Design and Development of All-Terrain Vehicle Roll Cage

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Abstract. ATV is an off-roading vehicle and one of its essential parts is its roll cage on which all parts are mounted. The roll cage not only protects the passenger inside the vehicle it also acts as a structural defense for the vehicle. Now because of the above-mentioned properties, the roll cage is required to be structurally robust and it should tolerate high Von mises stresses and should have the least possible deformation during a crash while protecting the motorist inside the vehicle. Hence due to these high concerns of the roll cage, it is necessary to undergo simulation of the design to detect points that are vulnerable to stresses and high deformation. High Impact forces are applied on the roll cage in analysis to achieve real world actions of the chassis, which in fact helped us in developing a design that have mandatory safety standards and adequate potency to withstand these loading.

Keywords: Baja ATV, Roll cage Design, static structural analysis, structural tests, impact force calculation.

1. Introduction
ATV stands for All-Terrain Vehicle, defined by ANSI (American Standard National Institute) as an “automobile which travels on low-pressure tires, with a seat that is straddled by the operator, along with handlebars for steering control”. An ATV is a type of vehicle that can be used on any type of terrain; it is generally used for extreme off-roading. The proper material selection is an essential part of the design and development of the chassis of ATVs. Various papers and thesis have been written on this topic but the main focus of some 190 plus papers was based on the accidents and injuries that are caused during extreme off-roading on ATVs. [1]. Clinging on to the safety concerns and strength of the chassis, it should have the capability to withstand high stresses that are generated during ATV operation [2]. Material selection for roll cage manufacturing is among AISI 1018, AISI 4130, AISI 1020, E-Glass epoxy, Carbon fiber [3], and various other factors are also considered before selecting a material like cross-section, design ergonomics of the vehicle, and Factor of safety (FOS). Another important factor in material selection is the weldability of the material, in R. Soundararajan et al. [4] paper focuses on TIG welding, where they analyzed experimentally the weld made by TIG welding by the process of shot peening (a process in which a material is bombarded with small spherical balls). Now since we know that ATVs are used in extreme off-roading, therefore, driver’s safety has to be focused on, this all roll cages must have Seat Belts, Shoulder Belts, Lap
Belts, Anti-submarine belts, Arm restraint, Head restraint and Driver Equipment like Arm restraint, Safety shoes, Knee guards, Tear off goggles etc. [5-6].

For designing, software like SolidWorks, CATIA, Creo Parametric 1.0, and CAD programs can be used whereas Ansys and SimScale software can be used for analysis. Different tests like Rear Impact, Side Impact, Front Impact, and Rollover Analysis are being performed [7]. Design Failure Mode and Effective Analysis (DFMEA) is used for the investigation of the chassis components. Monocoque chassis, Ladder-Frame chassis, and Space frame chassis are used in today’s industries. For vehicle dynamics control, there is a need for Global Chassis Control GCC [8-9]. Different parameters like Ground Clearance, driver’s safety, and weight of the structure were considered while designing the Chassis and focus is to achieve a factor of safety above the given limits in all loading situations [10].

2. Methodology and Design
Roll cage is a base component of any vehicle; any other components like engine, CVT, etc. are all mounted on the roll cage. Since ATVs are mostly used for off-roading it is required that the roll cage of the vehicle must bear with various loads and it should also protect the driver in case of a mishappening. In the roll cage there are two types of members namely:
A. Primary member
B. Secondary member
Primary members are better for higher stress endurance than secondary members. Secondary members are there for equal distribution of stresses [11]. For the material of the roll cage in the BAJA rulebook it is specified that the minimum carbon content of the material should be 0.18%.

2.1. Material Selection
As the design of the roll cage is finalized then we need to decide the material of the roll cage with the required 0.18% minimum carbon content as advised by the SAE Baja rulebook. Other important factors that have to be kept in mind during material selection are vehicle weight, the process of fabrication, the weight to strength ratio of the material, and the good weldability of the material selected [4]. The materials that are taken into consideration are AISI 1018, AISI 1020, and AISI 4130.
Properties like carbon content, tensile strength, yield strength, etc. of the materials AISI 1018, AISI 1020, and AISI 4130 that are considered for the manufacturing of the roll cage is given in Table 1.

| Properties        | AISI 1018 | AISI 1020 | AISI 4130 |
|-------------------|-----------|-----------|-----------|
| Carbon Content (%)| 0.18      | 0.27      | 0.30      |
| Tensile Strength (MPa) | 440      | 463.7     | 731       |
| Yield Strength (MPa)   | 370      | 341.3     | 460       |
| Bending Strength (Nm)  | 392.68   | 477.62    | 662.78    |
| Bending Stiffness (Nm2) | 2763.1   | 4258.2    | 2786.1    |
| Weight/meter (kg/m)   | 1.686    | 1.47      | 1.122     |
| Cost (Rs. /meter)      | 325      | 325       | 920       |

Therefore, based on the above Table 1, availability and broad study in the market we decided that AISI 4130 should be best for our ATV.

