required tubing cross-section.

Sy= yield strength (AISI1018)

Diameter: 1 inch (25.4 mm)

Wall thickness: 3mm (0.12 inch)

Bending strength= SyI/C

I=22/7*{(31.75)4 – (28.45)4}/64 = 17723.37mm4

B strength = (365*13478.6/12.7)N-mm

B strength = 387377.08 N-mm = 387.37N-m

Bending stiffness = E*I = 2763.12 N-m^2

The material used in BAJA 2022: AISI-4130 (secondary pipe)

DO = Outer diameter = 25.4 mm

DI = inner diameter = 23.9 mm

Thickness = 1.5 mm

I = π {(25.4)4 -(23.9)4 }/64 = 4413.19mm4

Bending stiffness = E*I

B stiffness = 205*103 /64{(25.4)4 -(23.4)4} N-mm^2

B Stiffness = 904.70N-m^2

Here,

C= center distance from the neutral axis to extreme fiber = 12.7 mm

Bending strength = SyI/C

B Strength = (734*5711.33)/12.7 N-mm

B strength = 255050.551 N-mm = 255.05 N-m

AISI-4130 (Primary pipe)

DO = Outer diameter = 29.21 mm

DI = inner diameter = 25.91 mm

Thickness = 1.65 mm

I = π {(29.21)4 -(25.91)4 }/64 =13617.8992 mm4

Bending stiffness = E*I

B stiffness = 205*103 /64{(29.21)4 -(25.91)4 }N-mm^2

B Stiffness = 2791.6693N-m^2

Here C= center distance from the neutral axis to extreme fiber = 14.905mm

Bending strength = SyI/C

B Strength = (734*13617.89)/14.905 N-mm

B strength = 670615.9 N-mm = 670.615 N-m

Since the calculated values satisfy the needs, the chosen dimensions of the

3.2 Structural design

The structural design of the roll cage was carried out in SOLIDWORKS 2021. The roll cage was designed in such a way that all the safety requirements stated by SAE BAJA are met along with the needs of the driver and in a way that it can be manufactured with ease.

Various designs were formulated, of which the best was selected, and its different views can be seen below

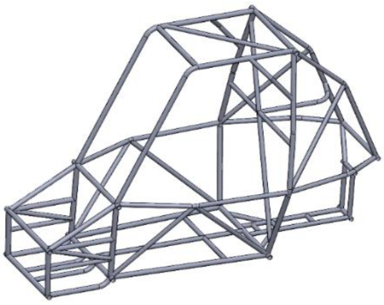

Fig. 2 Roll cage Isometric View

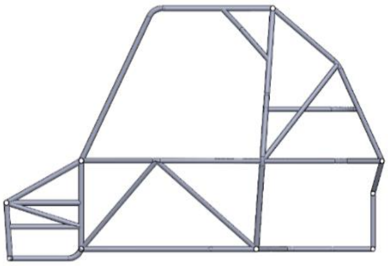

Fig. 3 Roll cage Side view

An Ergonomics check was performed on the chosen roll cage to ensure the driver has a smooth ride. The check was done using CATIA V5 software, where a mannequin was designed based on the size of the driver, and the check was performed by placing the driver in the various positions he would encounter sitting in the vehicle and also in the process of getting out.

