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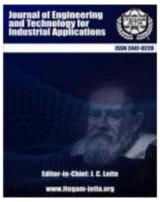

RESEARCH ARTICLE OPEN ACCESS

DESIGN AND STRUCTURAL EVALUATION OF A ROLL CAGE FOR BAJA ALL-TERRAIN VEHICLES

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ABSTRACT

The roll cage is a critical structural element of an all-terrain vehicle (ATV), providing essential rigidity and enhancing occupant safety during off-road operation. This study presents the design and structural evaluation of an ATV roll cage, focusing on CAD modeling, finite element preprocessing, and static structural analysis. The roll cage geometry was developed using Creo to satisfy key requirements such as strength, weight efficiency, and compatibility with the vehicle chassis. The completed model was then discretized using Hyper mesh, where appropriate meshing was applied to ensure reliable numerical results. Static structural analysis was carried out using the Opti Struct solver to evaluate stress distribution, deformation behavior, and potential failure regions under representative loading conditions, including gravitational effects and external impact loads encountered during off-road use. The results confirmed that the roll cage design meets safety and performance criteria, with factor of safety values maintained within acceptable limits, supporting its suitability for demanding off-road environments.

I. INTRODUCTION

Commonly developed from steel or other high-strength materials, a roll confinement comprises an organization of bars or cylinders decisively situated around the vehicle's traveler compartment. Furthermore, it builds up the vehicle's case, improving, generally speaking, its unbending nature and stability. All-territory vehicles are quite possibly the most renowned vehicle, which was first made in the USA in the mid-70s, and from that point forward, the utilization of these vehicles has been expanded fundamentally. This will be accomplished through the use of simulation and testing methods to evaluate structural integrity, material selection, and optimization strategies. Consequently, to check the security of the vehicle, different investigations are performed on different parts of this primary examination performed on the roll-enclosure of the vehicle. The underlying trustworthiness of the roll confine is resolved utilizing the FOS. The vehicle's loss of momentum in relation to the object it collides with can be seen in the graph's fall in momentum. The effect power and FOS obtained from the examination results underscore that ePA-CF has preferred execution over ASTM A36 steel roll confinement [1]. The ergonomics of the vehicle are likewise remembered while planning so the driver can drive the ATV with outright solace and prosperity. More noteworthy and more prominent will be the capacity of the roll enclosure to support different burdens in various landscapes. All the effect tests were performed, and in light of the most extreme pressure, the variable of wellbeing (FOS) was determined. The element of security was well over as far as possible, which is 1.5, and hereafter it is reasoned that the modular of the ATV that was introduced in this paper is protected to be manufactured [2].

Design Study of Electric Vehicle Roll-Cage Obtained Using Modal Analysis, this paper provides the optimum design parameters (thickness, width, height, and diameter) of a roll cage considering the modal analysis. With different static, structural, and explicit dynamic analyses to show that the roll cage is secure when load it statically and dynamically. The factor of safety for the roll-cage reaches 2, which is safe from a design point of view. The naturally produced first bending mode will meet the dynamic frame performance requirements under different conditions. The frequency of the first mode is higher than the frequency of road excitation in the most common operating conditions and is also higher than the frequency of the electric motor, thus trying to avoid these common resonance problems [3]. Static and Modal Analysis of All Terrian Vehicle Roll-Cage, a bigger production line of security infers the huge capacity of an ATV to endure all sorts of burdens and be equipped for continuing on different landscapes. This paper has outlined the whole plan strategy of roll enclosures and understands the basic parts of the plan. Additionally, static examination is used in limited component investigations alongside modular examination to avoid the peculiarity of reverberation [4]. Effect of metallic substrate and rubber elastic materials, the study investigated the effect of the Constrained Layer Damper on boring hardened AISI 4340 steel, focusing on tool wear, surface finish, and vibration. The damper, using copper as the substrate and polyurethane as the elastic material, significantly reduced tool vibration, enhancing tool life by approximately 97.5%, improving surface finish by about 83%, and reducing vibration by around 98%.

Computational analysis aligned closely with experimental results, validating the method's accuracy. The Constrained Layer Damper proved to be an effective and versatile solution, significantly improving the cutting performance of boring tools in machining hardened steel [5]. Stress Analysis of Roll Cage for an All-Terrain Vehicle, this roll cage structure's resistance to side, front, and rear collisions. Under is a safety factor. The secure level. The roll cage can withstand forces of 4G from the front and rear and 2G from the sides. Thus, distortion and stresses are below the cutoff [6]. Analysis of A Roll Cage Design against Various Impact Load and Longitudinal Torsion for Safety, the car's ability to bear heavy loads was demonstrated by the impact analysis. Both front and side effect examinations were completed, and the most extreme and least extreme qualities were classified. When aluminum was used instead of steel, the impact was found to be less significant. An examination of roll confinement against longitudinal twist was performed. The findings demonstrated that increasing the number of local thicknesses can lessen the member's stress. Another option is to increase the number of stiffeners [7]. Design and Development of Roll Cage for All Terrain Vehicles, the total frontal impact and frontal impact force deformation following a collision is obtained using ANSYS 16.0 software. The overall deformation of the vehicle depends on the force exerted on the vehicle during the crash, and the torsion can be reduced by using better construction materials for the vehicle. The results show that it is designed to withstand the track bump and impact to be applied, ensuring the safety of the driver and the performance of the vehicle [8].

