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CAE Analysis and Material Selection for the Chassis of a 4-Wheel Efficycle

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Abstract

This paper presents a comprehensive Computer-Aided Engineering analysis and material selection study for the chassis of a four-wheel Efficycle – a hybrid human–electric powered vehicle designed for student competitions and sustainable mobility applications. The objective of the study is to evaluate the structural integrity, stiffness, and crashworthiness of the chassis under various loading scenarios, including front impact, side impact, rollover, and torsional loads. Using CAD models developed in SolidWorks and structural simulations performed in ANSYS Workbench, different design configurations were virtually tested to assess stress distribution, deformation patterns, and safety margins. Three candidate materials – AISI 1018, AISI 1020, and AISI 4130 – were compared based on mechanical properties, manufacturability, cost, and availability. The analysis revealed that AISI 1018 provides the most balanced solution, offering adequate strength, good ductility, weldability, and affordability. The CAE results confirmed that under defined loading conditions, the AISI 1018 chassis design performs within permissible deformation limits while ensuring driver safety and regulatory compliance. The study builds upon existing research on CAD/CAE integration and validates the effectiveness of simulation-based design in reducing prototyping costs, improving reliability, and accelerating the development cycle of student-level vehicles such as the SAE Effi cycle and BAJA SAE. In addition, the research highlights key design considerations for lightweight hybrid chassis structures, including reinforcement strategies in high-stress regions and stiffness optimization for rollover resistance. The findings provide a robust framework for future design optimization and material selection in academic vehicle engineering projects. Further extensions of this work could involve fatigue testing, dynamic load simulations, and topology optimization to improve durability and weight efficiency. Overall, the research demonstrates how simulation-driven design and careful material selection contribute to safer, lighter, and more cost-effective vehicles.

Keywords: CAE analysis, chassis design, AISI 1018, structural simulation, efficycle, impact testing

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INTRODUCTION

The objective of this research paper is to perform a comprehensive Computer-Aided Engineering (CAE) analysis of the chassis of a four-wheel hybrid vehicle. The chassis, often referred to as the backbone of a vehicle, plays a critical role in ensuring overall performance, durability, and safety. It is the main structural framework on which all other subsystems – including suspension, powertrain, and body panels – are mounted. To serve its purpose effectively, the chassis must be designed to withstand a variety of external forces and dynamic loads encountered during real-world driving conditions. These loads include vertical forces caused by the vehicle's weight and road irregularities, lateral forces generated during cornering, and longitudinal forces arising from braking and acceleration. An optimized chassis design must not only endure these forces without failure but also minimize weight in order to enhance efficiency and vehicle handling.

In modern engineering practice, the use of CAE tools has revolutionized the way vehicle structures are designed and validated. CAE enables engineers to simulate and analyze the structural behavior of the chassis under different loading conditions before committing to costly physical prototypes. This simulation-driven approach offers multiple advantages such as significant cost reduction, faster development cycles, and the ability to evaluate numerous design alternatives in a virtual environment. Techniques, like finite element analysis (FEA) in software such as ANSYS and SolidWorks Simulation, provide insights into stress distribution, deformation, and safety factors, allowing engineers to refine designs with high precision.

In the specific case of hybrid and electric vehicles, like the Efficycle – a lightweight, human–electric powered four-wheel tricycle designed for student competitions – chassis design, is particularly challenging. The design must strike a delicate balance between rigidity, weight reduction, and ease of manufacturability. Safety is paramount, especially in scenarios, such as frontal and side impacts, rollovers, and torsional loads, encountered during uneven terrain traversal or high-speed cornering. At the same time, cost-effective material selection is essential to meet budgetary constraints while ensuring reliability and compliance with competition rulebooks.

Therefore, this study focuses not only on analyzing the strength, stiffness, and impact resilience of the Efficycle chassis using advanced CAE techniques but also on evaluating suitable material options. By integrating CAD modeling with structural simulations, this research aims to demonstrate how virtual testing and intelligent material selection can improve safety, performance, and manufacturability, providing a strong framework for future student-level vehicle projects and sustainable mobility solutions.

LITERATURE REVIEW

CAE has become an indispensable component of modern product design, enabling engineers to virtually test and optimize components before manufacturing. The integration of Computer-Aided Design (CAD) and CAE has been widely explored in literature, to establish a seamless platform for addressing complex engineering challenges. This integration is particularly valuable in the automotive sector, where safety, efficiency, and cost-effectiveness are critical. The amalgamation of CAD and CAE provides designers with analysis capabilities at the conceptual stage, thereby reducing costs, shortening development cycles, and improving structural reliability [1, 2].