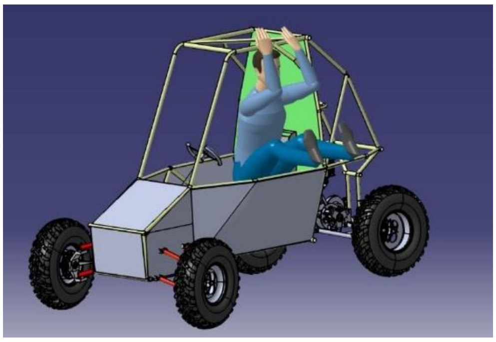

Fig. 4 Roll cage Ergonomics check

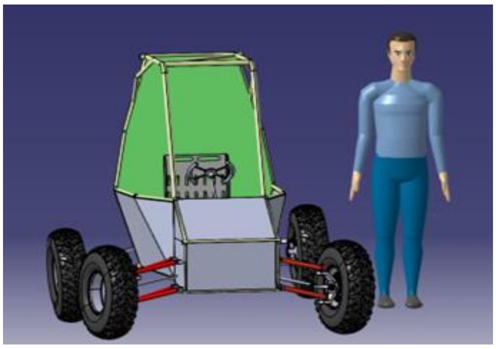

Fig. 5 Roll cage Ergonomics check

Fig. 6 Roll cage Ergonomics check

3.3 Analysis

The analysis is one of the most critical aspects of designing a roll cage as it helps us understand the structural integrity of the roll cage.

Static analysis has been performed on the roll cage where the roll cage was subjected to the following loading conditions.

- Front crash
- Rear crash
- Side crash
- Torsional stiffness
- Rollover
- Drop test

3.3.1 Front crash

For the front crash, the vehicle is subjected to a load opposite to the direction of the vehicle's motion, and it is applied to the member where the impact first happens.

Let the velocity of our vehicle is 50km/hr=13.88m/s.
Suddenly, within 0.3 sec, it strikes a rigid wall then the deceleration of the vehicle.
$v=u + at$
$0=13.88m/s+a\times0.3$

a=46.26 m/s2
Mass of buggy with driver =260kg
So, force of impact F= m ×a
=260 ×46.26
= 12027N

The deformation and the von Mises stresses generated can be seen in Fig 7 and Fig 8, respectively.

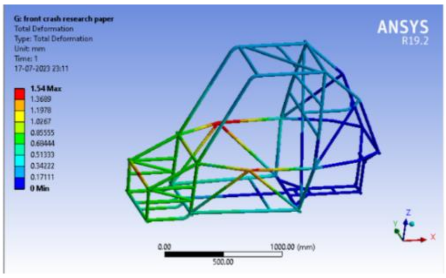

Fig. 7 Front Crash - Deformation

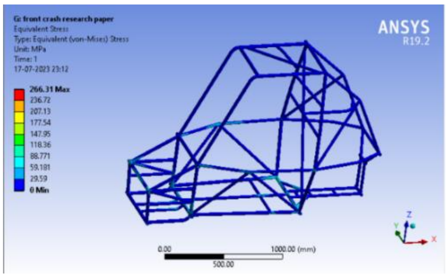

Fig. 8 Front Crash- Stress

3.3.2 Rear crash

Let the velocity of our vehicle is 50km/hr=13.88m/s. Suddenly, within 0.3 sec, it strikes a rigid wall, then the deceleration of the vehicle.
v=u+at
0=13.88m/s+a
×0.3sec a=46.26 m/s2
Mass of buggy with driver =26k0g
So, force of impact F= m ×a
=260 ×46.26
=12027N
12027N force is applied.

The deformation and the von Mises stresses generated can be seen in Fig 9 and Fig 10, respectively.

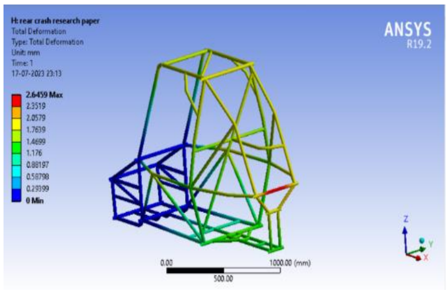

Fig. 9 Rear Crash - Deformation

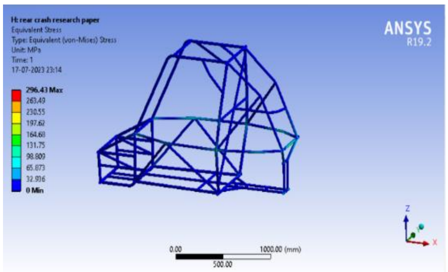

Fig. 10 Rear Crash - Stresses

3.3.3 Side crash

Let the velocity of our vehicle is 50km/ hr=13.88m/s. Suddenly, within 0.3 sec, it strikes a rigid wall, then the deceleration of the vehicle.
v=u+at 0=13.88m/s+a
×0.3sec a=46.26 m/s2
Mass of buggy with driver =26k0g
So, force of impact F= m ×a
=260 ×46.26
=12027N
12027N force is applied.