Iterative static analysis was used to refine an all-terrain vehicle roll cage, improving the factor of safety and ensuring occupant protection under severe operating conditions [9]. Related studies show that optimized joint configurations in composite structures and simplified roll cage layouts using ASTM 106 Grade B steel can enhance load capacity while reducing fabrication effort without compromising safety [10], [11]. Thermal stability was assessed through thermo gravimetric analysis and differential scanning calorimetry, confirming the positive impact of hybridization. Overall, incorporating aloe vera fibres into the composites markedly increased their dynamic, thermal, and mechanical performance, indicating the potential of these eco-friendly materials for various applications [12]. Design and Analysis of Roll Cage for an Electric Hybrid Tricycle, in front-facing, side, and rollover crashes, the roll enclosure's solidity and safety have been successfully tested. For a front impact load of 5G, optional impact load of 3G, rollover load of 3G, and wind load of 2G, a reasonable limit was considered. Tensions and deformations are within acceptable ranges. Therefore, both the assembly and the vehicle's development have adopted this roll limit [13]. This product, with its high-level apparatuses, can set several boundaries. Relating and definite qualities that can't be resolved tentatively, like CATIA, ANSYS, solid works, hyper mesh, and supportive of e, are a few instances of programming accessible to the clients. Static Analysis of ATV Roll Cage, this paper concentrated on the display, material choice, lattice, and static examination of ATV.

They have carried out a number of the necessary analyses for the vehicle's safety, including side impact analysis, front impact analysis, and so on. They can conclude from the above table that the vehicle is protected since the upsides of FOS (Element of Security) are more noteworthy than 1 [14]. Static Analysis of the Roll Cage of an All- Terrain Vehicle (SAE Baja), the examination was useful in figuring out the most extreme twisting, Von Mises pressure, and the element of security. The plan of the vehicle is kept extremely straightforward, keeping in view its manufacturability. The plan, improvement, and creation of the roll confine are done effectively. The roll confine is utilized to construct an ATV by coordinating the wide range of various auto frameworks like transmission, suspension, brakes, directing, and so on [15], [16]. Previous studies indicate that both geometry and material selection play a major role in controlling stress distribution and deformation, enabling the development of lightweight yet strong chassis structures [17-20]. Research on ATV and buggy roll cages consistently emphasizes their importance in occupant protection during off-road operation, with optimized structural layout and material choice being key to meeting safety demands under different impact conditions [21-24].

Beyond structural components, vehicle safety has been enhanced through monitoring systems that track driver posture and operating conditions, helping to reduce accident risk by identifying unsafe states early [25-28]. Crash studies further show that five-point seat belt systems, when properly integrated with vehicle structures, improve occupant restraint during frontal impacts [29-31]. Investigations into motorcycle rider fatigue reveal that both physical strain and vehicle design influence rider safety, highlighting the need for fatigue-conscious design approaches [32-34]. Additional performance studies demonstrate that improvements in intake design, fuel strategies, aerodynamics, suspension materials, thermal management, and electronic integration contribute to better efficiency, stability, and overall vehicle safety without extensive redesign of core systems [35-36]. The study proposed an improved automotive braking system that enhances braking response and stability, thereby improving overall safety in passenger vehicles and study shows the measuring devices used for analysising the output results from motorised accurancy is due to sensor perfomance [37-39].

II. METHODOLOGY

The vehicle safety cage is designed to balance strength and weight while protecting occupants during impact and rollover events. Material choice, member shape, and structural layout strongly influence its performance, with selective reinforcement improving load transfer and limiting deformation. Finite element analysis is used to identify critical stress areas and guide design refinements for safe real-world operation.

II.1 CREO PARAMETRIC

Over the long time, the computer program progressed, solidifying advanced highlights and advanced progresses. In 2011, PTC rebranded Pro/ENGINEER as Creo Parametric, impelling it underneath the broader Creo suite, which as well consolidates Creo Facilitate, Creo Reenact, and Creo Arrange, among others. This rebranding pointed to highlight the software's extended capabilities past conventional design, such as item lifecycle administration (PLM), expanded reality (AR), and Web of Things (IoT) integration. Creo Parametric remains a driving CAD apparatus broadly utilized over businesses for product design, designing, and fabricating. Including parametric and coordinate modeling, get together administration, simulation, rendering, and 2D drafting. With each unused discharge, PTC proceeds to improve Creo Parametric with cutting-edge advancements, ensuring it remains at the cutting edge of CAD innovation.

II.2 CREATION OF PART USING DRAWING

The initial step while opening Creo, a 3D computer-aided design demonstrating programming, is regularly sending off the application on your PC. Then select the function catalog on the PC. Choose the format, such as part, assembly, or other, in which we will produce the model. Further select subtypes in that strong ought to be appointed. Give a document name for the model record in the configuration of part (prt001). Select any one of the three planes for the sketch option to use to start it. The next step is to align the plane of view so that the model drawing can begin with the bottom line and connect the lines so that the shapes can be made one at a time. Creo parametric, permitting aspect-driven changes for size and shape. Key utilization of relationships and aspects improves with adjustments. Go for the gold elements north of a couple of intricate ones for simpler work and diminished blunders. In Creo parametric, part creation is streamlined by planning and adhering to these principles. This is the essential procedure in Creo. Parametric demonstrating permits you to make 3D models by characterizing boundaries and requirements. Start with fundamental mathematical shapes like expulsions, clears, rotations, and so on, and then apply aspects, relations, and limitations to make a completely characterized model. Changes made to aspects or boundaries engender the model, considering simple plan adjustments.