Studies in manufacturing have highlighted the benefits of consolidating CAD and CAE tools into a unified workflow. Bhandari [3] emphasized that simulation-driven design allows engineers to evaluate structural behavior under realistic load conditions, reducing reliance on physical prototyping. Such integration bridges the gap between design and application by providing immediate performance feedback, enabling efficient decision-making, and optimizing product development [1, 3].

In vehicle design, the role of CAE has been revolutionary. Seward [1] noted that CAD–CAE integration in early stages of chassis development helps predict stiffness distribution and impact response, preventing late-stage design failures. The Efficycle rulebook [4] further reinforces the importance of simulation-driven design by mandating crashworthiness, energy absorption zones, and driver safety requirements, all of which necessitate CAE-based validation of impacts and torsional loads.

Several studies demonstrate the successful application of CAE in student-level and industrial vehicle projects. Grover et al. [5] applied CAE in the optimization of lithium–ion battery enclosures for electric vehicles [6–9], showing that simulations significantly enhance safety. Similarly, Jindal et al. [10]

validated torsional stresses in a BAJA SAE chassis using gyroscopic sensor techniques [11], confirming strong agreement between simulation and experimental results. Saini and Rana [12] also highlighted the role of CAE in Formula SAE suspension system design, demonstrating that simulations can reliably predict real-world performance.

Virtual testing has consistently been shown to improve durability while lowering costs. Upadhyaya et al. [13] optimized a BAJA ATV brake caliper through finite element methods, reducing weight without compromising strength [14–16]. Sharma et al. [17] designed and optimized an Efficycle suspension and steering system using CAE, ensuring both safety and performance. These studies underline that virtual testing is not only cost-effective but also instrumental in enhancing reliability across academic vehicle design projects.

Parameter optimization through CAE has also been addressed in multiple contexts. Saini [6] examined process parameters in EDM machining, while Upadhyaya et al. [13] applied optimization techniques for brake master cylinder design in ATVs. Such approaches directly parallel chassis optimization, where geometry, thickness, and reinforcement placement can be tuned virtually to achieve optimal results.

In summary, the literature strongly supports CAD–CAE integration as a foundation for modern vehicle engineering. By enabling virtual evaluation of impacts, rollovers, and torsional loads, CAE reduces prototyping requirements while enhancing safety and efficiency. Prior works across Efficycle [4], BAJA SAE [9, 10, 13], and Formula SAE [7, 12] contexts consistently validate the importance of simulation-based design. This study builds on these insights by applying CAE to the design of a four-wheel Efficycle chassis and systematically comparing materials to achieve an optimal balance of performance, safety, and cost.

Methodology

To analyze and optimize the structural performance of the Efficycle chassis, a systematic methodology integrating CAD modeling and CAE simulations was adopted. The workflow consisted of four stages: CAD modeling, meshing and boundary condition definition, load case identification, and simulation-based evaluation. This approach ensured that the chassis design was rigorously tested for safety, stiffness, and manufacturability.

CAD Modeling

The chassis geometry was designed in SolidWorks 2018, considering ergonomic requirements for driver seating, pedal assembly, and safety clearances as specified in the Efficycle Rulebook [4]. The frame was modeled using tubular members, adhering to geometric constraints for minimum and maximum dimensions. The design incorporated frontal crash members, side protection bars, and rollover protection structures to satisfy competition standards.

Meshing and Boundary Conditions

For CAE analysis, the CAD model was imported into ANSYS Workbench 19.0. A tetrahedral element mesh was generated with refinement in high-stress regions such as joints, bends, and load application points. Mesh sensitivity tests were performed to ensure convergence of results. Boundary conditions were applied by fixing wheel contact points and constraining degrees of freedom at critical joints. Loads were applied as per the calculated impact and torsional conditions.

Load Cases Considered

The chassis was subjected to four critical loading conditions representing realistic scenarios of vehicle operation.

- *Front Impact Test*: A force equivalent to the vehicle's momentum during a frontal collision was applied to the front members [4].

- *Side Impact Test:* A lateral force representing a collision from the side was applied at the midpoint of the chassis side members. Stress concentrations were expected at joint intersections [1].
- *Rollover Test:* Vertical loads equivalent to 1.5 times the vehicle weight were applied on the rollover protection structure to simulate overturning scenarios [4, 10].
- *Torsional Rigidity Test*: Opposite forces were applied diagonally on the front and rear suspension mounts to evaluate torsional stiffness during cornering [12].

Material Property Evaluation

Three materials – AISI 1018, AISI 1020, and AISI 4130 – were selected based on prior use in automotive chassis design [3, 13]. Their properties (yield strength, modulus of elasticity, density, and cost) were collected from ASM handbooks and previous studies [2, 7]. Simulations were repeated for each material to compare deformation and stress under identical loading conditions.