2.2. Roll cage Tube Cross Section
The tube’s size is also an important factor in ATV manufacturing. It is responsible for factors like weight of the roll cage, the strength of the roll cage, and the cost of the roll cage. Generally, there are two different cross-sectional pipes namely circular and square. Although it is said that circular cross-section pipes are a cut above their counterpart square-shaped pipes [13].

Based on the Baja SAE rulebook primary members of the roll cage should have a cross-section of 25.4mm outer diameter and 3mm inner diameter whereas the secondary members of the roll cage should have a cross-section of 25.4mm outer diameter and a minimum of 0.89mm inner diameter [14-15].

2.3. Ergonomics
The ergonomics deal with the following factors:

- Safety of the Driver
- Comfort for all types driver (fat, slim) while driving
- Roof clearance
- Seated eye height – so that the driver can clearly see the road up ahead

Ergonomics of the vehicle like lap angle, ankle angle, seat angle etc. and the values that we have considered for our ATV is mentioned in Table 2.

| Parameter          | Range      | Value That We Have Incorporated In Our Atv |
|--------------------|------------|-------------------------------------------|
| Lap Angle          | 110°-130°  | 120°                                      |
| Ankle Angle        | 85°-110°   | 90°                                       |
| Seat Angle         | 95°-100°   | 95°                                       |
| Elbow Angle        | 80°-165°   | 105°                                      |
| Upper Arm Angle    | 0°-35°     | 19°                                       |
| Angle of vision    | 20°-40°    | 30°                                       |
| Steering Column Angle | 20°-50°     | 50°                                       |

2.4 Proposed dimensions Of ATV
The Solidworks based three dimensional model has been developed with the consideration of weight of the vehicle should be kept as minimum as possible because additional mass and incorrect geometry can disturb the constancy of the ATV and would affect its perfect execution in the dynamic rounds [16]. Also the design and material selection of the roll cage should be as such that it takes minimum time and cost during fabrication [17]. Isometric View is a method of representing a 3-D engineering or technical drawing in 2-D. Figure 1-3 represent the Isometric View, Side View and Front View obtained from CAD based software solidworks respectively.

![Figure 1. Isometric View of Rollcage](image1)

![Figure 2. Side View of Rollcage](image2)

![Figure 3. Front View of Rollcage](image3)
Length, Width and Height of our designed ATV is given in Table 3 below.

| Parameters          | Value (mm) |
|---------------------|------------|
| Length of the ATV   | 1526.57    |
| Width of the ATV    | 1620       |
| Height of the ATV   | 1016       |

3. Static Analysis of ATV
After the design and material of the rollcage was finalized we moved on to analysis part of the rollcage. The best part of software based simulations is that it is economical and it takes less time and arrangement than analyzing with an actual model. [18]. The following test were performed on Ansys 19.2.
- Front Impact Test
- Side Impact Test
- Rollover Impact Test
- Rear Impact Test
- Dump Test
- Bump Test
- Torsional Rigidity
- Modal Analysis

Assumptions taken for Structural Analysis of ATV
- Roll cage act as distorted body.
- Impact time is considered 0.30 seconds in case of deformable body.
- Impact time is considered 0.15 seconds in case of rigid body.

3.1 Mechanical Impact & Strength Analysis
Calculations are obtained from mechanical system design handbook referred in reference no. [19-20].
Data that we have considered for our ATV:
- ATV Weight (m) = 210 kg
- Initial velocity (V\_\text{initial}) = 16.67 m/s (60 Km/hr.)
- Final Velocity (V\_\text{final}) = 0 m/s
- Time of Impact (t) = 0.30 seconds. (Since we have considered our rollcage as a deformable body)

Impact Force Calculations for Front, Side and Rear Impact Test:
From Principle of Work and Energy,
Work done = Change in Kinetic Energy,
\[ W = \frac{1}{2} m (V_{\text{final}})^2 - \frac{1}{2} m (V_{\text{initial}})^2 \]  \hspace{1cm} (1)
\[ W = \frac{1}{2} m (V_{\text{initial}})^2 = 29178.33 \text{ Nm} \]
Displacement (S):
\[ S = (V_{\text{initial}}) \times t \] (V\_\text{initial} = max. speed of vehicle at the time of impact) \hspace{1cm} (2)
\[ S = 16.67 \times 0.3 = 5.001 \text{ m} \]
Now we know that “Work is said to be done when an object moves (displaces) along the direction of application of force” hence by the formula:
\[ W = F \times S \rightarrow F = W/S \rightarrow F = 29178.33/5.001 = 5834.49 \text{ N} \approx 5900 \text{ N} \]  \hspace{1cm} (3)

3.2 Front Impact Test:
This test is performed to know what will happen if the vehicle crashes into an object or into another vehicle head-on and what will be the stresses and deformation on the roll cage.

Impact Points - Front Bracing Members (FBM) and if there is no FBM then apply ¼ of the load on the front 4 nodes.

Fixed Support - Fire wall behind the driver.

Total deformation of the roll cage and Equivalent (von mises) stress acting on the roll cage for Front Impact Test, performed on Ansys software is given below in Figure 4 and Figure 5 respectively.

3.3 Side Impact Test:
This test is performed to know what will be the deformation and stress generated if two vehicles crash into each other making a 90-degree angle.

