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DESIGN AND ANALYSIS OF ROLL CAGE OF AN ALL-TERRAIN VEHICLE (ATV)

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Abstract: The roll cage serves as the primary structural shell and driver safety framework for All-Terrain Vehicles (ATVs), engineered to withstand high-speed off-road collisions and severe rollover events. This study presents a comprehensive structural design, material selection framework, and Finite Element Analysis (FEA) of an ATV roll cage compliant with SAE BAJA design specifications. Three candidate structural steels—AISI 1020, AISI 1018, and AISI 4130 Chromoly—were systematically evaluated based on yield strength, strength-to-weight ratio, bending stiffness, weldability, and fabrication viability. AISI 4130 was selected due to its high yield strength (460 MPa) and superior energy absorption characteristics. A 3D CAD framework was modeled using SolidWorks weldment features, followed by static structural impact simulations in ANSYS Workbench under multi-directional loading conditions: Front (8g force / 7503 N), Rear (6g force / 7503 N), Side (4g force / 5625 N), and Rollover (3450.59 N). Finite Element Analysis yielded minimum factors of safety of 1.826 for front impact, 1.0411 for rear impact, 1.0827 for side impact, and 1.538 for rollover impact, with maximum von-Mises stresses remaining safely below the yield strength threshold. The results demonstrate an optimal integration of driver ergonomics, structural rigidity, dynamic impact resistance, and mass efficiency.

Keywords: All-Terrain Vehicle (ATV), Roll Cage Design, Finite Element Analysis (FEA), AISI 4130 Chromoly, Impact Analysis, Factor of Safety (FOS), Structural Integrity.

1. INTRODUCTION

The rapid evolution of off-road automotive engineering has elevated the operational demands placed on All-Terrain Vehicles (ATVs). ATVs operate across rugged terrains, steep inclines, and unpredictable obstacles, exposing both the mechanical subsystems and the operator to high dynamic impact loads and rollover risks. In these vehicles, the roll cage acts as the skeletal chassis. It forms a 3D protective space surrounding the driver while providing structural mounting points for the suspension, powertrain, steering, and braking assemblies.

The primary design objectives for an ATV roll cage center on five key engineering criteria:

1. **Protection in Rollover Accidents:** Preventing structural intrusion during severe inverted crashes and maintaining a safe survival zone for the driver.
2. **Structural Integrity:** Providing high torsional rigidity and bending stiffness to sustain dynamic cornering and landing forces without localized yielding.
3. **Safety Features Integration:** Supporting multi-point harness seatbelt mountings and absorbing frontal, side, and rear impact kinetic energy.
4. **Regulatory Compliance:** Adhering strictly to collegiate off-road competition standards (e.g., SAE BAJA rulebook) regarding driver clearances and minimum member dimensions.
5. **Occupant Ergonomics and Confidence:** Ensuring proper visibility, unhindered ingress/egress, and driver comfort within a lightweight framework.

From a structural mechanics perspective, tube selection relies on two foundational parameters: bending stiffness (K_B) and bending strength (S_b). For circular structural tubing, these parameters are defined mathematically as:

$$K_B = E \cdot I$$

$$S_b = \frac{S_y \cdot I}{c}$$

Where E represents the Modulus of Elasticity (205GPa to 250 GPa across structural steels), S_y is the material yield strength, c = D/2 is the distance from the neutral axis to the outer edge, and I is the second moment of area for a tubular

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cross-section with outer diameter D and inner diameter d:

$$I = \frac{\pi}{64}\left(D^4 - d^4\right)$$

Evaluating these mechanical relationships ensures that alternative lightweight materials match or exceed the structural benchmark established by baseline competition regulations.

2. LITERATURE REVIEW

The regulatory foundation for off-road vehicle crashworthiness was initially established by the American National Standards Institute (ANSI) in conjunction with Federal Motor Vehicle Safety Standards (FMVSS Part 571 and Part 574) and Consumer Product Safety Commission (CPSC) guidelines (16 CFR Parts 1307 and 1410). These standards mandate rigorous testing protocols for off-road vehicles, emphasizing occupant safety, rollover mitigation, and crash energy management.