Verification of Results

The CAE outcomes were validated against published results from Efficycle and BAJA SAE chassis studies. Jindal et al. [10] confirmed torsional stress patterns with experimental gyroscopic measurements, while Sharma et al. [17] validated deformation limits under impact. The results from this study were cross-checked with these works to ensure consistency.

MATERIAL SELECTION CALCULATION

- $Abbreviations$
- $Mass\ transfer\ =\ mt$
- $Vertical\ load\ on\ front\ corner\ = vlf$
- $Front\ mass\ of\ the\ car\ =\ fm$
- $Mass\ transfer\ =\ mt$

Front Impact Analysis

- $Mass\ of\ the\ vehicle\ with\ driver = 220\ kg$
- $Impact\ speed\ of\ vehicle = 16.67\ m/s$
- $Impact\ time\ =\ 0.3\ s$

$$V = u\ +\ at \tag{1}$$

- $a = -\ 55.57\ m/s^2$
- $F = 12225.4\ N$
- $Mass\ transfer\ =\ mt$
- $Vertical\ load\ on\ front\ corner\ = vlf$
- $Mass\ transfer\ =\ mt$
- $Mass\ transfer\ =\ mt$

Side Impact Analysis

- $Total\ mass\ of\ hitting\ body\ =\ 300\ kg$
- $Impact\ speed\ of\ vehicle = 16.67\ m/s$
- $Impact\ time = 0.3\ s$
- $V = u\ +\ at$
- $a = -55.7\ m/s^2$
- $F = M \times a$
- $F = 16671\ N$

Rollover Analysis

$$Lateral\ G\ force = \frac{Speed}{Curve\ radius} \times 15 \tag{2}$$

- $Speed = 16.667\ m/s$
- $Curve\ radius = 4\ m$
- $Lateral\ G\ force = 4.63\ m/s^2$

$$Force = vehicle\ weight \times g \times G \tag{3}$$

- $Force = 9992\ N$

Torsional Analysis

- During cornering
- *Front-load transfer*

$$mt \times g \times track\ width = fm \times cornering\ g \times COG \tag{4}$$

- $mt\ \times g \times 0.939\ = (200 \times 0.40) \times 1.2 \times g \times 0.6$
- $Lateral\ mass\ transfer\ (front) = 61.34\ kg\ =\ 601.15\ N$
- $vlf\ = (200 \times 0.402) \times g + 61.34 \times g = 993.15\ N$

MATERIAL SELECTION CALCULATION

Material – 1 (AISI 1018)

- $Carbon\ \% = 0.18\ \%$
- $Outer\ diameter = 25.4\ mm$
- $Thickness = 2\ mm$

Bending Strength

$$M = \frac{Sy \times I}{C} \quad c \tag{5}$$

- $C = 12.7\ mm$
- $Sy = 365\ MPa$

$$I\ = \frac{\pi((O.D)^4 - (I.D)^4)}{64} \tag{6}$$

- $I = 10316.74\ mm^4$
- $M = 291.331\ Nm$

Bending Stiffness

- $E = 205\ GPa$
- $I\ =\ 10316.74\ mm^4$
- $EI\ =\ 2078.031\ Nm^4$

Material – 2 (AISI 1020)

- $CARBON\%\ =\ 0.20\%$
- $Outer\ Diameter = 25.4\ mm$
- $Thickness = 2\ mm$

Bending Strength

- $M = \frac{Sy \times I}{C}$
- $C = 12.7\ mm$
- $Sy = 351.6\ MPa$

$$I = \frac{\pi((O.D)^4 - (I.D)^4)}{64}$$

- $I = 10316.74\ mm^4$
- $M = 285.619\ Nm$

Bending Stiffness

- $E = 199\ GPa$
- $I = 10316.74\ mm^4$
- $EI = 2053.031\ Nm^4$

Material –3 (AISI 4130)

1. $CARBON\% = 0.3\%$
2. $Outer\ Diameter = 25.4\ mm$
3. $Thickness = 2\ mm$

Bending Strength

- $M = \frac{Sy \times I}{C}$
- $C = 12.7\ mm$
- $Sy = 435\ MPa$

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

- $I = 10316.74\ mm^4$
- $M = 353.368\ Nm$

Bending Stiffness

- $E = 190\ GPa$
- $I = 10316.74\ mm^4$
- $EI = 1960.18\ Nmm^4$

We have selected AISI 1018 for our chassis as it meets all the requirements according to the rulebook. The following are the reasons behind the selection of AISI 1018.

