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Evaluating the Static and Dynamic Response of All-Terrain Vehicle Under Varying Conditions

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Abstract

A Roll cage is a reinforced framework installed within a vehicle's passenger area, designed to shield occupants by absorbing impact forces during crashes. It enhances safety by preventing the cabin from collapsing under extreme conditions. In All Terrain Vehicle the main outer structure is that provides protection to the Driver any crash or rollover. The Roll cage also acts as the vehicle main fame providing mountings to the component like suspension system, transmission system, and steering system. The roll cage is fabricated using AISI 4130, a high-strength, low-alloy steel known for its durability and excellent impact resistance. The 3D solid modelling of roll cage is designed in the SolidWorks' 2022 as per the requirements of vehicle sub-systems and assembly. The dynamic behavior of the roll cage is carried out in ANSYS workbench 2023 with different collisions like Front impact, Rear impact and rollover. The main objective of the analysis is to develop a roll cage design that is both robust enough to withstand harsh conditions and lightweight to enhance vehicle performance. The objective is to achieve an optimal safety factor, ensuring that the ATV's roll cage remains secure under all circumstances.

Keywords
CAD modelling, Meshing, Static and Dynamic Analysis

1. Introduction
All-Terrain Vehicle is a straddle seating position with a handle bar steering and the ability to maneuver through various Terrain conditions including dirt trails, mud, sand, and rocky surfaces. This design is for an Off-Highway Vehicle (OHV) intended for rugged terrains, featuring four low-pressure or non-pneumatic tires. The vehicle is built with a straddle-style seat and handlebars for steering, providing the operator with optimal control. It is designed specifically for a single rider, with no additional passenger capacity.

The roll cage of an all-terrain vehicle (ATV) is a crucial structural framework designed not only protects the driver but also provides structural support for essential systems. like the suspension, steering, and powertrain. The success of an ATV heavily depends on the roll cage, as its failure could significantly endanger the driver. Therefore, the roll cage design emphasizes driver safety alongside structural integrity and performance ease of manufacturing, durability, compactness, lightweight construction, and ergonomic considerations. The roll cage is typically constructed from thin, seamless pipes welded together to form a rigid structure capable of withstanding vehicle rollover sand harsh conditions.

The process of designing and developing the roll cage includes several key steps, such as selecting the right material, determining the cross- sectional dimensions, designing the structure, and performing finite element analysis. The material selected for the main components of the roll cage and the bracing must adhere to specific standards. For example, the material should be seam less steel tubing with a 25.4 mm outer diameter, a 3 mm wall thickness, and a carbon content of at least 0.18%. Furthermore, it must have a minimum bending stiffness of 2.76×10^9 Nm² and a bending strength greater than that of the specified steel tubing. Regardless of the material or its shape, the tubing profile must have a minimum wall thickness of 1.57 mm and a carbon content of at least 0.18%. Bending stiffness and strength calculations must consider the neutral axis to satisfy the minimum requirements. To meet these standards, AISI 4130 steel is being used.

The goal of this study is to design and develop a robust roll cage for an ATV. The design process focuses on ensuring safety, ease of manufacturing, durability, maintenance, and creating a compact, lightweight, and ergonomic frame. This paper emphasizes the importance of subjecting the roll cage to various impact tests, including front, rear, side, and rollover impacts, to assess its ability to withstand different types of forces. A software model of the roll cage is created using SolidWorks, and the design is then analyzed for potential failure modes through simulations and stress analysis using Ansys software. The design is adjusted and enhanced based on the test results obtained.

1.1 Objectives

- This document aims to detail the steps involved in creating a roll cage with standard dimensions in SolidWorks 2022. Following the design, simulations will be conducted in ANSYS Workbench 2023 using AISI 4130 steel as the material.
- The simulations will test how the roll cage responds to various impact scenarios—such as front, rear, side, and rollover— by performing static structural analysis.
- Additionally, explicit dynamics simulations will be used to model front and rear crash events.
- The objective is to determine whether the roll cage can endure extreme impact forces and maintain structural integrity.

2. Literature review

Aru, S et al. (2014). The optimized roll cage design is stronger and stiffer, with deformation in front and side impacts kept below 10% of driver clearance, ensuring safety. Front and side impacts have factors of safety of 1.116 and 1.446, respectively, with deformation within safe limits. In the front rollover, deformation (4.6033 mm) is prioritized over stress, confirming driver safety. Side rollovers are important for ATVs due to rough terrain.

Shubham Khole, et al. (2018) Finite element analysis (FEA) was essential in designing and analyzing the roll cage for achieving the SAE BAJA All-Terrain vehicle, successfully testing it for front, rear, and side collisions. The paper focuses on load analysis and weight optimization, achieving a design ideal for the BAJA SAE event. Material selection prioritized strength, weight, durability, and cost. FEA tools like SolidWorks and ANSYS simulated real conditions, ensuring safety and optimization. The project resulted in a lightweight, cost- effective roll cage with reduced material wastage, suitable for mass production, and offering safety and ease of use on rough terrains.

Shivam Mishra et al. (2017). The FEA analysis confirmed the roll cage's structural strength with a low weight-to-strength ratio, prioritizing safety for the driver, crew, and environment. The analysis identified key factors like deformation, stress, and safety. The design was kept simple for easy manufacturing, and the roll cage was successfully built, serving as the core for the ATV, integrating systems like transmission, suspension, brakes, and steering.

Raina, D.et al. (2014). Safety was a top priority, with a significant Factor of Safety (FOS) implemented in the roll cage design to Minimize the likelihood of failure and injury., ensuring the vehicle can endure extreme conditions. Finite element analysis (FEA) was crucial in designing and analyzing the ATV frame. The design process involved numerous tests and constraints, aiming to create a chassis capable of withstanding various loads and navigating tough terrains like hills and rocky areas. This paper focused on load analysis, concluding that the selected roll cage design is the safest and most reliable for long terrains. Aakash et al. [5] July 2020. A four-wheel drive design for the ATV was tested, proving the chassis is capable of withstanding various impacts and collisions while ensuring the driver's safety. and key components like the driveline, powertrain, and electrical parts.