Numerous academic investigations have explored ATV chassis modeling, material selection, and structural simulation. Gupta et al. highlighted the role of integrated CAD/CAE workflows in designing ergonomic, aerodynamic, and easily manufacturable ATV frameworks capable of navigating extreme off-road environments. Momin et al. and Satputaley et al. demonstrated the utility of 3D Finite Element Analysis (FEA) in evaluating localized von-Mises stress concentrations and dynamic deformation patterns under multi-directional crash forces. Gulhane and Patil further bridged theoretical design and physical realization by integrating 1D analytical beam equations to validate member dimensions prior to complex 3D FEA meshing.

Recent investigations by Raj et al., Nagendra Varma et al., and Raina et al. validated the performance of chromoly steel alloys (such as AISI 4130) over conventional low-carbon steels. Their structural comparisons showed that AISI 4130 provides higher yield strength (460 MPa) and superior weldability, allowing thin-walled tubing (1.25 in outer diameter * 0.06 in wall thickness) to achieve high bending stiffness without adding excess weight.

Additional studies by Sharma et al., Ramasubramanian et al., and Maradey Lazaro et al. emphasized optimizing roll cage triangulation to enhance torsional stiffness during heavy impact loads.

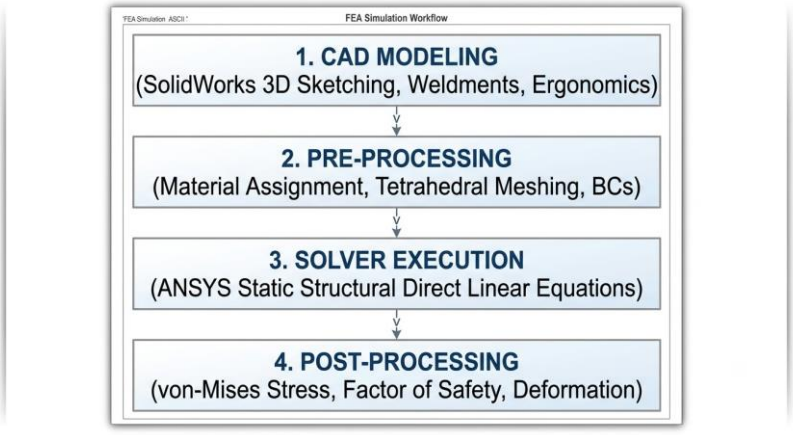


Fig. 1 Block diagram of Computer-Aided Engineering (CAE) Structural Simulation Workflow

As illustrated in *Fig. 1*, modern computer-aided structural design transitions systematically from 3D geometry packaging to numerical discretization, solver execution, and post-processing evaluation.

3. RESEARCH GAP

Despite extensive research on vehicle crashworthiness, balancing weight reduction, dynamic strength, and manufacturing feasibility in off-road roll cages remains an ongoing design challenge. Many conventional roll cage designs rely on empirical sizing, which often leads to over-engineered, excessively heavy structures or under-reinforced frames vulnerable to localized joint buckling.

Furthermore, existing studies frequently evaluate material candidates based solely on ultimate tensile strength, overlooking key practical factors such as heat-affected zone (HAZ) weld degradation, availability in seamless tubing, and cost constraints. There is also a need for unified comparative analyses that evaluate roll cage performance across all four primary collision scenarios—Front, Rear, Side, and Rollover—using consistent boundary conditions and loading criteria.

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Property / Metric	AISI 1020	AISI 1018	AISI 4130 (Selected)
Ultimate Tensile Strength (MPa)	420	965	560
Yield Strength (MPa)	350	585	460
Density ({g/cm}^3)	7.87	7.87–8.03	7.85
Bending Strength - Primary Pipe ({N/mm}^2)	456,875	207,656.73	259,110.23
Bending Stiffness - Primary Pipe ({N}*{mm}^2)	3,540,104	1,833,134.51	1,833,135.51
Weldability & Machinability Index	Moderate	Poor / Rare Availability	Superior (TIG/MIG)
Strength-to-Weight Ratio Index	Low	Moderate	High

TABLE 1 presents the quantitative material comparison evaluated during the pre-design phase.

