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Design and Analysis of Roll Cage (Chassis) for Sae E-Baja Vehicle

Vipul Mahesh Yeole[1], Akanksha Bhausaheb Datir[2], Prof. K.D. Dagale[3]
[123]Department of Mechanical Engineering,
Amrutvahini College of Engineering, India

Abstract: *The design and analysis of a roll cage (chassis) play a crucial role in ensuring the safety, stability, and performance of an all-terrain vehicle (ATV) developed for the SAE India E-BAJA competition. This project focuses on developing a robust, lightweight, and cost-effective roll cage that complies with SAE rulebook standards while providing maximum protection to the driver under various impact conditions.*

The design process involves understanding competition requirements, selecting suitable materials, and developing a structural model using CAD tools. The chosen material, DOCOL steel, offers high strength, good weldability, and adequate ductility, making it ideal for roll cage construction. Finite Element Analysis (FEA) is performed to evaluate the structural behavior of the chassis under different loading scenarios such as front, rear, side, and rollover impacts.

Ergonomic considerations are incorporated to ensure driver comfort, ease of ingress and egress, and proper visibility. The design also focuses on weight optimization without compromising structural integrity, resulting in improved vehicle efficiency. The final roll cage design demonstrates a balance between safety, durability, and performance while adhering to competition standards.

Keywords: Roll Cage ,Chassis Design, All-Terrain Vehicle (ATV), SAE E-BAJA, Finite Element Analysis (FEA), Ergonomics, DOCOL Steel, Structural Analysis, Vehicle Safety, Weight Optimization

I. INTRODUCTION

The development of safe and efficient off-road vehicles has become a significant area of focus in modern automotive engineering, especially in student-driven competitions like the SAE India E-BAJA. This competition challenges engineering students to design, fabricate, and validate an all-terrain vehicle (ATV) that can withstand rugged environments while ensuring reliability and driver safety [1]. It provides a practical platform where theoretical knowledge is applied to real-world engineering problems, including structural design, material selection, and performance evaluation [2].

An ATV is composed of several critical subsystems such as the powertrain, suspension, steering, braking, and chassis system. Among these, the chassis—commonly referred to as the roll cage—is the backbone of the vehicle, responsible for supporting all components and protecting the driver during collision or rollover events [3]. The roll cage must be designed to absorb and distribute impact forces effectively, thereby minimizing deformation and preventing injury to the occupant [4].

The design of a roll cage requires careful consideration of strength, stiffness, and weight. A well-designed chassis not only enhances safety but also contributes to improved handling and vehicle stability on uneven terrain [5]. In off-road conditions, vehicles are subjected to complex loading scenarios such as torsional loads, bending stresses, and sudden impacts, making structural integrity a key design requirement [6]. Therefore, engineers must ensure that the roll cage meets strict safety standards defined in competition rulebooks while maintaining optimal performance characteristics [7].

Material selection plays a vital role in achieving the desired balance between strength and weight. High-strength low-alloy steels, such as DOCOL, are commonly used due to their superior mechanical properties, including high yield strength, good weldability, and adequate ductility [8]. These properties enable the structure to withstand high stress without failure while allowing efficient fabrication processes.

In addition to structural strength, ergonomics is an essential aspect of roll cage design. The chassis must provide sufficient space for the driver, ensure proper visibility, and allow quick ingress and egress, especially during emergency situations [9]. A well-planned ergonomic design improves driver comfort and reduces fatigue, ultimately enhancing vehicle performance during endurance events.

Modern design methodologies incorporate computer-aided design (CAD) and finite element analysis (FEA) tools to model and evaluate the roll cage before fabrication. These tools help in predicting stress distribution, deformation, and failure points under various loading conditions, thereby reducing the need for costly physical prototypes [10]. By integrating analytical and practical approaches, engineers can develop a roll cage that meets both safety and performance requirements.

II. PROBLEM STATEMENT

Designing a roll cage for an all-terrain vehicle (ATV) used in competitions such as the SAE India E-BAJA presents a complex engineering challenge. The roll cage must provide maximum safety to the driver under various impact conditions such as frontal collision, side impact, and rollover, while also maintaining a lightweight structure that does not compromise vehicle performance.