S. Jacob at al. (2021). The study examined how different loads affect the vehicle chassis. The roll cage is engineered to endure different types of impacts, such as rollovers, torsional forces, and frontal crashes as well as dynamic crash situations. It includes extra space below the driver's cockpit for safe driveline placement. The design protects the driver's foot from crumpling in the front and keeps the head and shoulders safe during rollovers or side impacts. Additionally, the roll cage safeguards the powertrain and electrical components by minimizing structural displacement from external loads.

G. D. Gautam et al. (2020). The front and rear impact test analysis revealed that increased stress levels lead to reduced deformation. Conversely, both front rollover and side-impact tests indicated that greater stress correlates with increased deformation. Overall, these findings suggest that AISI 1020 material is suitable for developing a lighter and safer roll cage design. This is in comparison to traditional Formula 1 roll cages, highlighting its effectiveness in enhancing safety while minimizing weight.

We developed a roll cage design for Formula SAE competitions, considering all essential design factors. Through Finite Element Analysis (FEA) under static and dynamic conditions, we concluded that the roll cage meets the required Factor of Safety, ensuring driver safety.
Khelan Chaudhari et al. (2013). The roll cage has been successfully designed, developed, and fabricated. It serves as the foundation for the ATV, incorporating various automotive systems, including transmission, suspension, steering, brakes, and other components.

Amit R. Parate et al. (2018). Finite element analysis (FEA) played a crucial role in designing and analyzing the frame for the off- road vehicle. The roll cage's strength was successfully tested against front, rear, and side collisions. This paper covers various load analyses, leading to weight optimization of the roll cage. The final design is ideal for the event, with all systems securely integrated. Sivasubramaniam R et al. (2020).The design, development, analysis, and optimization of the roll cage have been successfully completed. Our work examined different wall thicknesses, yielding valuable insights into the ATV's performance under various conditions. Finite Element Analysis (FEA) was essential for designing and analyzing the frame of the off-road vehicle. Safety remained a top priority for the driver, crew, and environment. The analysis results were crucial for determining equivalent stress, maximum deformation, and the safety factor.

3. Methods

The roll cage design was created using SolidWorks 2022, a 3D modelling software. The design involves building a detailed digital representation of the roll cage, considering all the structural and safety aspects. This process includes defining the geometry, dimensions, and material properties to ensure that the roll cage meets the required specifications and performance standards. The software allows for precise control over the design, enabling the creation of a model that can be tested and modified as needed before fabrication is built. The roll cage is designed with safety as the primary focus, ensuring it provides protection in case of accidents. Additionally, the roll cage is carefully engineered to serve as a secure framework for mounting various sub-systems. This means that it not only protects the occupants but also supports and integrates with other critical components of the vehicle, such as the suspension, engine, and other essential systems. The design ensures that all parts are securely attached and function harmoniously within the overall structure.

The roll cage is designed with specific dimensions: it stands 60 inches tall, with a wheelbase of 47 inches and a track width of 52inches. These measurements are carefully chosen to ensure the roll cage provides ample protection while fitting the overall structure of the vehicle. The height, wheelbase, and track width are all crucial for maintaining stability, safety, and performance. Figure 1 and Figure 2 show the views of the roll cage.

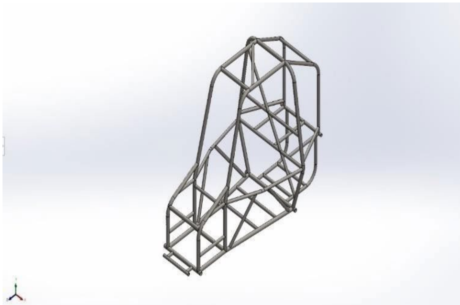


Figure 1: Isometric View of Roll cage

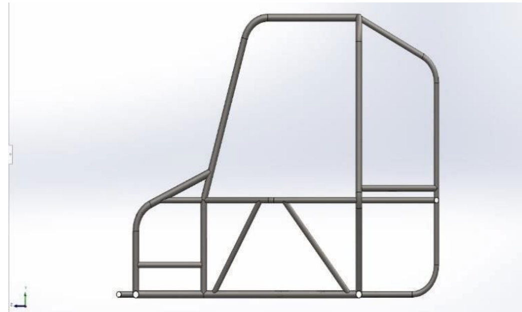


Figure 2: Side view of the Roll cage

3.1. Nomenclature

The roll cage is constructed using both primary and secondary members. The primary members form the main structural framework, providing the essential support and strength needed for safety. The secondary members are additional supports that reinforce the structure, enhancing its overall rigidity and stability. Together, these components ensure that the roll cage can effectively protect the occupants and withstand impacts.

Primary Members

The primary pipes used in the roll cage have an outer diameter of 31.75 mm and a wall thickness of 1.65 mm. These dimensions are selected to provide the necessary strength and durability for the main structural components of the roll cage, ensuring it can withstand high forces and protect the occupants effectively. Figure 3 shows the primary members of the roll cage.

RRH Rear Roll Hoop
RHO Roll Hoop Overhead Members FBM Front Bracing Members ALC Aft Lateral Cross Member
BLC Overhead Lateral Cross Member CLC Upper Lateral Cross Member DLC SIM Lateral Cross Member
FLC Front Lateral Cross Member LFS Lower Frame Side
Members ***Secondary members***

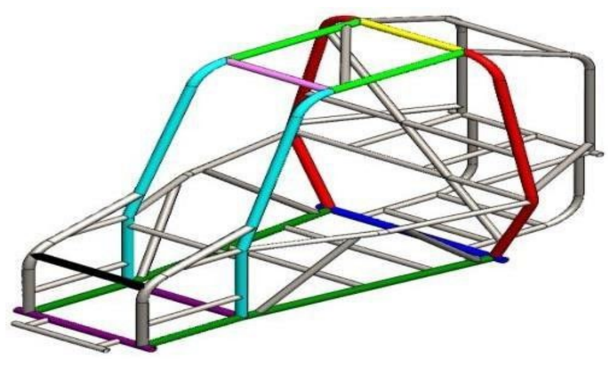


Figure 3: Primary Members of Roll cage

The secondary pipes used in the roll cage have an outer diameter of 25.4 mm and a wall thickness of 1.65 mm. These dimensions are chosen to provide the necessary strength and support while keeping the overall weight of the structure manageable. The precise sizing of the pipes ensures they can effectively reinforce the roll cage and contribute to its durability and safety (Figure 4).