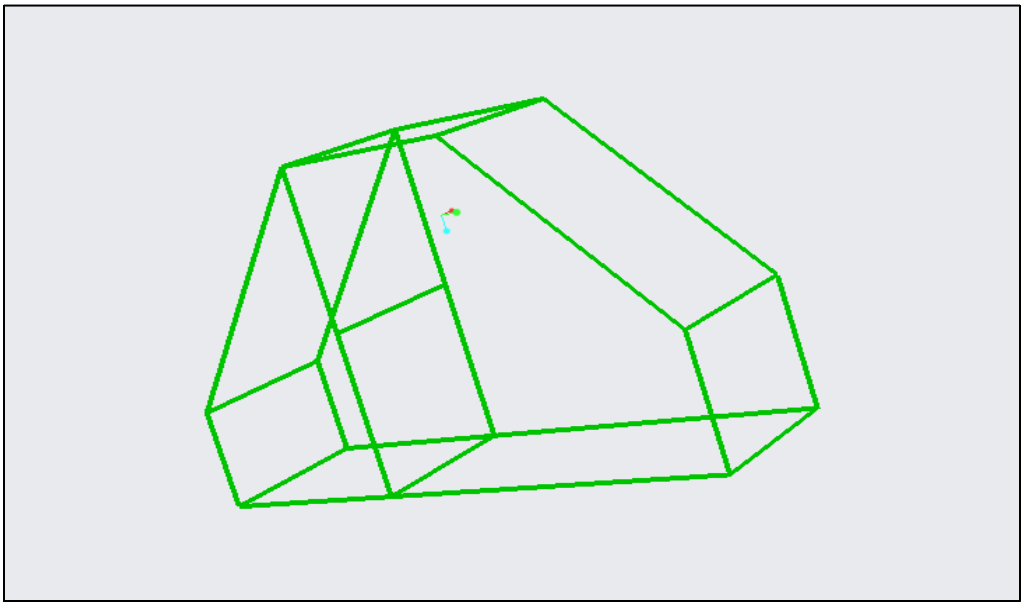

Figure 1: Wireframe Model of Roll cage.

Source: Authors, (2026).

Table 1. Dimensions of Roll cage.

Parameter	Length	Width	Height	Overall-Weight
Dimensions	2000mm	650mm	1300mm	400kg

Source: Authors, (2026).

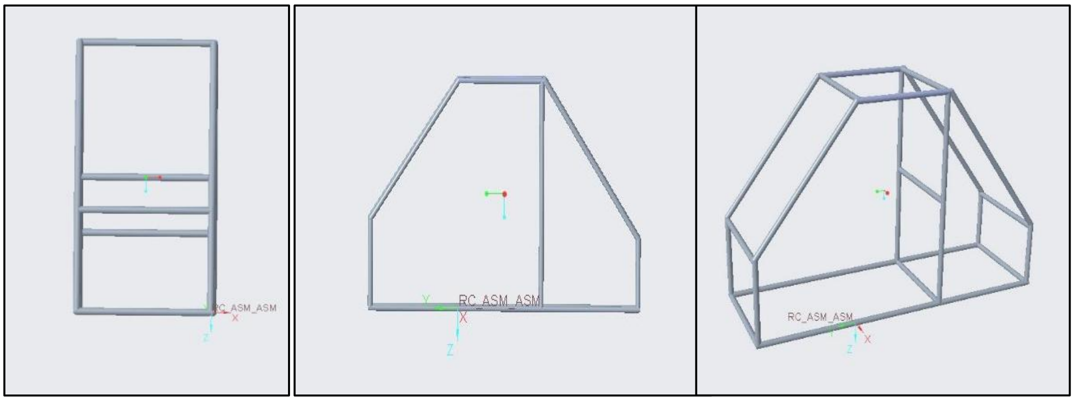

Figure 2: Three Views of Roll cage (Front View, Side view, Isometric View).
Source: Authors, (2026).

II.3 FINITE ELEMENT METHOD (FEA)

Limited Component Examination (FEA) is a computational strategy used to break down complex designs and frameworks by separating them into more modest, less difficult components. These components are interconnected at discrete points called hubs. By settling numerical conditions that address the actual way of behaving of every component and their associations, FEA is generally utilized in designing and science for plan streamlining, execution expectation, and investigating. It saves time and resources during the product development process by allowing engineers to evaluate the behavior of structures and systems without the need for costly physical prototypes.

II.4 MESHING

The geometry is meshed next, with the surface meshing tools creating elements on the geometry's surfaces. This step is basic as it characterizes the exactness and effectiveness of the investigation. HyperMesh offers a variety of meshing algorithms for a variety of geometries and analysis needs. These calculations incorporate tetrahedral, hexahedral, and shell coinciding, each reasonable for various kinds of designs and stacking conditions.

II.4.1 Assigned Before Meshing

- Element Type: mechanical
- Element Shape: quads
- Element size: 4mm
- Element Density: Automatic
- Materials used: chromium molybdenum alloy steel.

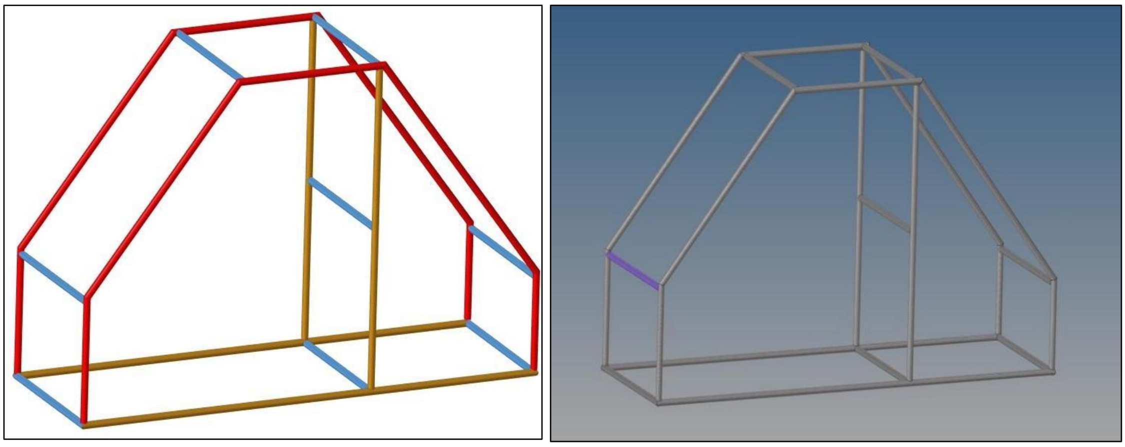

Figure 3: Mid Surface Creation and Completely meshed Roll cage.
Source: Authors, (2026).