A major difficulty lies in achieving an optimal balance between strength and weight. Increasing structural strength often leads to higher weight, which negatively affects acceleration, fuel efficiency (or battery performance in electric ATVs), and maneuverability. Conversely, reducing weight without proper analysis can weaken the structure and pose safety risks. Therefore, the challenge is to design a roll cage that is both strong and lightweight while meeting strict competition regulations.

Another issue is ensuring that the design complies with the dimensional and safety requirements specified in the SAE rulebook. Any deviation from these standards can lead to disqualification or unsafe vehicle conditions. Additionally, the roll cage must accommodate ergonomic considerations such as sufficient driver space, proper visibility, and quick ingress and egress during emergency situations.

Material selection and manufacturing constraints also add to the problem. The chosen material must offer high strength, good weldability, and cost-effectiveness, while the fabrication process must ensure dimensional accuracy and structural integrity. Improper material choice or fabrication defects can lead to failure under load conditions.

Furthermore, the roll cage is subjected to complex loading conditions during off-road operation, including vibrations, shocks, and torsional stresses. Without proper analysis and validation, these factors can cause structural deformation or failure.

Hence, the problem is to develop a roll cage design that ensures maximum safety, complies with competition standards, optimizes weight, supports ergonomic requirements, and withstands real-world off-road conditions, while remaining economically feasible and manufacturable.

III . OBJECTIVES

- To design and develop a robust roll cage that ensures maximum safety and protection for the driver under various impact conditions.
- To ensure compliance with SAE India E-BAJA rulebook standards for dimensions, materials, and safety requirements.
- To optimize the strength-to-weight ratio of the chassis for improved vehicle performance and efficiency.
- To incorporate ergonomic design principles for driver comfort, visibility, and easy ingress and egress.
- To select appropriate materials and fabrication techniques that provide durability, weldability, and cost-effectiveness.

IV. LITERATURE SURVEY

1. Design and Fabrication of Roll Cage for BAJA Vehicle (2024)

Authors: Swaroop G., Shreyas Tandel

Journal: International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering (IJIREEICE)

Year: 2024

This study focuses on the design and fabrication of a roll cage for a BAJA vehicle using high-strength steel materials such as AISI 4130. The authors emphasize achieving a high strength-to-weight ratio while maintaining structural rigidity. The roll cage geometry was modeled using CAD software and evaluated using ANSYS for stress and deformation under different loading conditions. The research highlights that the circular cross-section of members improves load distribution and torsional rigidity. Simulation results confirmed that the structure could withstand impact loads and met SAE safety standards, ensuring protection of both the driver and vehicle components in off-road conditions .

2. Design and Development of All-Terrain Vehicle Roll Cage (2021)

Authors: S. Venkatesh, R. Soundararajan, P. Ashoka Varthanan

Journal: ResearchGate Publication

Year: 2021

This paper presents a comprehensive approach to the conceptual design and analysis of an ATV roll cage. Multiple design models were developed and tested under various impact conditions such as front, rear, and side collisions. The study also explored different materials to achieve an optimal balance between weight and strength. Finite Element Analysis (FEA) was used to determine stress distribution, deformation, and factor of safety. The authors concluded that proper material selection and structural optimization significantly improve vehicle safety and performance while reducing overall weight .

3. Design and Finite Element Analysis of Four-Wheel Drive Roll Cage (2022)

Author: Naik Burye Nishidh Shailesh

Journal: International Journal of Engineering Research & Technology (IJERT)

Year: 2022

This research focuses on the design of a roll cage for a four-wheel-drive ATV used in BAJA competitions. The study integrates CAD modeling with finite element analysis to evaluate the chassis under real-world loading conditions. Key factors such as driver safety, structural strength, and weight reduction were considered during the design process. The results demonstrated that the roll cage effectively withstands impact loads while maintaining structural integrity. The study also highlights the importance of maintaining a low center of gravity for better vehicle stability .

4. Design and Structural Analysis of BAJA Frame with Conventional and Composite Materials (2020)

Authors: M.P.D.R. Rao et al.