- LDB Lateral Diagonal Bracing
- SIM Side Impact Members
- FAB Fore/Aft Bracing Members
- USM Under Seat Member
- RLC Rear Lateral Cross Member

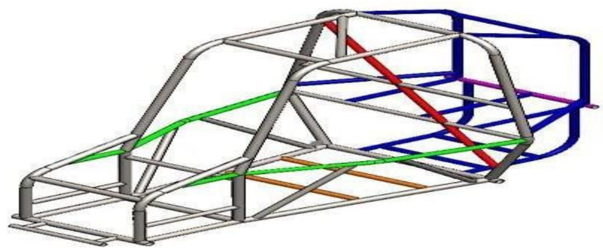


Figure 4: Secondary members of Roll cage

3.1 Properties of Raw material

The AISI 4130 has been selected as a material for the roll cage. The various properties of these materials are listed in the below mentioned (Table 1).

Table 1: Properties of Raw Materials

S.N0	Properties	AISI 4130
1	Density (kg/m^3)	7850
2	Young's Modulus (GPa)	205
3	Yield Strength (MPa)	435
4	Ultimate Strength (MPa)	670
5	Poisson's Ratio	0.29
6	Elongation	25.50%
7	Melting Point (^{o}C)	1432

3.2 Vehicle Parameters

The vehicle designed parameters which include track width, wheel base and ground clearance which is given in the Table 2.

Table 2: Vehicle parameters

S.NO	Vehicle Dimensions	Front	Rear
1	Overall length and width	Length=1841.5mm and Width=1371.6mm	
2	Overall Height	1524mm	
3	Wheelbase	1270mm	
4	Track width	1193.8mm	
5	Curb weight	250 kg	
6	Weight distribution	38%	62%
7	Designed Ground Clearance	13inch	

3.3 Analysis Methods

When performing an analysis of an ATV roll cage in ANSYS Workbench, it’s essential to use a range of techniques to thoroughly evaluate how the roll cage responds to different impact conditions. The objective is to ensure the cage can handle various stress scenarios effectively. Below is an alternative explanation of the steps involved in the analysis process**:**

***Model Preparation*:**

- Import the roll cage design from SolidWorks into ANSYS. Ensure the model is error-free, with no defects like overlapping surfaces or unintended gaps.
- Simplify the geometry where possible to reduce the complexity of the analysis, while maintaining the key structuralfeatures.
- Assigning Material Properties
- Define the material characteristics for AISI 4130, such as stiffness, density, and yield strength.
- Apply these properties to all parts of the roll cage to reflect its real-world behavior.

Meshing the Model

To ensure accurate results for your roll cage simulation, you have employed a tetrahedral mesh with an initial element size of 5mm, chosen based on the structure's complexity. Recognizing that certain regions, like corners and joints, experience higher stress concentrations, you applied finer meshing in these critical areas to capture the detailed stress distribution.

After defining the mesh, you performed a grid independence test (or mesh convergence study) to ensure that the results are not affected by the mesh size.

Setting Boundary Conditions:

Model real-life constraints like the mounting points of the roll cage. Ensure appropriate loads are applied based on the type ofimpact being analyzed (e.g., front, side, or rollover impacts).

Defining Loading Conditions:

For each impact scenario, apply forces or pressures where impacts would occur. Distribute forces to prevent extreme stress at a single point.

3.5 Explicit Dynamic (Simulating Crashes):

Setting Up Crash Simulations:

For dynamic crash events like front and rear collisions, use the explicit dynamics approach. Input realistic initial speeds and crash conditions based on typical ATV impact scenarios.

Contact Conditions:

- Define interactions between different parts of the roll cage and other objects during the crash using frictional or bonded contacts. Time Step Control:
- Use short time steps to ensure the simulation accurately captures the crash process in detail.

3.6 Force Calculations:

Force calculations for Front, Rear and Side Impacts

We use kinetic energy and work energy principle to know the range of the force.

Weight of the ATV (M)Initial velocity ($V_{initial}$) Final Velocity (V_{final}) Impact time (t)

From work energy principle, work done = Change in K.E,

$$W=\frac{1}{2}\times M\times(V_{initail}^2-V_{final}^2)$$

Displacement (s) = Velocity(V) x Time (t) s = V_{final} x t

W=Force(F)x Displacement (s)

F = W/s - - - - - - - - 1

Force Calculations for Rollover

Weight of the ATV (M) Impact time (t)

Potential Energy = Kinetic Energy

$$M\times g\times h=\frac{1}{2}\times M\times(V_{inital}^2-V_{final}^2)$$

4. Results and Discussions

4.1 Front Impact

Front impact evaluation is carried out to find the behavior of roll cage when the front portion is subjected to collision with another ATV or any other external body. This analysis is done in ANSYS workbench under static structural analysis. The ATV is treated as a deformable body. For analysis purposes, the ATV is considered stationary, and a force is employed to the front part of the roll cage, associated to a velocity of 60 km/h. The rear suspension mounting is fixed to simulate the realistic conditions of the impact (Figure 5 and 6).