II.5 SEAM WELDING

Crease welding is a welding interaction that includes joining two covering metal sheets along their edges by making a progression of covering spot welds or ceaseless welds along the crease. It is frequently utilized in automotive components and leak-proof containers in the manufacturing sector. In HyperMesh, a product usually utilized for limited component examination (FEA) and pre-handling errands in the field of designing and reenactment, the kind of crease weld utilized would depend upon the particular necessities of the investigation being led. In order to accurately simulate the behavior of welded structures, HyperMesh provides a variety of options for the definition of welds, including seam welds. Crease welds in HyperMesh can regularly be characterized as utilizing components like shell components.

In HyperMesh, "RBE2" alludes to "Unbending Body Component Type 2." It's a kind of unbending component utilized in limited component examination (FEA) demonstrating. You can connect multiple degrees of freedom (DOFs) at a single grid point to a collection of independent grid points using RBE2 elements. When you want to impose rigid behavior on various parts of a finite element model, this is helpful for connecting them. For instance, on the off chance that you have a design where you believe specific hubs should move together unbendingly (like a joint), you can utilize RBE2 components to interface those hubs and guarantee that they move as a solitary, inflexible body.

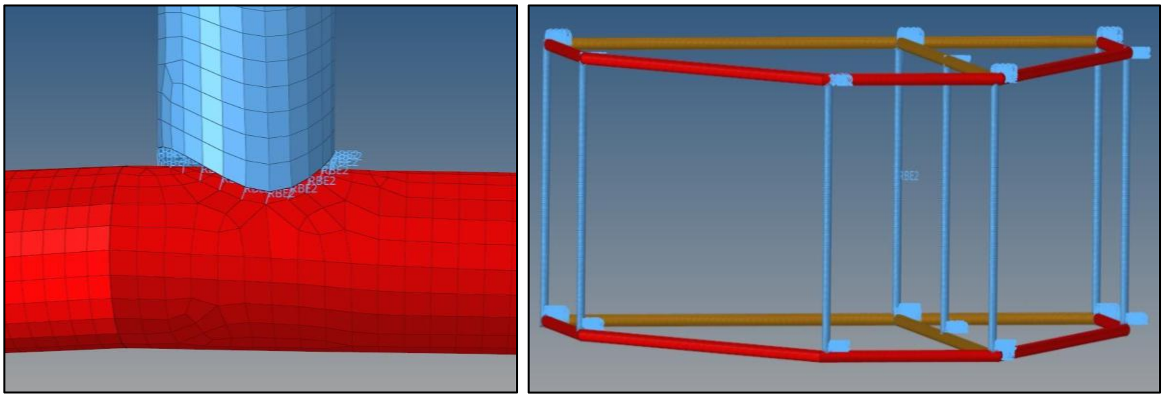

Figure 4: Seam Welding done at the Corners.
Source: Authors, (2026).

II.6 MATERIAL

Material was chosen by considering different boundaries like level of carbon, elasticity of material, Young's modulus, compressive strength, Poisson's proportion, thickness, and so on. AISI 4130 is chosen for roll cage. Chromium and molybdenum are the main alloying elements in AISI 4130, a low-alloy steel. It is also known as chromoly steel. The specific chemical makeup of this steel can be determined by looking at its designation, "4130.

Table 2: Material Properties.

Properties	**AISI 4130**	**AISI 1018**
Density	7850 Kg/m^3	7870 Kg/m^3
Young’s modulus	210Gpa	205Gpa
Poisson’s ratio	0.3	0.29
Ultimate tensile strength	670Mpa	450Mpa
Yield tensile strength	460Mpa	370Mpa
Iron	98.22%	99.26%
Manganese	0.60%	0.90%
Carbon	0.330%	0.20%
Sulfur	0.040%	0.05%
Phosphorous	0.035%	0.04%

Source: Authors, (2026).

III. RESULTS AND DISCUSSIONS- EVALUATION OF MATERIAL PERFORMANCE FOR IMPACT SCENARIOS

III.1 MODAL ANALYSIS

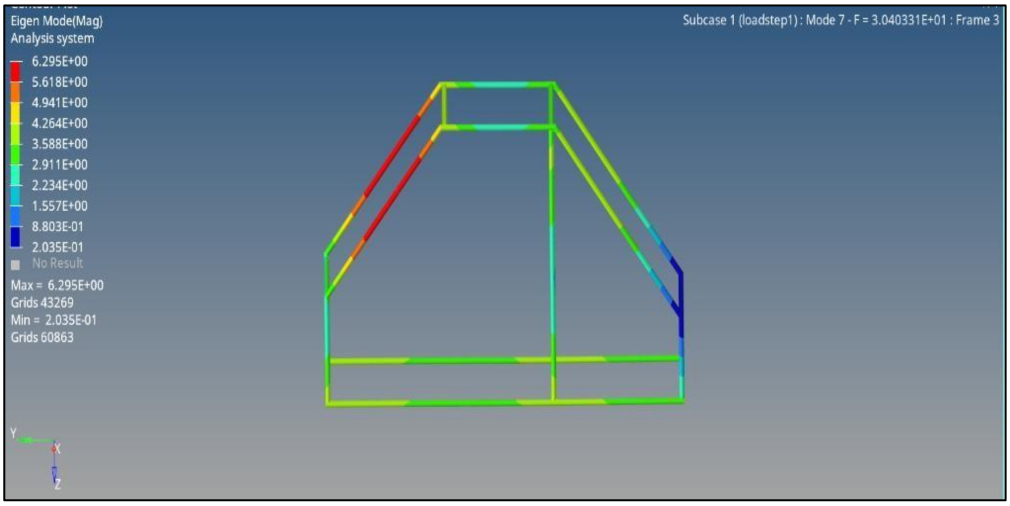

Figure 5: Modal Analysis Result.
Source: Authors, (2026).