Impact Points - Side Impact Members (SBM) or the outer part of the side of the vehicle.

Fixed Support - opposite side’s SBM.

Total deformation of the roll cage and Equivalent (von mises) stress acting on the roll cage for Side Impact Test, performed on Ansys software is given below in Figure 6 and Figure 7 respectively.

3.4 Rear Impact Test:
In this test, the vehicle is bumped head-on by another vehicle from behind.

Impact Points - Rear part of the vehicle.

Fixed Points - Front Bracing Members (FBM).

Total deformation of the roll cage and Equivalent (von mises) stress acting on the roll cage for Rear Impact Test, performed on Ansys software is given below in Figure 8 and Figure 9 respectively.
3.5 Dump Test:
This test is performed to know what will happen to the vehicle after it falls from a height or jumps from a ramp.

Impact Points - Front Lateral Cross Member (FLC), Aft Lateral Cross Member (ALC) and Rear part of the ATV.

Fixed Points – Pipes on which Suspension would be fixed.

Impact Force Calculations:
The distribution of weight of most ATVs is 55:45 ratio (Rear: Front) which is also our case.

ATV Weight (m) = 210 kg
Time of impact (t) = 0.15 seconds.
Height (h) = 1 m
Velocity, \( V = \sqrt{2gh} = 4.42 \) m/s

Weight at the Front of ATV, \( m_f = \text{Ratio Of weight at front axle} \times \text{Actual weight of the ATV} \) (8)

\[ m_f = 0.45 \times 210 = 94.5 \text{ kg} \] (9)

Force at Front of the vehicle, \( F_f = m_f \times V/t = 94.5 \times 4.42/0.15 = 3213 \text{ N} \approx 3300\text{N} \) (10)

Weight at the Rear of ATV, \( m_r = \text{Ratio Of weight at front axle} \times \text{Actual weight of the ATV} \) (10)

\[ m_r = 0.55 \times 210 = 115.5 \text{ kg} \] (11)

Force at Rear of the vehicle, \( F_r = m_r \times V/t = 115.5 \times 4.42/0.15 = 3927 \text{ N} \approx 4000\text{N} \) (11)

Total deformation of the roll cage and Equivalent (von mises) stress acting on the roll cage for Dump Test, performed on Ansys software is given below in Figure 10 and Figure 11 respectively.

4. Dynamic Analysis:
Since ATVs used for off-roading it is subjected to several uneven loading. So due to these uneven loadings, the vehicle vibrates this can cause resonance of forced and natural frequencies which is quite disastrous for the ATV’s roll cage. Hence Modal Analysis is performed to check the natural frequencies of the ATV that are generated due to its self-weight.

Fixed Support – Fire wall of the ATV behind the driver’s seat.

The Natural Frequencies that are obtained during modal analysis in Ansys 19.2 software is cited below in Table 4.

Table 4. Natural Frequencies of the Rollcage.

| Serial No. | Frequency |
|------------|-----------|
| 1.         | 32.602    |
| 2.         | 51.031    |
| 3.         | 60.035    |
| 4.         | 77.41     |
| 5.         | 82.742    |
5. Results and Discussion
The acquired results Maximum Stress, Maximum Deformation and Factor of Safety is well within the range of what is given in the Baja SAE rulebook and previously published papers that are cited in this paper. Also the highest Factor of Safety 4.39 is obtained in Dump Test whereas the lowest Factor of safety is obtained in the Front impact test which is 1.93 and that is also above the mentioned lower limit of 1.5 Factor of safety. Henceforth it can be concluded that it is safe to begin the manufacturing of the roll cage. The Tabulated Data for the calculations of the proposed work is given in Table 5.

| Force Applied | Maximum Stress (MPa) | Maximum Deformation (mm) | Factor of Safety (FOS) |
|---------------|----------------------|--------------------------|------------------------|
| Front Impact Test | 5900 | 378.67 | 0.72931 | 1.93 |
| Side Impact Test | 5900 | 345.25 | 2.0266 | 2.11 |
| Rear Impact Test | 5900 | 325.24 | 3.5552 | 2.24 |
| Dump Test | Front -- 3300 | 166.28 | 0.29041 | 4.39 |
| Rear -- 4000 | |

6. Conclusion
This paper helped us in having better understanding of the Static Analysis of the ATV and the following conclusions are made:-
- Finite element analysis was the main key card in this entire project as it gave us critical knowledge about the design of the rollcage.
- The ergonomics of the vehicle is also kept in mind while design so that the driver can drive the ATV with absolute comfort and well-being.
- Greater the value of factor of safety greater will be the ability of the roll cage to sustain various loads in different terrains.
- All the impact test were performed and based on the maximum stress, factor of safety (FOS) was calculated. The factor of safety was well above the anticipated limit which is 1.5 and henceforth it is deduced that the modal of the ATV that was presented in this paper is safe to be fabricated.

The below Figure 14 show the Graph of Natural Frequencies that obtained during modal analysis performed on Ansys 19.2 software.

Figure 14. Graph of Natural Frequencies obtained from Modal Analysis (Taken from Ansys Software).
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