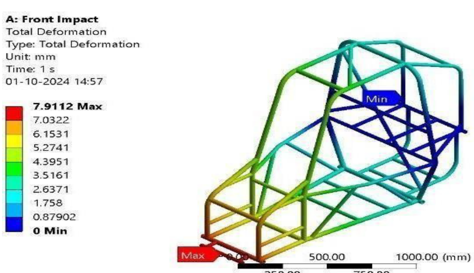


Figure 5: Total deformation for Front Impact

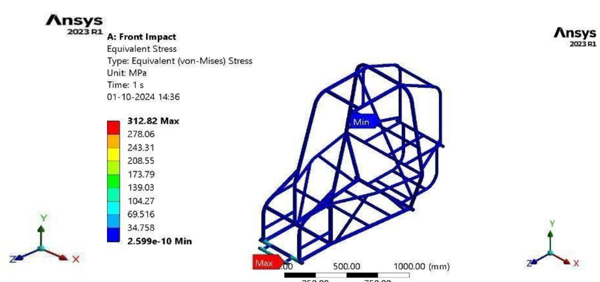


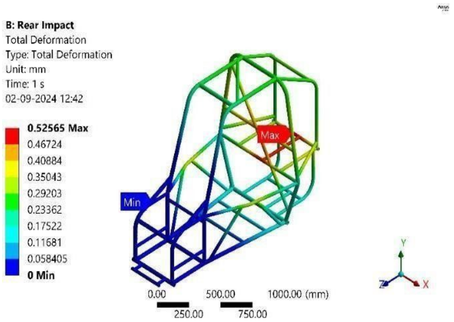
Figure 6: Von-Mises stress- Front impact

Result deliberation:

Based on Equation 2, the force applied in the analysis is calculated to be between 5000N and 10000N. The structure experiences maximum Von Mises stress of 312.82 MPa, as depicted in Figure 7, leading to a factor of safety (FOS) of 1. 4705.The total deformation recorded, shown in Figure 6, is 7.91 mm, which falls within the design's allowable range. These findings indicate that the roll cage is capable of withstanding the front impact forces without surpassing the stress limits of the material or undergoing excessive deformation.

4.2 Rear Impact

In a rear impact investigated is carried out to find the behavior of roll cage when the rear portion is subjected to collision with another TV or any other external body. This analysis is done in ANSYS workbench under static structural analysis. The ATV is treated as a deformable body. For analysis purposes, the ATV is considered stationary, and a force is applied to the rear part of the roll cage, as the vehicle moves minimum speed with a velocity of 30 km/h in a reverse gear. The front suspension mounting is fixed to simulate the realistic conditions of the impact (Figure 7 and 8).



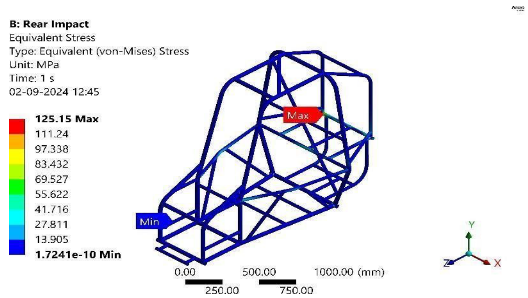
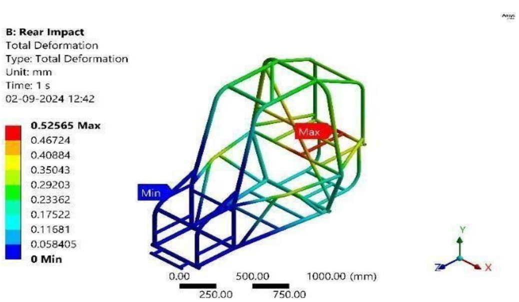


Figure 7: Von mises stress-Rear Impact   Figure 8: Total Deformation -Rear Impact

Result deliberation:
Based on Equation 1, the force applied in the analysis is calculated to be between 4000N and 10000N. The structure experiences a maximum Von Mises stress of 125.5 MPa, as depicted in Figure 8, leading to a factor of safety (FOS) of 3. 675.The total deformation recorded, shown in Figure 9, is 0.5256 mm, which falls within the design's allowable range. These findings indicate that the roll cage is capable of withstanding the rear impact forces without surpassing the stress limits of the material or undergoing excessive deformation.

4.3 Side Impact
In a side impact examination, the behavior of the roll cage is evaluated when the side of the ATV is subjected to a collision with another ATV or an external object. This analysis is performed using ANSYS Workbench under static structural conditions. The ATV is modelled as a deformable body. To replicate real-world conditions, the topmost part of the roll cage is fixed during the simulation (Figure 9 and 10).



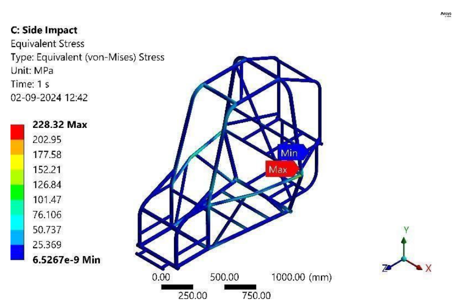


Figure 9: Total Deformation-Side Impact   Figure 10: Von mises stress-Side Impact

Result deliberation:
Based on Equation 1, the force applied in the analysis is calculated to be between 5000N and 10000N. The structure experiences a maximum Von Mises stress of 228.32 MPa, as depicted in Figure 11, leading to a factor of safety (FOS) of 2.0147. The total deformation recorded, shown in Figure 10, is 3.284 mm, which falls within the design's allowable range. These findings indicate that the roll cage is capable of withstanding the side impact forces without surpassing the stress limits of the material or undergoing excessive deformation.

4.4 Rollover
An ATV rollover occurs when the vehicle loses its balance and flips over, landing on its side, roof, or even continuing to roll multiple times. This can happen when the ATV becomes unstable due to sudden maneuvers, changes in speed, or uneven ground. The high center of gravity and narrow wheelbase of most ATVs make them particularly susceptible to rolling over, especially if the rider makes a sharp turn, rides across a steep slope, or encounters obstacles like rocks or ruts.
There are three types of Rollover occurrence

- Front Rollover
- Rear Rollover
- Side Rollover

Front Rollover

In a front rollover situation, it's assumed that the ATV (All-Terrain Vehicle) could drop onto its rollover hoop from a height of 3 meters. This height is selected because it's greater than what might typically occur at any track. Since the road or ground won't deform upon impact, the duration of the impact is calculated. For the purpose of investigated, the ATV is considered stationary. This force is then applied to the top of the roll cage, while the lower part of the roll cage is to be fixed (Figure 11 and 12).