In Hyper mesh, eigenvalue analysis is the process of finding the natural frequencies and mode shapes of a finite element model by solving an eigenvalue problem. In the first place, the model is made and fit, characterizing its calculation and material properties. Limit conditions are then applied to reproduce certifiable requirements. Hyper mesh conducts the examination by ascertaining the eigenvalues (normal frequencies) and comparing the eigenvectors (mode states) of the model. These eigenvalues address the frequencies at which the construction normally vibrates, while eigenvectors portray the related mode shapes or examples of vibration. Figure 5. shows that, the total frequency range of the rolling cage as determined by Eigen mode or modal analysis, which extends from mode 7 to mode 12. This analysis determines the natural vibration frequencies necessary to ensure the integrity and performance of the structure by predicting and mitigation. resonant vibrations that can affect.

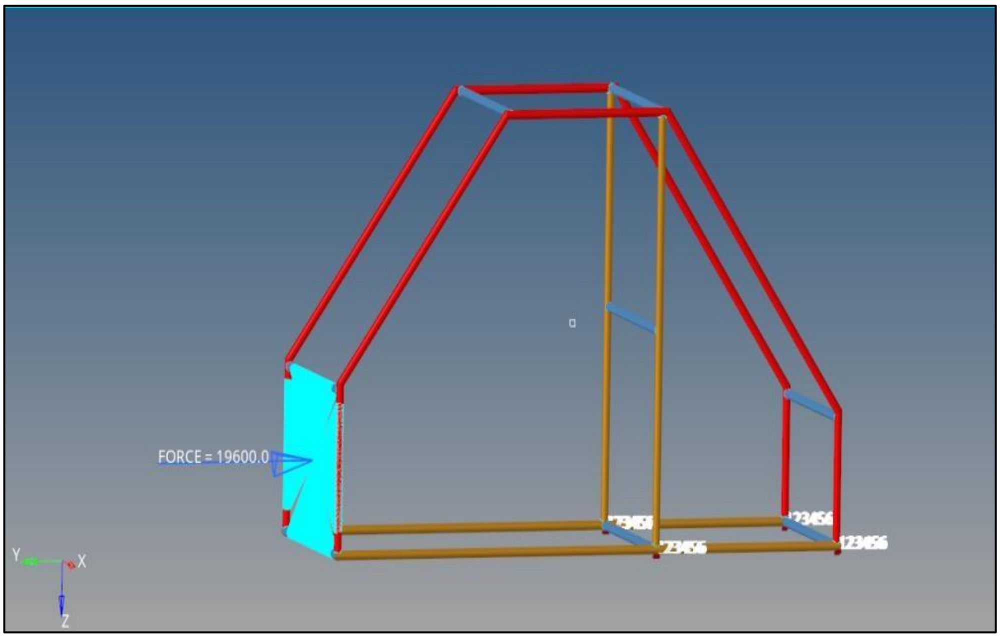

Figure 6: Fixed Supports and Load of the Roll cage.
Source: Authors, (2026).

Figure 6. shows that, front impact test the rear bottom four corners have been constrained with 5G force. The Constrained parts is mentioned as “RBE 2” known as Rigid Body Element. The same RBE 2 is mentioned in Seam Welding. Where the force is acting at the centre of the front part as “spc” known as single point constraint.

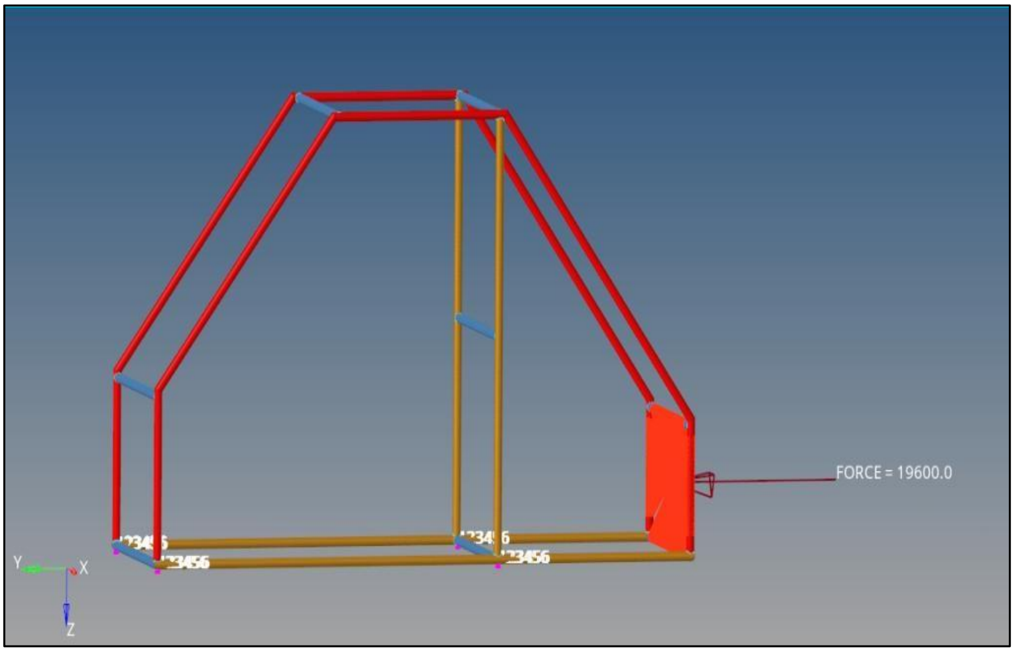

Figure 7: Fixed Supports and Load of the Roll cage.
Source: Authors, (2026).

Figure 7. shows that, rear impact test the front bottom four corners have been constrained with 5G force. The Constrained parts are mentioned as “RBE 2” known as Rigid Body Element. The same RBE 2 is mentioned in Seam Welding. Where the force is acting at the centre of the rear part as “spc” known as single point constraint.