Journal: International Journal of Advanced Science and Engineering Research (IJASRET)

Year: 2020

This paper compares conventional steel materials with composite materials for designing a BAJA vehicle chassis. The authors discuss the role of the roll cage as the primary structural framework that connects all vehicle subsystems. The study evaluates different materials based on strength, weight, and durability. Analysis results indicate that composite materials can reduce weight significantly while maintaining structural strength. However, practical challenges such as cost and manufacturability make steel a preferred choice in most cases .

5. Design, Assembly, Analysis of Roll Cage and Mountings of an ATV (2025)
Authors: Arun Kumar Wamankar, Eshann Agrawal, Ansh Jain, et al.
Journal: International Journal of Advanced Research in Engineering and Technology (IJARET)
Year: 2025
This research presents a detailed methodology for designing and analyzing an ATV roll cage using modern tools like SolidWorks and ANSYS. The study considers both static and dynamic loading conditions, including vibration and thermal effects. Multiple design iterations were performed to optimize the structure for durability and performance. The findings highlight that simulation-driven design significantly improves reliability and reduces the risk of structural failure. The study also emphasizes the importance of integrating manufacturing considerations during the design phase .

6. Design and Analysis of Roll Cage Chassis (2020)
Author: BESS Aakash
Journal: Materials Today: Proceedings (Elsevier)
Year: 2020
This paper proposes an improved roll cage design aimed at overcoming limitations of conventional chassis structures. The design was developed using CATIA and analyzed using ANSYS under various impact and torsional conditions. A comparative study of different materials was conducted to identify the most suitable option for fabrication. The results showed that optimized design and proper material selection enhance safety without affecting performance. The study concludes that simulation-based validation is essential for developing efficient and reliable roll cage structures .

Comparison Table

Author & Year	Method Used	Advantages	Limitations
Swaroop G. (2024)	CAD + FEA (ANSYS)	High strength design, good safety validation	Limited focus on cost optimization
Venkatesh S. (2021)	Concept design + FEA	Balanced weight & strength, multiple load analysis	Less emphasis on manufacturing process
Nishidh S. Naik (2022)	CAD + Structural Analysis	Improved stability, good impact resistance	Limited ergonomic considerations
M.P.D.R. Rao (2020)	Material comparison + FEA	Weight reduction using composites	High cost and fabrication complexity
Wamankar A. (2025)	Simulation-based design	High accuracy, better durability	Time-consuming design iterations
BESS Aakash (2020)	CATIA + ANSYS analysis	Optimized structure, improved safety	Limited real-world testing

IV. WORKING OF SYSTEM

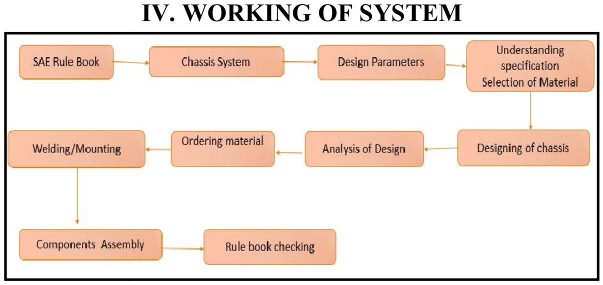

Fig 1: Design of the system

The working of the roll cage (chassis) system follows a systematic and sequential process starting from understanding the rules to final validation and assembly.

Initially, the process begins with studying the SAE Rule Book, which provides all mandatory safety and dimensional guidelines for the chassis design. Based on these rules, the chassis system requirements are identified, and important design parameters such as dimensions, angles, and structural constraints are defined.

Next, a detailed understanding of specifications is carried out along with the selection of suitable material (such as DOCOL steel) considering strength, weight, and weldability. After this, the designing of the chassis is performed using CAD software, where the complete roll cage structure is modeled.

Once the design is prepared, it undergoes analysis of design using simulation tools like FEA to check stress distribution, deformation, and safety under different loading conditions. After successful validation, the required materials are ordered as per design specifications.

The fabrication phase begins with welding and mounting of the chassis members, ensuring proper alignment and joint strength. Following this, all necessary parts are integrated during the components assembly stage to form the complete structure.