The deformation and the von Mises stresses generated can be seen in Fig 11 and Fig 12, respectively.

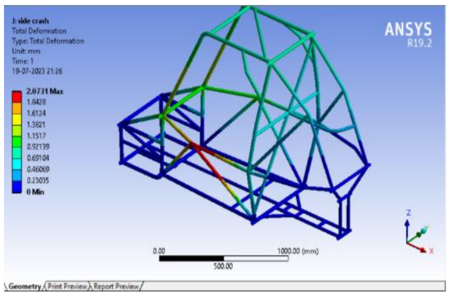

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Fig. 11 Side Crash - Deformation

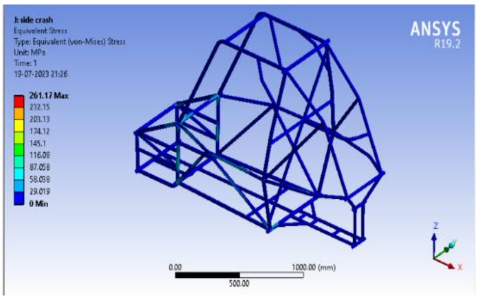

Fig. 12 Side Crash - Stresses

3.3.4 Torsion rigidity

The weight distribution of our vehicle is 53:47(Rear: Front)
So,

Force transfer from rear to front after the application of brake at bump is 32% of the total weight.
So, the weight on the front axle
F=0.53 ×260×9.81
=1351.818N
A couple is generated, which tries to twist the roll Cage, so 1351.818N force is applied on four mounting points of wishbone, i.e.

337.95 N on each mounting point.

A couple is created by four forces in an upward direction & four in downward direction.
Let us suppose the forces of couple are acting on the mean of the nose
Length i.e. (300+300)/2 = 300mm
Tanθ = Deflection / (mean of nose length/2)
Tanθ = 0.020
θ= 1.145deg
Now, for torque
Our Front track width is 1.35 m
So, applied torque on the front section of our roll cage is T=F ×1/2(track width)
=1351.818N ×0.675m
=911.477 N-m
So, the Torsional stiffness of our roll cage is K=T/θ
=911.477/0.1451N-m/deg
=796.60 N-m/deg

The deformation and the von Mises stresses generated can be seen in Fig 12 and Fig 13, respectively.

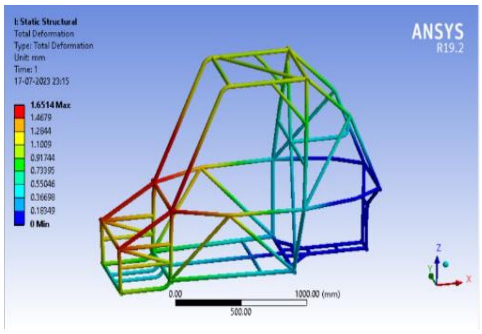

Fig 12 Torsional rigidity – Deformation

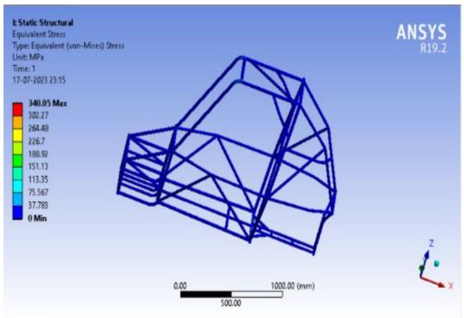

Fig 13 Torsional rigidity- Stresses

3.3.5 Rollover

In case of a rollover, the effect on the roll cage is due to the self-weight of
the vehicle
i.e.
1g force so, F=260× 2 × 9.81=2550.6 N

The deformation and the von Mises stresses generated can be seen in Fig 13 and Fig 14, respectively.