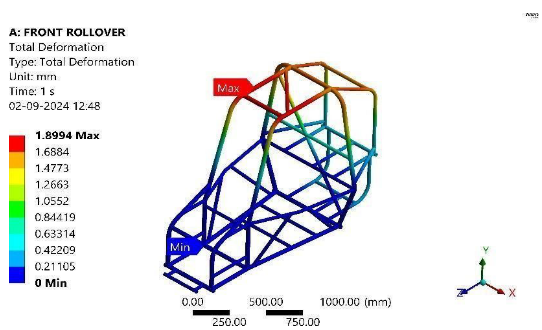


Figure 11: Total Deformation- Front Rollover

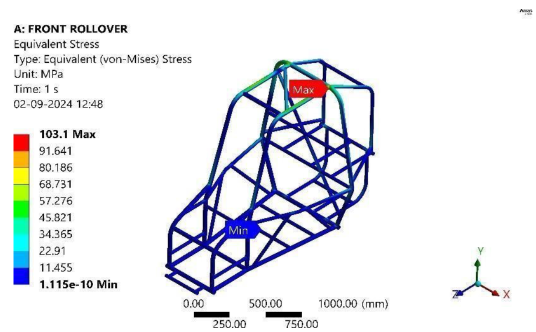


Figure 12: Von Mises -Front Rollover

Result deliberation:

Based on Equation 2, the force applied in the analysis is calculated to be between 5000N and 10000N. The structure experiences a maximum Von Mises stress of 103.1 MPa, as depicted in Figure 13, leading to a factor of safety (FOS) of 4.4619 The total deformation recorded, shown in Figure 13, is 1.8994 mm, which falls within the design's allowable range. These findings indicate that the roll cage is capable of withstanding the front roll over forces without surpassing the stress limits of the material or undergoing excessive deformation.

Side Rollover

In a side rollover situation, it's assumed that the ATV (All-Terrain Vehicle) could drop onto its side part from a height of 1 meter. Since the road or ground won't deform upon impact. For the purpose of analysis, the ATV is considered stationary. This force is then applied to the side part of the roll cage, while the upper part of the roll cage is to be fixed (Figure 14).

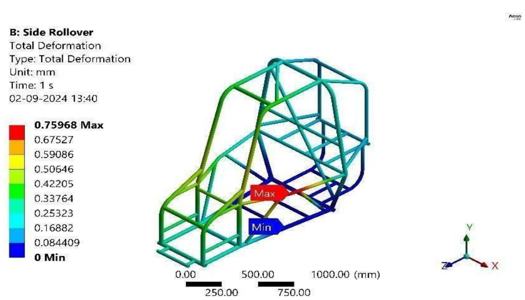


Figure 13: Total Deformation-Side Rollover

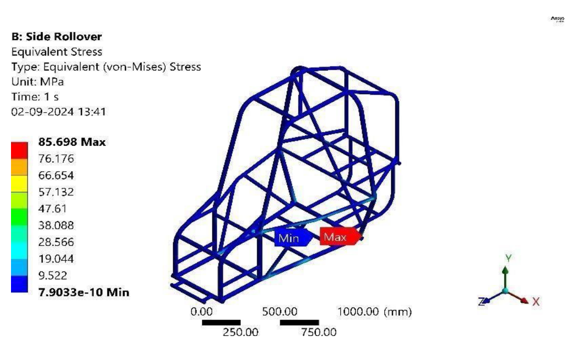


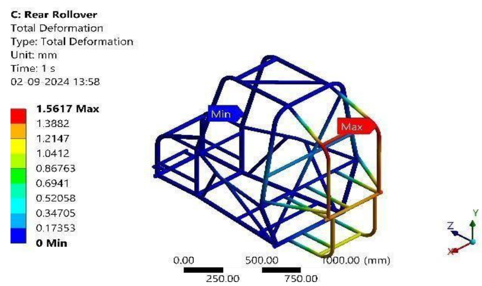
Figure 14: Von mises stress-Side Rollover

Result deliberation:

Based on Equation 2, the force applied in the analysis is calculated to be between 5000N and 10000N. The structure experiences maximum Von Mises stress of 85.69 MPa, as depicted in Figure 15, leading to a factor of safety (FOS) of 5.3677. The total deformation recorded, shown in Figure 14, is 0.7596 mm, which falls within the design's allowable range. These findings indicate that the roll cage is capable of withstanding the side roll over forces without surpassing the stress limits of the material or undergoing excessive deformation.

Rear Rollover

In a Rear rollover situation, it's assumed that the ATV (All-Terrain Vehicle) could drop onto its rear side from a height of 2 meters. Since the road or ground won't deform upon impact. For the purpose of analysis, the ATV is considered stationary. This force is then applied to the rear part of the roll cage, while the front part of the roll cage is to be fixed (Figure 15 and 16).



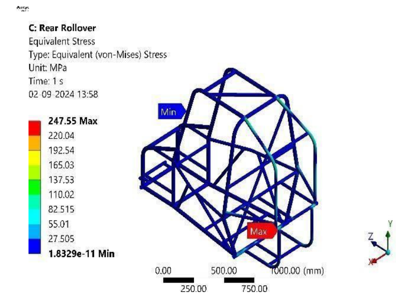


Figure 15: Total Deformation- Rear Rollover

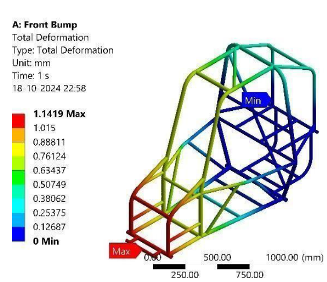
Figure 16: Von Mises Stress-Rear Impact

Result deliberation:
Based on Equation 2, the force applied in the analysis is calculated to be between 5000N and 10000N. The structure experiences a maximum Von Mises stress of 247.55 MPa, as depicted in Figure 17, leading to a factor of safety (FOS) of 1.8582. The total deformation recorded, shown in Figure 16, is 1.5617 mm, which falls within the design's allowable range. These findings indicate that the roll cage is capable of withstanding the rear roll over forces without surpassing the stress limits of the material or undergoing excessive deformation.