III.2 FRONT IMPACT TEST RESULTS

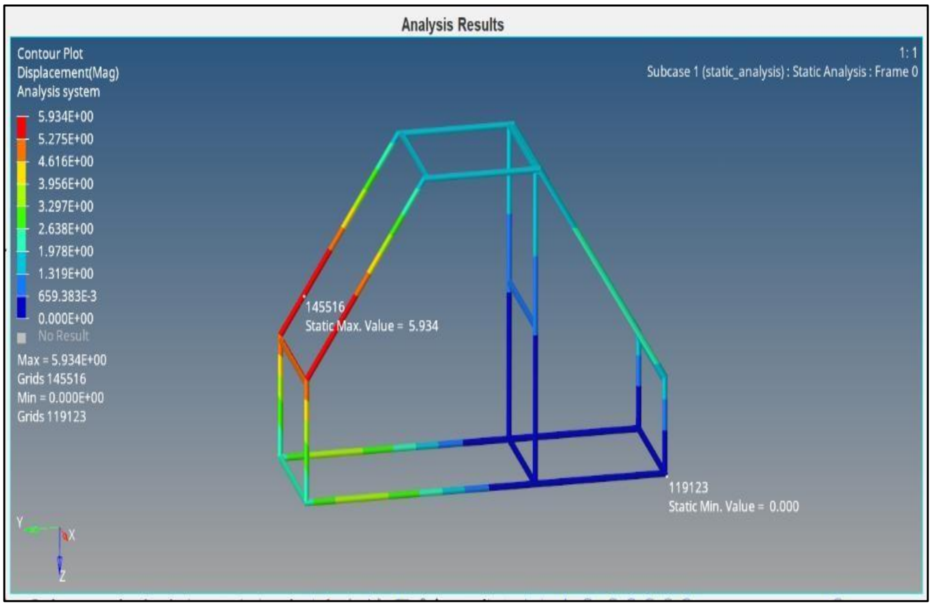

Figure 8: Maximum Deformation of AISI 4130.
Source: Authors, (2026).

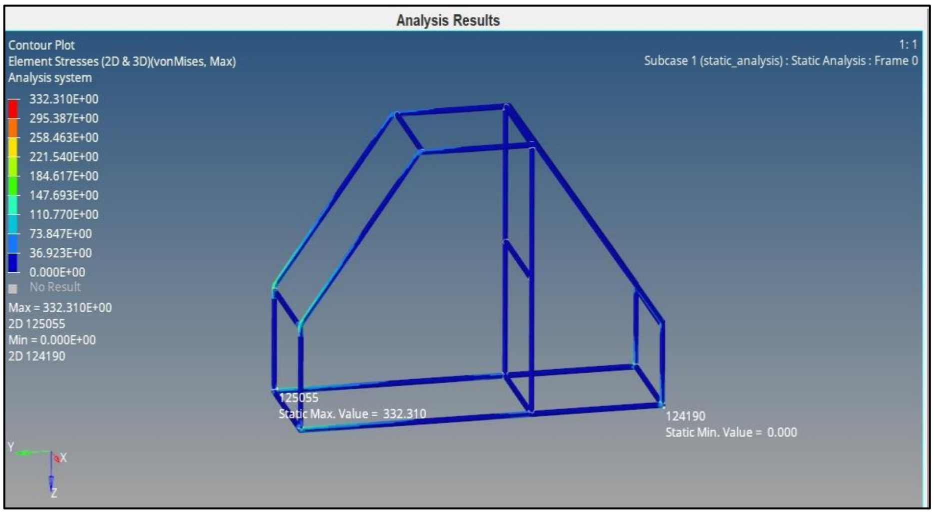

Figure 9: Stress Distribution of AISI 4130.
Source: Authors, (2026).

III.3 REAR IMPACT TEST RESULTS

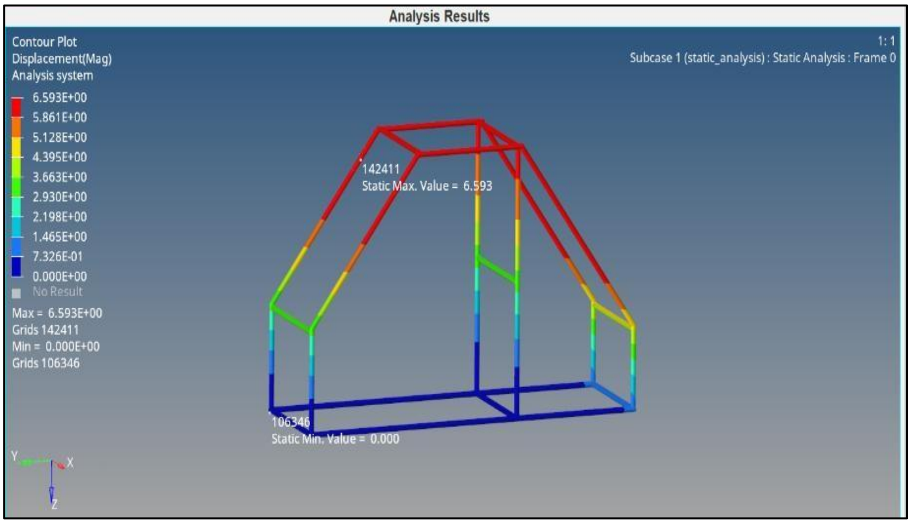

Figure 10: Maximum Deformation of AISI 4130.
Source: Authors, (2026).