Although AISI 1018 displays high nominal tensile properties, its limited domestic market availability in seamless thin-walled profiles and poor weldability make it less practical for roll cage fabrication. AISI 4130 Chromoly provides the best overall balance of yield strength, toughness, strength-to-weight ratio, and clean TIG welding characteristics.

To validate the structural safety of the AISI 4130 roll cage, multi-directional static impact simulations were executed in ANSYS Workbench based on a total vehicle mass of 270\text{ kg} traveling at designated impact velocities. The dynamic work-energy principles governing impact forces (F) are expressed as:

$$Work = \frac{1}{2}mv_f^2 - \frac{1}{2}mv_i^2$$

$$F = \frac{Work}{s} = \frac{Work}{v_i \cdot t_{imp}}$$

Where m = 270 kg, v_f is final velocity, v_i is impact velocity, s is displacement, and t_{imp} = 0.3s is the assumed impact duration.

Impact Test Mode	Applied Force / Acceleration	Max Equivalent (von-Mises) Stress	Min Factor of Safety (FOS)	Max Total Deformation	Structural Status
Front Impact Test	7,503 N (8g load)	251.79 MPa	1.8269	0.7790 mm	Safe (S_{max} < S_y)
Rear Impact Test	7,503 N (6g load)	441.83 MPa	1.0411	1.2311 mm	Safe (Elastic Range)
Side Impact Test	5,625 N (4g load)	424.88 MPa	1.0827	3.6691 mm	Safe (Elastic Range)
Rollover Impact Test	3,450.59 N (Drop height 3m)	298.97 MPa	1.5386	0.6407 mm	Safe (S_{max} < S_y)

TABLE 2 summarizes the Finite Element Analysis results obtained across all four collision conditions. Across every test case, the maximum generated equivalent stress remains below the 460 MPa yield limit of AISI 4130 chromoly steel, maintaining a minimum Factor of Safety above 1.0 and keeping deformations within acceptable operational thresholds.

4. FUTURE SCOPE

Building upon the structural performance validated in this study, future research directions for ATV roll cage development include:

1. **Topology Optimization and Generative Design:** Applying algorithms to iteratively remove non-load-bearing material from gussets and structural junctions, minimizing overall chassis mass while preserving torsional rigidity.

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2. **Advanced Composite & Hybrid Structures:** Investigating thin-walled carbon-fiber reinforced polymer (CFRP) sleeves or aluminum-chromoly hybrid spaceframes to improve strength-to-weight performance.
3. **Physical Crash Testing and Telemetry Validation:** Constructing physical prototype frameworks instrumented with strain gauges and accelerometers to validate FEA simulation models against real-world impact data.
4. **Perceptual and Dynamic Crash Energy Management:** Integrating progressive deformation zones and energy-absorbing mounting elements to reduce peak deceleration forces transmitted to the driver.

5. CONCLUSION

This study presented the structural design, material selection, and finite element impact analysis of an All-Terrain Vehicle (ATV) roll cage compliant with SAE BAJA safety standards. Through analytical calculations and numerical FEA simulations in ANSYS Workbench, the structural framework was evaluated under Front, Rear, Side, and Rollover impact scenarios.

Key outcomes of this investigation include:

- **Material Suitability:** AISI 4130 chromoly steel was confirmed as an optimal material choice, offering a yield strength of 460 MPa, high bending stiffness (1,833,135.51N.mm^2), strong energy absorption, and reliable weldability.
- **Crashworthiness & Safety:** FEA simulation confirmed structural integrity across all impact modes: Front Impact (Max Stress: 251.79 MPa, FOS: 1.826), Rear Impact (Max Stress: 441.83 MPa, FOS: 1.0411), Side Impact (Max Stress: 424.88 MPa, FOS: 1.0827), and Rollover Impact (Max Stress: 298.97 MPa, FOS: 1.538).
- **Deformation Management:** Total structural displacement was constrained to minor levels (ranging from 0.64 mm in rollover to 3.66 mm in side impact), preserving the driver's safe survival space without structural intrusion.

The engineered roll cage successfully balances driver safety, structural stiffness, lightweight performance, and manufacturing feasibility, establishing a reliable framework for off-road vehicle design.

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