4.5 Bump Analysis

The bump analysis is performed in the roll cage to find the damping behavior of the roll cage when it is travelling in the heavy bumps, bolters and irregular surfaces.
The Indian Road Congress code specifies that a standard speed breaker should have a rounded radius of 17 meters, with a width of 3.7 meters and a height of 0.10 meters. This design helps slow down vehicles effectively while ensuring smoother crossing for drivers.

Front Bump
This analysis is conducted to replicate the conditions when the front wheels of the ATV go over a bump with a maximum speed of vehicle 60Kmph, causing the roll cage to experience a moment or rotational force. The force is applied to front suspension mounting and rear suspension mountings are fixed to simulate the realistic conditions of the impact (Figure 17 and 18).



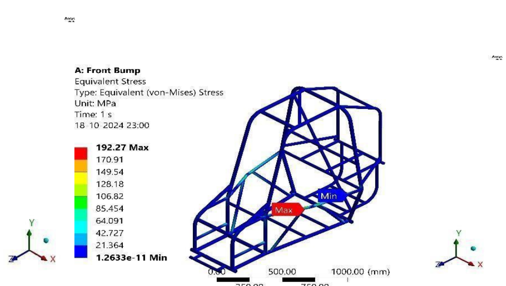


Figure 17: Total deformation-Front Bump

Figure 18: Von mises stress: Front Bump

Result deliberation:
Based on Equation 3, the force applied in the analysis is calculated to be between 5000N and 10000N. The structure experiences a maximum Von Mises stress of 192.27 MPa, as depicted in Figure 20, leading to a factor of safety (FOS) of 2.4445. The total deformation recorded, shown in Figure 19, is 1.1419 mm, which falls within the design's allowable range. These findings indicate that the roll cage is capable of withstanding the Front bump forces without surpassing the stress limits of the material or undergoing excessive deformation.

Rear Bump

This analysis is conducted to replicate the conditions when the rear wheels of the ATV go over a bump with a maximum speed of vehicle 60Kmph, causing the roll cage to experience a moment or rotational force. The force is applied to rear suspension mountingand front suspension mountings are fixed to simulate the realistic conditions of the impact.

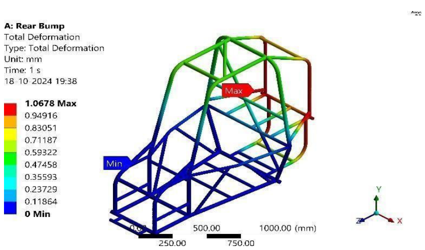


Figure 19: Total Deformation- Rear Bump

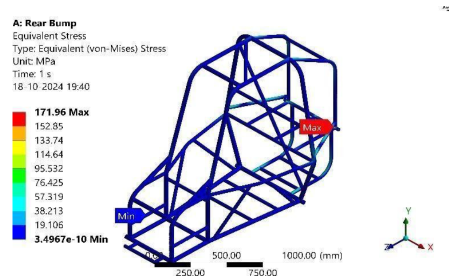


Figure 20: Von mises Stress-Rear Bump

Result deliberation:

Based on Equation 3, the force applied in the analysis is calculated to be between 5000N and 10000N. The structure experiences a maximum Von Mises stress of 171.96MPa, as depicted in Figure 21, leading to a factor of safety (FOS) of 2.7332. The total deformation recorded, shown in Figure 21, is 1.0678mm, which falls within the design's allowable range. These findings indicate that the roll cage is capable of withstanding there are bump forces without surpassing the stress limits of the material or undergoing excessive deformation.

4.5 Torsion Impact

The torsional analysis of the roll cage is performed to assess its torsional stiffness when the ATV encounters bumps at the front and rear when it is ride. The primary goal of this analysis is to ensure that the roll cage has sufficient stiffness to effectively handle the dynamic loads exerted by the suspension.

Front Torsion Impact

In the front torsional analysis, a twisting force is applied to the roll cage, generated by a couple. Force is distributed across the four suspension mounting points, while the rear suspension mounting is fixed in place (Figure 21 and 22).

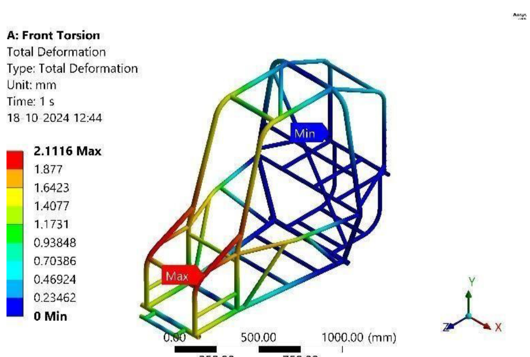


Figure 21: Total Deformation-Front Torsion Impact

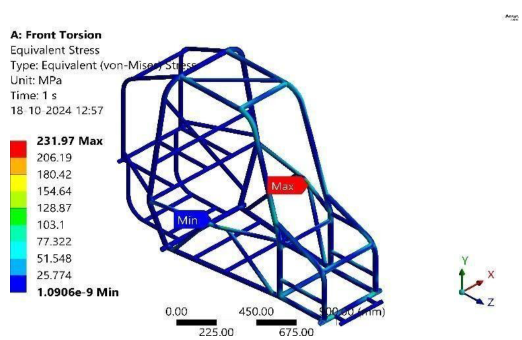
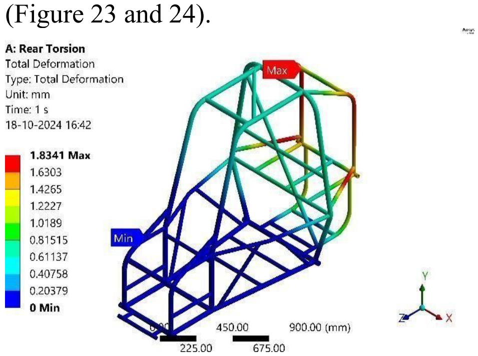