Finally, the entire system is subjected to rule book checking, where the finished roll cage is inspected to ensure it meets all SAE standards and safety requirements.

This step-by-step process ensures that the final chassis is safe, reliable, cost-effective, and compliant with competition regulations.

V. SYSTEM DESIGN

1. System Overview:

The system design of the roll cage is developed by considering safety, strength, ergonomics, and compliance with SAE India E-BAJA standards. The key design aspects are as follows:

1. Structural Design

- The roll cage is designed as a space frame structure using tubular members.
- It provides high strength with minimum weight.
- Ensures proper load distribution during impact conditions.

2. Design Parameters

- All dimensions are selected as per SAE rulebook guidelines.
- Critical members like BLC, CLC, DLC, ALC, and FLC are properly defined.
- Roll hoop angles and frame width are maintained within safety limits.

3. Material Selection

- DOCOL steel is selected for its high strength and good weldability.
- Provides excellent strength-to-weight ratio.
- Suitable for harsh off-road conditions.

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4. CAD Modeling

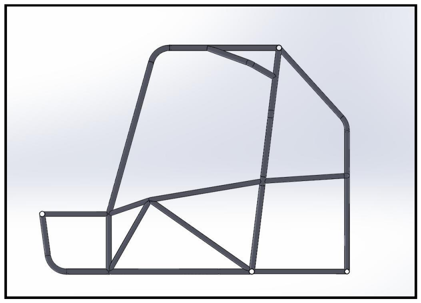

Fig.2 Side View

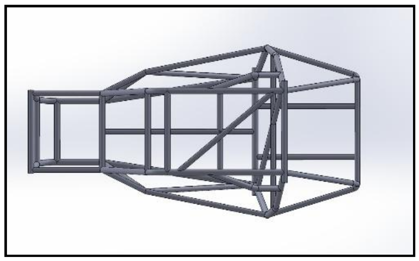

Fig.3 Top View

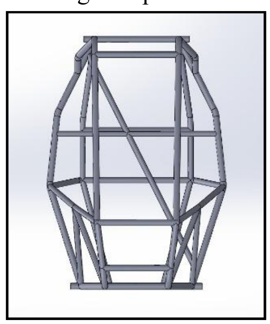

Fig.4.Front View

- The complete chassis is modeled using CAD software (SolidWorks).
- Accurate geometry ensures proper fabrication and assembly.
- Helps in visualizing the final structure.

5. Structural Analysis

- Finite Element Analysis (FEA) is performed using ANSYS.
- Different load cases like front, side, rear, and rollover impacts are analyzed.
- Ensures safety and reliability of the design.

6. Ergonomic Design

- Adequate space is provided for driver comfort.
- Proper positioning of steering and controls.
- Easy ingress and egress within required time.

7. Manufacturing Design

- Tube bending, cutting, and welding processes are considered.

- Joint design ensures strong and defect-free connections.
- Fabrication feasibility is maintained.

8. Safety Considerations
- Roll cage protects the driver during accidents.
- Maintains structural integrity under extreme conditions.
- Meets all safety standards of the competition.

9. Weight Optimization
- Design focuses on reducing unnecessary weight.
- Maintains balance between strength and efficiency.
- Improves vehicle performance.

10. Validation & Testing
- Final design is checked against SAE rules.
- Physical inspection and testing are conducted.
- Ensures readiness for competition.

VI. MATHEMATICAL EQUATIONS

1. Acceleration-Based Impact Force

From Newton's second law:

$$F = m \cdot a$$

Where,

$$a = \frac{v^2}{2d}$$

$$a = \frac{(15.27)^2}{2 \times 7.8} = 14.98\, m/s^2$$

$$F = 265 \times 14.98 = 3977.46\, N$$

$$g - force = \frac{a}{9.81} = 1.53G$$

2. Frontal Impact Force Calculation

The frontal impact force is calculated considering kinetic energy and stopping distance.
Given:
Mass of vehicle (m) = 265 kg
Velocity (v) = 55 km/h = 15.27 m/s
Stopping distance (d) = 7.8 m
Using energy method:

Impact Force $= \frac{m \cdot v^2}{2d}$

$$F = \frac{265 \times (15.27)^2}{2 \times 7.8}$$

$$F = 3977.46\ N$$

Thus, Frontal Impact Force = 3977.46 N

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3. Side Impact Force

For side impact, load is considered as 3G condition:

$$F = m \cdot 3g$$

$$F = 265 \times 3 \times 9.81$$

$$F = 7798.95 \text{ N}$$

Thus, Side Impact Force = 7798.95 N

4. Rear Impact Force

Rear impact is generally higher due to sudden deceleration:

$$F = 5089.31 \text{ N}$$

5. Rollover Impact Force

For rollover condition:

$$F = m \cdot g \times \text{factor}$$
$$F = 265 \times 9.81 \times 2$$
$$F \approx 5199.3 \text{ N}$$

Thus, Rollover Force = 5199.3 N

6. Bump Impact Force

In bump condition, load is distributed at two points:

$$2F = m \cdot g$$
$$F = \frac{1}{2}.m.g$$
$$F = \frac{1}{2} \times 265 \times 9.81$$
$$F = 1299.82 \text{ N}$$

Applying factor of safety (1.2):

$$F = 1299.82 \times 1.2 = 1559.79 \text{ N}$$

Thus, Bump Load = 1559.79 N

7. Torsional Force

$$F = 5194.3 \text{ N}$$

VII. RESULTS

1. Frontal Impact

Parameter	Value
Load Applied	3977.46 N
Max Stress	294.91 MPa
Max Deformation	0.74511 mm
Factor of Safety (FOS)	2.34
Material Used	Docol R8
Yield Strength	690 MPa
Ultimate Strength	800 MPa

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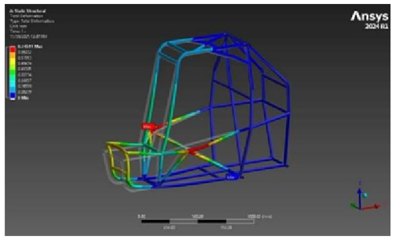

Fig .5

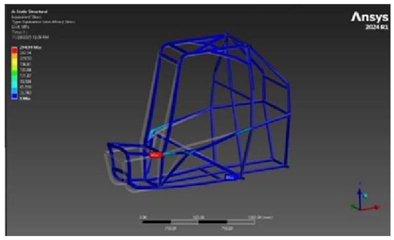

Fig .6

2. Rear Impact

Parameter	Value
Load Applied	5089.31 N
Max Stress	307.07 MPa
Max Deformation	2.0449 mm
Factor of Safety (FOS)	2.24
Material Used	Docol R8
Yield Strength	690 MPa
Ultimate Strength	800 MPa

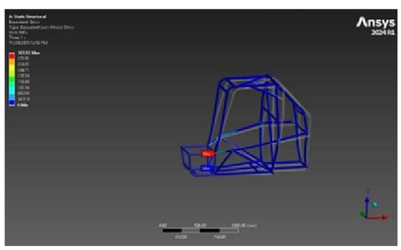

Fig.7

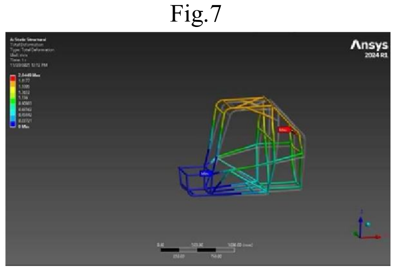

Fig.8

DOI: 10.48175/568

3. Side Impact

Parameter	Value
Load Applied	7798.95 N
Max Stress	321.52 MPa
Max Deformation	1.9149 mm
Factor of Safety (FOS)	2.14
Material Used	Docol R8
Yield Strength	690 MPa
Ultimate Strength	800 MPa