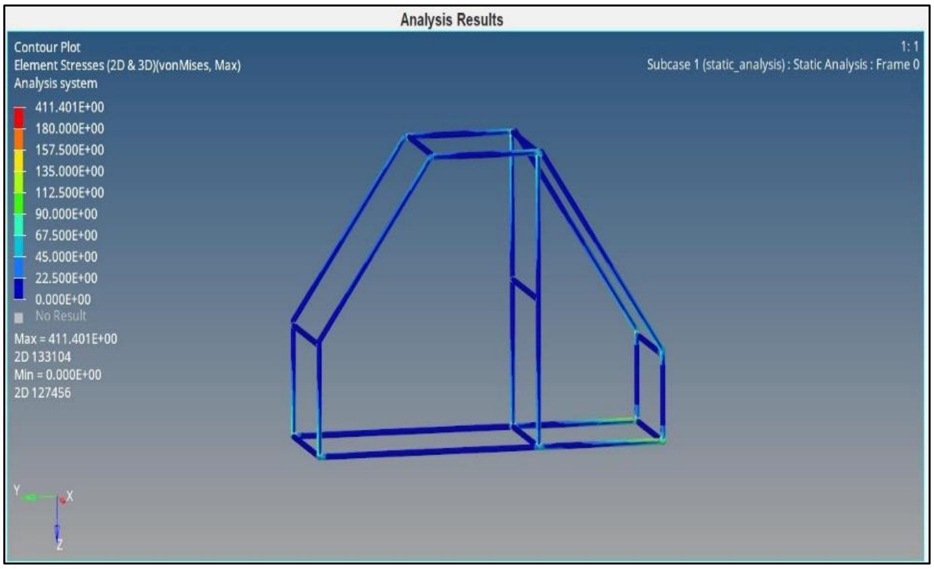

Figure 11: Stress Distribution of AISI 4130.
Source: Authors, (2026).

III.4 FRONT IMPACT TEST RESULTS

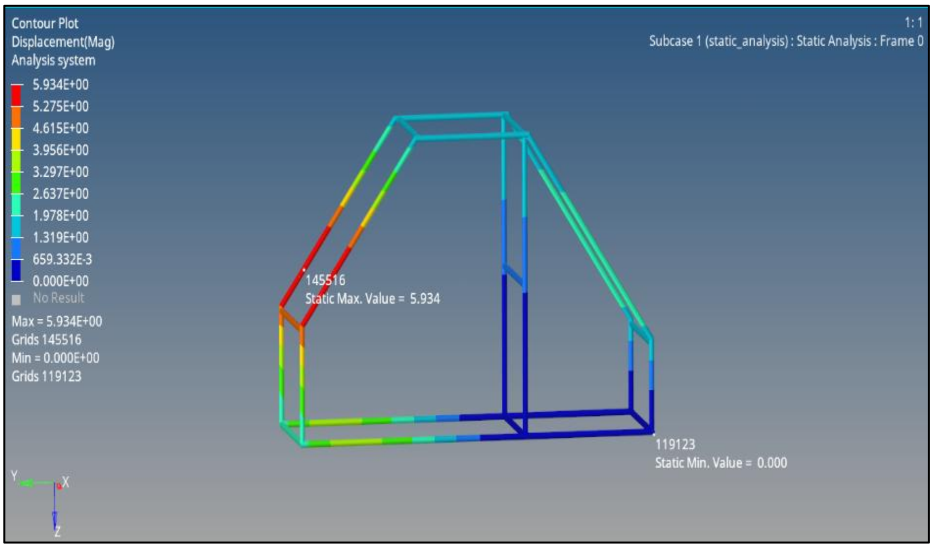

Figure 12: Maximum Deformation of AISI 1018.
Source: Authors, (2026).

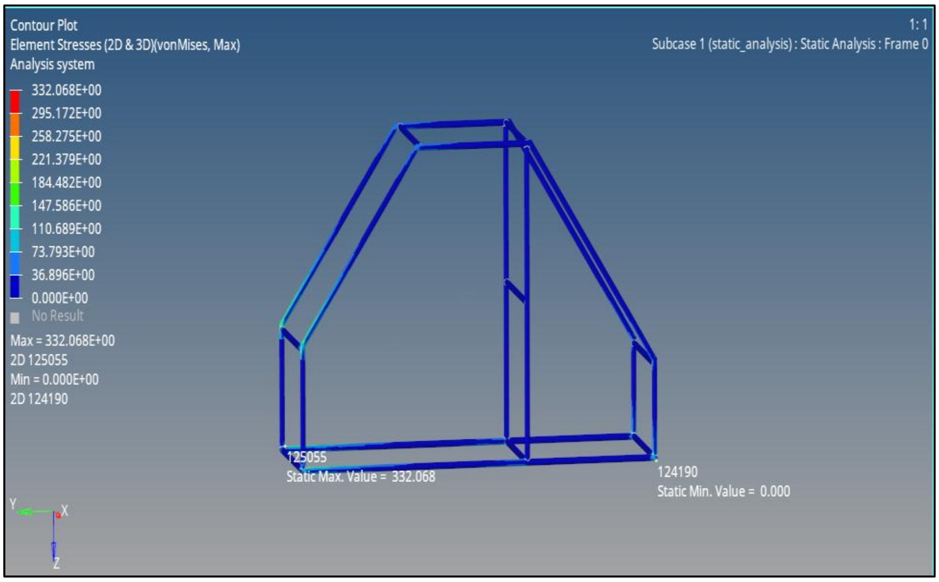

Figure 13: Stress Distribution of AISI 1018.
Source: Authors, (2026).