Figure 22: Von mises Stress-Front Torsion Impact

Result deliberation:

Based on Equation 4, the force applied in the analysis is calculated to be between 5000N and 10000N. The structure experiences a maximum Von Mises stress of 231.97 MPa, as depicted in Figure 23, leading to a factor of safety (FOS) of 2.0262. The total deformation recorded, shown in Figure 22, is 2.1116 mm, which falls within the design's allowable range. These findings indicate that the roll cage is capable of withstanding the front torsion forces without surpassing the stress limits of the material or undergoing excessive deformation.

Rear Torsion Impact
In the Rear torsional analysis, a twisting force is applied to the roll cage, generated by a couple. A force of is distributed across the four suspension mounting points, while the Front suspension mounting is fixed in place (Figure 23 and 24).



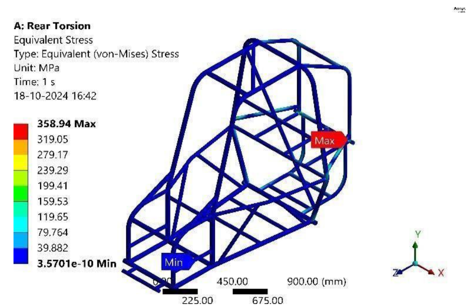


Figure 23: Total Deformation-Rear Torsion Impact Figure 24: Von mises stress-Rear Torsion Impact

Result deliberation:
Based on Equation 5, the force applied in the analysis is calculated to be between 5000N and 10000N. The structure experiences a maximum Von Mises stress of 358.94MPa, as depicted in Figure 23, leading to a factor of safety (FOS) of 1.3094. The total deformation recorded, shown in Figure 22, is 1.8341mm, which falls within the design's allowable range. These findings indicate that the roll cage is capable of withstanding there are torsion forces without surpassing the stress limits of the material or undergoing excessive deformation.

4.6 Dynamic Analysis
Dynamic analysis of a roll cage examines how it responds to different dynamic conditions like impacts, Drop test, vibrations, or sudden motion changes. We conducted an explicit dynamic analysis to understand how the roll cage behaves after an impact at a speed of 60 km/h.
This Analysis includes
* Front Crash
* Rear Crash

Front Crash
For the most extreme front impact scenario, it is assumed that the vehicle collides with a stationary wall at a speed of 60 km/h. Since the wall is non-deformable and the impact time is short, this will result in the highest possible stress on the vehicle. In this analysis, the vehicle is modelled as hitting the wall at 60 km/h, and the material chosen for the analysis is Concrete. Velocity is assign to roll cage and side part of the wall is fixed (Figure 25).

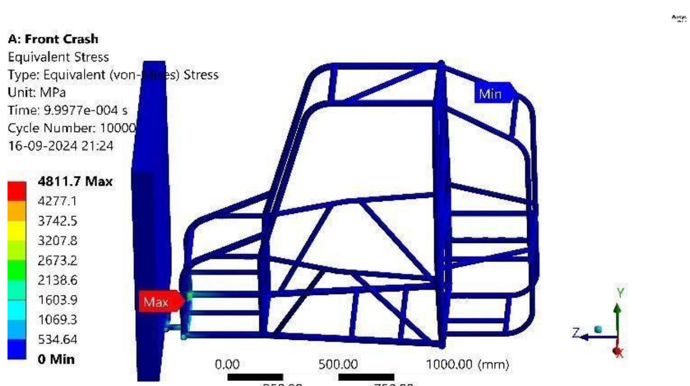


Figure 25: Von mises stress-Front Crash

Rear Crash
In the most severe rear-end collision scenario it is assumed that the vehicle collides with a stationary wall at a speed of 30 km/h when driver moves in a Reverse Gear. Since the wall is non- deformable and the impact time is short, this will result in the highest possible stress on the vehicle. In this analysis, the vehicle is modelled as hitting the wall at 30 km/h, and the material chosen for the analysis is Concrete. Velocity is assign to roll cage and side part of the wall is fixed (Figure 26).

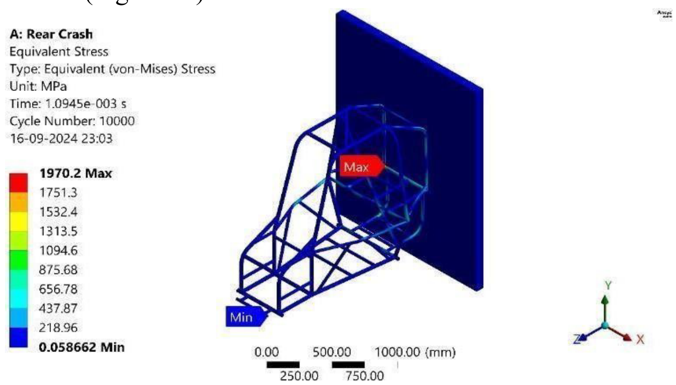


Figure 26: Von mises stress-Rear Crash

4.7 Boundary Conditions

The boundary conditions for static analysis at different impact scenarios can be described in Table 3.
The boundary conditions for Dynamic analysis at different impact scenarios can be described in Table 4.