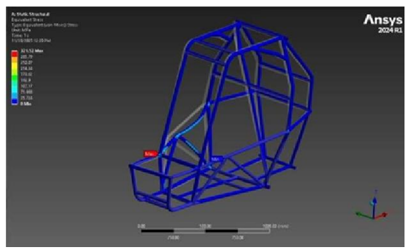

Fig.9

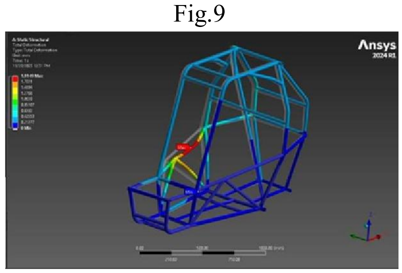

Fig.10

4. Rollover Analysis

Parameter	Value
Load Applied	5199.3 N
Max Stress	447.35 MPa
Max Deformation	4.467 mm
Factor of Safety (FOS)	1.54
Material Used	Docol R8
Yield Strength	690 MPa
Ultimate Strength	800 MPa

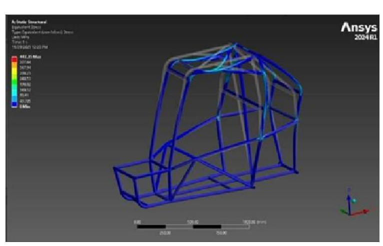

Fig.11

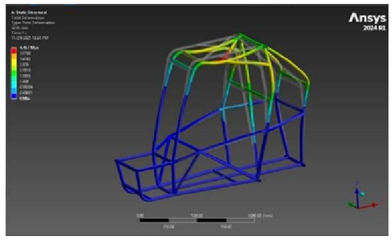

Fig.12

5. Bump Impact

Parameter	Value
Load Applied	1559.79 N
Max Stress	242.72 MPa
Max Deformation	0.90839 mm
Factor of Safety (FOS)	2.84
Material Used	Docol R8
Yield Strength	690 MPa
Ultimate Strength	800 MPa

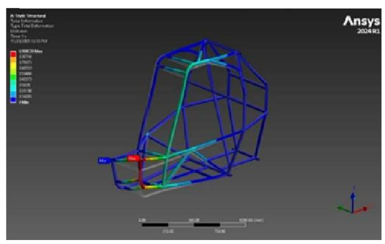

Fig.13

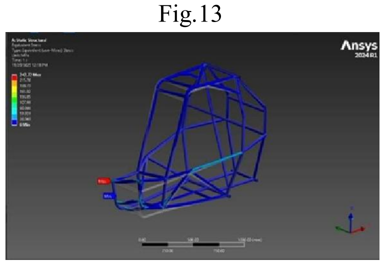

Fig.14

6. Torsional Analysis

Parameter	Value
Load Applied	5194.3 N
Max Stress	318.7 MPa
Max Deformation	3.4007 mm
Factor of Safety (FOS)	2.16
Material Used	Docol R8
Yield Strength	690 MPa
Ultimate Strength	800 MPa

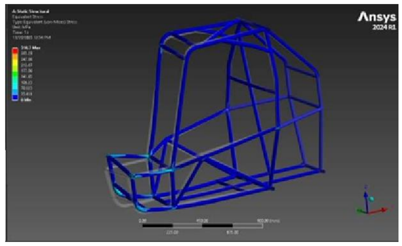

Fig.15

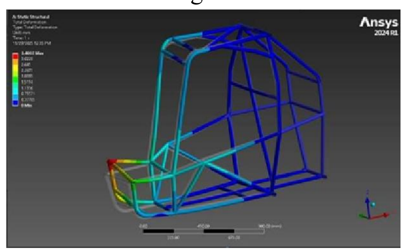

Fig.16

VIII. FUTURE SCOPE

The roll cage design can be further improved by exploring advanced materials such as alloy steels or hybrid composites to achieve greater weight reduction while maintaining high strength. Future work can focus on detailed crash and fatigue analysis under real-time conditions to better understand long-term performance and durability. The use of topology optimization techniques can help in removing unnecessary material and enhancing structural efficiency. Manufacturing processes can also be improved by adopting precision techniques such as robotic welding to ensure better joint quality and consistency.

Additionally, integrating sensor-based monitoring systems within the chassis can help in detecting stress, strain, and potential failures during operation. Further refinement in ergonomic design can enhance driver comfort, visibility, and safety during long endurance events. Continuous updates based on revisions in SAE India BAJA rules and advancements in simulation tools will also contribute to developing a more efficient, safer, and high-performance roll cage in future designs.

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