III.5 REAR IMPACT TEST RESULTS

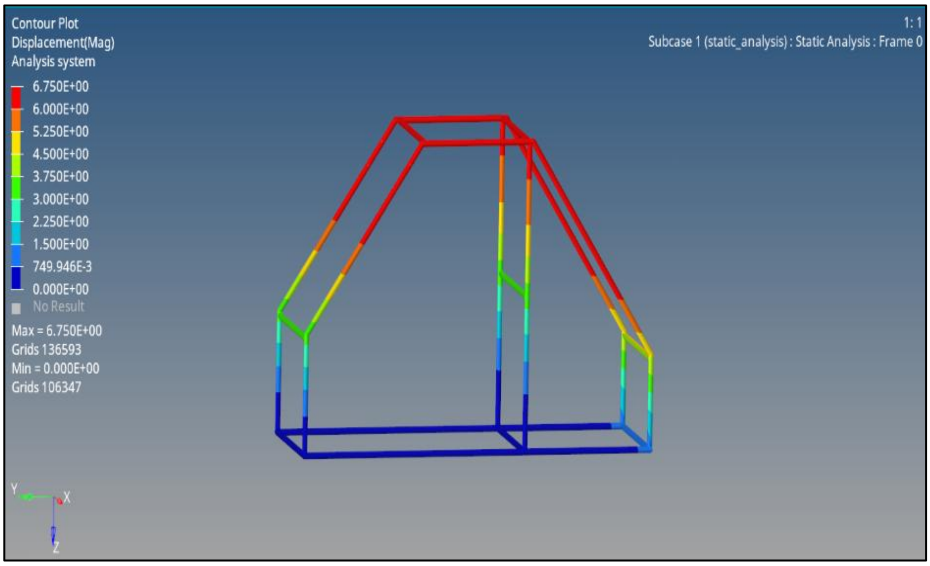

Figure 14: Maximum Deformation of AISI 1018.
Source: Authors, (2026).

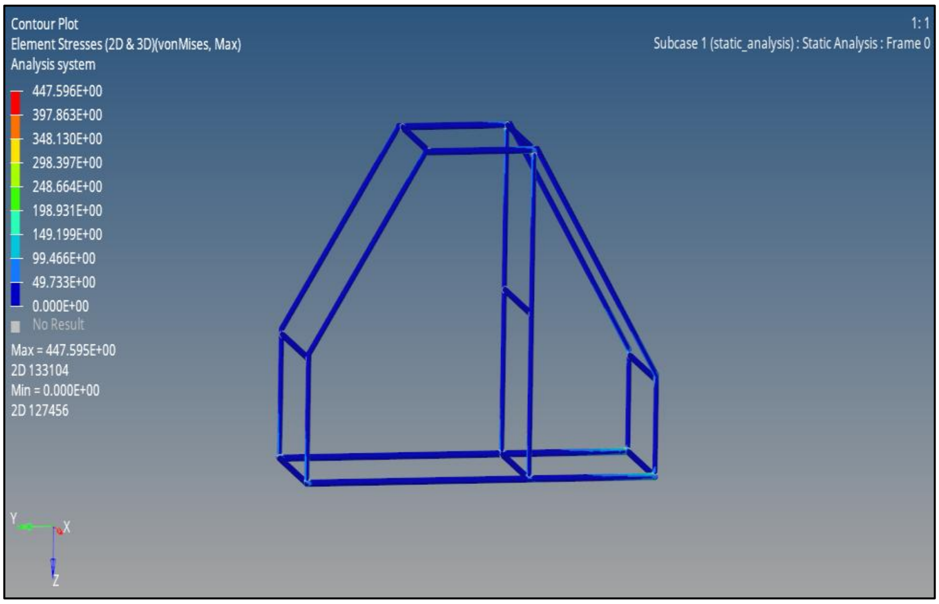

Figure 15: Stress Distribution of AISI 1018.
Source: Authors, (2026).

The deformation and stress results in Figure 8 and 9 show that frontal loading causes a maximum displacement of about 5.9 mm and peak stress of approximately 332 MPa at the front, while the rear remains largely unstressed. Under rear-impact conditions, Figure. 14 and 15 indicate higher rear deformation (around 6.5 mm) and stress levels reaching nearly 411 MPa, confirming effective energy absorption by the rear structure. Similar trends observed in Figure 15 identify the rear region as structurally critical, with maximum deformation of about 6.7 mm and peak stress approaching 447 MPa, suggesting the need for localized reinforcement.

Table 3: Stress and Deformation for the Selected Material.

Material	Type of Analysis	Stress (Mpa)	Total Deformation (mm)	FOS
AISI 4130	Front Impact	332.31	5.7	1.3
	Rear Impact	411.40	6.5	1.4
AISI 1018	Front Impact	332.06	5.9	1.3
	Rear Impact	447.59	6.7	1.0

Source: Authors, (2026).

Table 3 compares the performance of AISI 4130 and AISI 1018 steels under frontal and rear impact loading based on factor of safety, stress, and deformation. AISI 4130 shows better performance in rear impacts, with a factor of safety of 1.4, peak stress of 411.40 MPa, and deformation of 6.5 mm, indicating higher stiffness and strength. In contrast, AISI 1018 performs well under frontal loading, maintaining a factor of safety of 1.3 with controlled stress (332.06 MPa) and deformation (5.9 mm), which is beneficial for energy absorption. These results show that selecting materials based on impact location improves overall vehicle safety and structural reliability.

IV. CONCLUSION

This work examined the design and static performance of an ATV roll cage under front and rear impact conditions. In all cases, the factor of safety remained above one, indicating adequate strength and load-carrying capability. A simplified design approach was adopted to support ease of fabrication without compromising durability, allowing the roll cage to function as the main structural support for vehicle subsystems. Material comparison showed that AISI 4130 was more effective for rear impacts, while AISI 1018 performed better under frontal loading, highlighting the importance of selecting materials based on impact location.

V. AUTHOR'S CONTRIBUTION

Conceptualization: C Dineshkumar, M Tabrez, V Ashmitha.
Methodology: C Dineshkumar, N S Shafeer Ahmed.
Investigation: C Dineshkumar, N S Shafeer Ahmed.
Discussion of results: C Dineshkumar, A Abdul Rawoof.
Writing: Original Draft: A Abdul Rawoof, NM Faridh Ahamed.
Writing: Review and Editing: M Tabrez, Mushraf Ali, V Ashmitha.
Resources: C Dineshkumar, Mushraf Ali.
Supervision: C Dineshkumar, M Tabrez, V Ashmitha.
Approval of the final text: C Dineshkumar, V Ashmitha.

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