Table 3: Boundary Conditions For Static Analysis

S.NO	Analysis	Load Entity	Fixed supports
1	Front Impact	Nose Area	Rear Suspension
2	Rear Impact	Rear Members	Front Suspension
3	Side Impact	SIM	FBM
4	Front Rollover	FBM	Lower Part
5	Side Rollover	Side region	FBM
6	Rear Rollover	Rear part	Nose area
7	Front Bump	Front Suspension Mount	Rear Suspension Mount
8	Rear Bump	Rear SuspensionMount	Front Suspension Mount
9	Front Torsional Stiffness	Front Suspension Mount	Rear Suspension Mount
10	Rear Torsional Stiffness	Rear Suspension Mount	Front SuspensionMount

Table 4: Boundary Conditions for Dynamic Analysis

S. N0	Analysis	Direction of Velocity	Fixed Supports	Time(Sec)
1	Front Crash	Positive Z-direction towards the Wall	Edges of the wall	0.0003
2	Rear Crash	Negative Z-direction towards the wall	Edges of the wall	0.0006

4.8 Analysis Results

The analysis results for various impact scenarios on the ATV are given in Table 5:

Table 5: Outlines the analysis results

S.NO	Static	Load(N)	Total Deformation (mm)	Von-Misses Stress (MPa)	FOS	Fatigue	
						Life (Cycles) Min	Damage (Max)
1	Front Impact	8057.16	7.911	312.82	1.4705	3657.7	$2.73e^5$
2	Rear Impact	4026.16	0.52565	125.5	3.675	$1.0249e^5$	9757
3	Side Impact	8057.16	3.284	228.32	2.0147	4808.8	$2.0795e^5$
4	Front Roll over	9456.97	1.8994	103.1	4.4619	83340	11999
5	Side Rollover	3140.55	0.7596	85.698	5.3677	$1.7174e^5$	5822.9
6	Rear Rollover	6299.55	1.5617	247.55	1.8582	9256.8	$1.0803e^5$
7	Front Bump	7500	1.1419	192.27	2.4445	13602	73519
8	Rear Bump	6500	1.0678	171.96	2.7332	9679.6	$1.0331e^5$
9	Front Torsion Impact	8300	2.1116	237.97	2.0262	7705.9	$1.2977e^5$
10	Rear Torsion Stiffness	7500	1.8341	358.94	1.3094	1201.8	$8.321e^5$

Factor of Safety (FOS)

The Factor of Safety (FOS) for an ATV roll cage is critical to maintaining structural integrity and protecting occupants in various impact conditions. Different impact types demand unique FOS values based on the forces likely to be encountered. **Front impacts**, common in head-on collisions with obstacles, typically require an FOS of 1.0–2.5 to withstand moderate to severe impacts without structural failure. **Rear impacts**, usually less forceful, can be managed with a slightly lower FOS of 1.5–3.0, sufficient for sudden stops or minor rear-end collisions. **Side impacts** pose a direct risk to driver and passenger safety, so an FOS of 1.5–2.5 is recommended, emphasizing strong lateral cage support. **Rollover impacts**, among the most severe impact types, demand a higher FOS of 1.5–3.0 to safeguard occupants from compressive forces that could collapse the roof structure.

Fatigue Analysis

Fatigue analysis for an ATV roll cage is essential to ensure long-term durability under repeated loading and prevent unexpected failures. In fatigue analysis, the main factors considered are the number of load cycles and the cumulative damage that occurs over the life of the component due to cyclic stresses.

1. **Cycles:**

- ATV roll cages face repeated loads from vibrations, impacts, and terrain variations. Estimating the load cycles is based on the **typical lifespan** of the ATV and the frequency of encounters with rough terrain.
- **High-cycle fatigue** analysis is typically used if the stresses per cycle are low but the cycles are numerous, sometimes reaching millions for off-road vehicles.
- **Low-cycle fatigue** may be relevant in high-impact or competitive scenarios, where fewer, more intense cycles are expected due to heavy impacts.

2. **Damage:**

- Each load cycle contributes a fraction of damage depending on the load level and cycle count, with damage accumulating until it potentially reaches a critical level (1.0), indicating failure.
- A **damage tolerance factor** is applied to account for safety margins, with the goal of keeping damage below the critical threshold across the ATV's expected lifespan

Industrial Standards
ATV roll cages are critical safety structures designed to protect occupants during crashes, rollovers, and other off-road impacts. In the context of industry standards, safety guidelines, and competitive regulations, ATV roll cages must meet specific design, material, and testing requirements to ensure they provide sufficient protection under extreme conditions.

1. **ANSI/SVIA Standards**

- American National Standards Institute (ANSI) and Specialty Vehicle Institute of America (SVIA) set guidelines for the design, construction, and testing of ATVs.
- These standards emphasize safety measures, including the structural integrity of roll cages and the materials used.

2. **ISO Standards**

- The International Organization for Standardization (ISO) provides guidelines for vehicle safety and performance. For ATVs, ISO 13232 focuses on the safety aspects of all-terrain vehicles, including roll-over protection.
- ISO standards recommend testing methods for rollover resistance and overall vehicle stability.

3. **SAE International**

- The Society of Automotive Engineers (SAE) develops standards and guidelines for off-road vehicles, including ATVs. For example, SAE J2243 outlines the requirements for testing vehicle structural integrity and occupant protection.
- SAE standards often include specifications on materials, design protocols, and testing methods for roll cages.

5. Conclusions
The roll cage for the All-Terrain Vehicle (ATV) was meticulously designed and analyzed to prioritize occupant safety during potential crashes and rollovers. Constructed from AISI 4130, a material renowned for its exceptional strength and durability, the roll cage was subjected to both static and dynamic analyses across various impact scenarios, including front impact, rear impact, and rollover events. The analysis results indicated that the roll cage effectively withstood the forces encountered during these collisions, offering substantial protection to the driver while maintaining its structural integrity. Additionally, the roll cage functions as the main frame for critical vehicle systems, including the suspension, transmission, and steering, showcasing its multifaceted role in the ATV's design. Overall, the design proved to be sufficiently robust to endure harsh conditions while remaining lightweight, contributing to enhanced vehicle performance. The final configuration achieved a commendable safety factor, ensuring that the roll cage can reliably perform under extreme conditions, thus meeting both safety and performance standards essential for off-road vehicles.

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