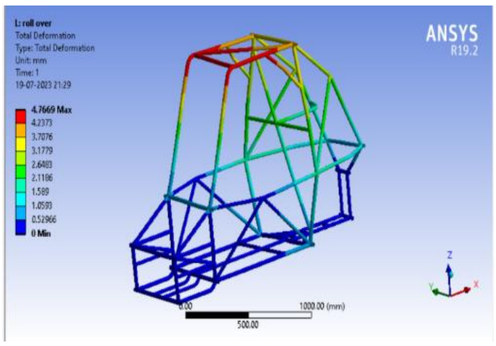

Fig 13 Rollover- Deformation

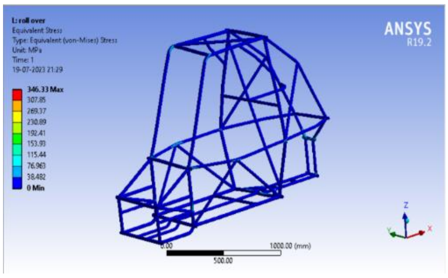

Fig 14 Rollover- Stresses

3.3.6 Drop test

Let us assume that our vehicle is dropped from 1m height and let the time of impact is 0.3 sec
$V=\sqrt{2gh}$
$= \sqrt{(2 \times 9.81 \times 1)}$
$= 4.42$ m/s
Damper compression= d = 0.8
Energy transfer by roll cage = w = 1/2mv2 = F.d Vertical force=
f = w/d = (1/2mv2
)/d= 3174.665 N

The deformation and the von Mises stresses generated can be seen in Fig 15 and Fig 16, respectively.

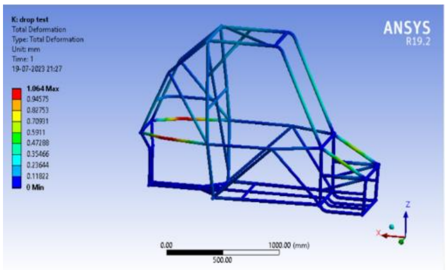

Fig 15 Rollover - Deformation

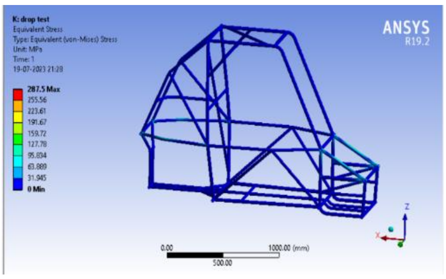

Fig 16 Rollover - Stresses

After performing the analysis, the results are tabulated and the Factor Of Safety (FOS) is calculated using the formula

Factor of safety = Yield strength / Maximum stress
Where maximum stress is the stress observed during the analysis

SNO	TYPE	DEF (mm)	STRESS (mpa)	FOS
1	FRONT CRASH	1.54	266.31	1.42
2	REAR CRASH	2.64	296.43	1.289
3	SIDE CRASH	2.07	261.17	1.45
4	TORSIONAL RIGIDITY	1.65	340.05	1.11
5	ROLL OVER	4.76	346.33	1.09
6	DROP TEST	1.064	287.5	1.39

Table -2

4. CONCLUSIONS

The design of the roll cage was successfully completed, meeting all the set goals and safety requirements. Achieving this involved a number of iterations in order to get the best possible results. Various calculations were performed to optimize the design and involved using various software like ANSYS, SOLIDWORKS 2021, CATIA V5, and LOTUS SHARK.

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