- *Strength:* AISI 1018 steel has a relatively low carbon content, which gives it good strength and ductility. This makes it suitable for use in structural applications where high strength is required.
- *Ductility:* AISI 1018 steel has good ductility, which means that it can be easily shaped and formed without breaking or cracking. This makes it well-suited for use in the chassis of a vehicle, which may need to withstand a wide range of stresses and deformations.
- *Affordability:* AISI 1018 steel is relatively inexpensive compared to other steel alloys, which makes it a cost-effective choice for use in the chassis of a vehicle.
- *Weldability:* AISI 1018 steel is easy to weld, making it convenient to work with during manufacturing.
- *Availability:* AISI 1018 steel is widely available, which makes it easy to source for use in the chassis of a vehicle.

RESULT

- *Front Impact:* The deformation was highest at the impact zone but within permissible safety margins. Maximum stress was 167 MPa, well below AISI 1018's yield strength (Figures 1 and 2) [12].
- *Side Impact:* Stress concentration was noted near the side members. Reinforcement is recommended in these areas for improved crash resilience (Figures 3 and 4).
- *Rollover Test:* Stress distribution was evenly spread along the upper bars. The deformation values confirmed the structural capacity to withstand overturn scenarios, consistent with expectations outlined in the efficycle rulebooks (Figure 5) [4].
- *Torsional Analysis:* The chassis experienced twisting under load but remained structurally sound with negligible permanent deformation. These results validate the stiffness of the frame, in agreement with prior suspension validation research (Figure 6) [10].

Overall, the CAE simulations showed that the selected material and design satisfy safety and performance standards. The results were consistent with experimental tests cited in earlier works [9, 10].

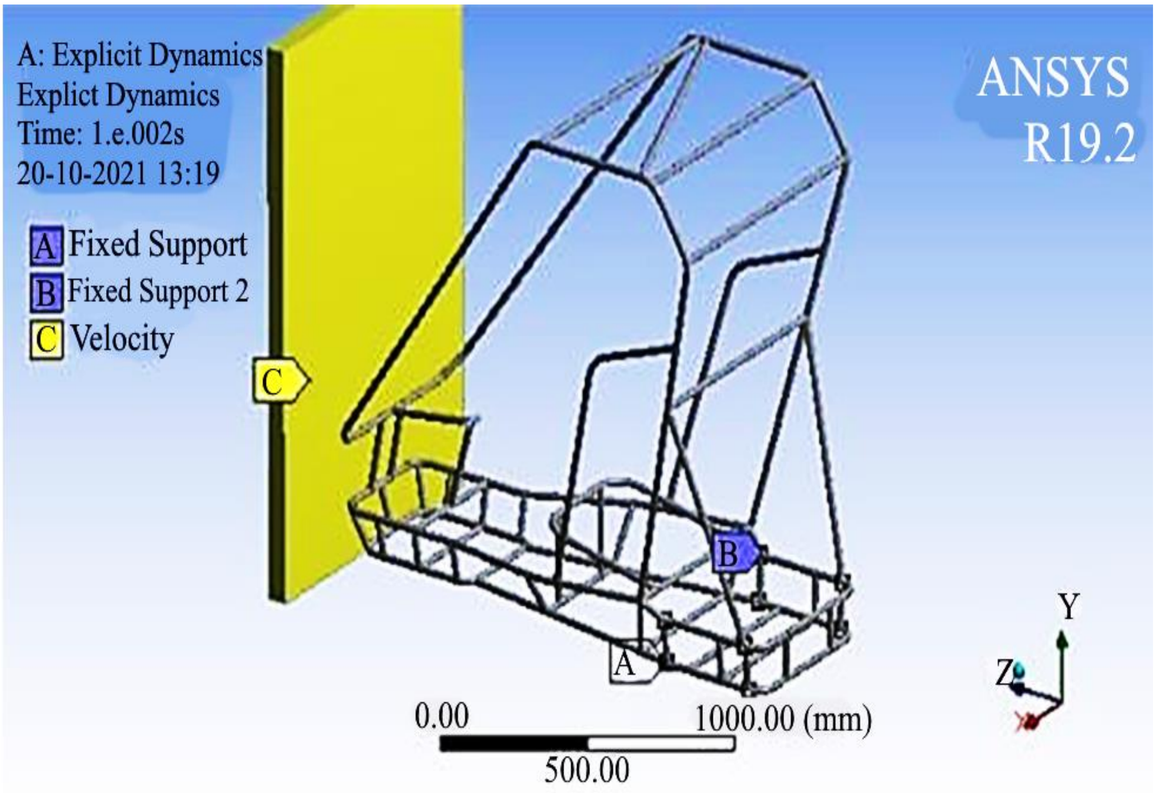

Figure 1. Boundary conditions for front impact analysis.

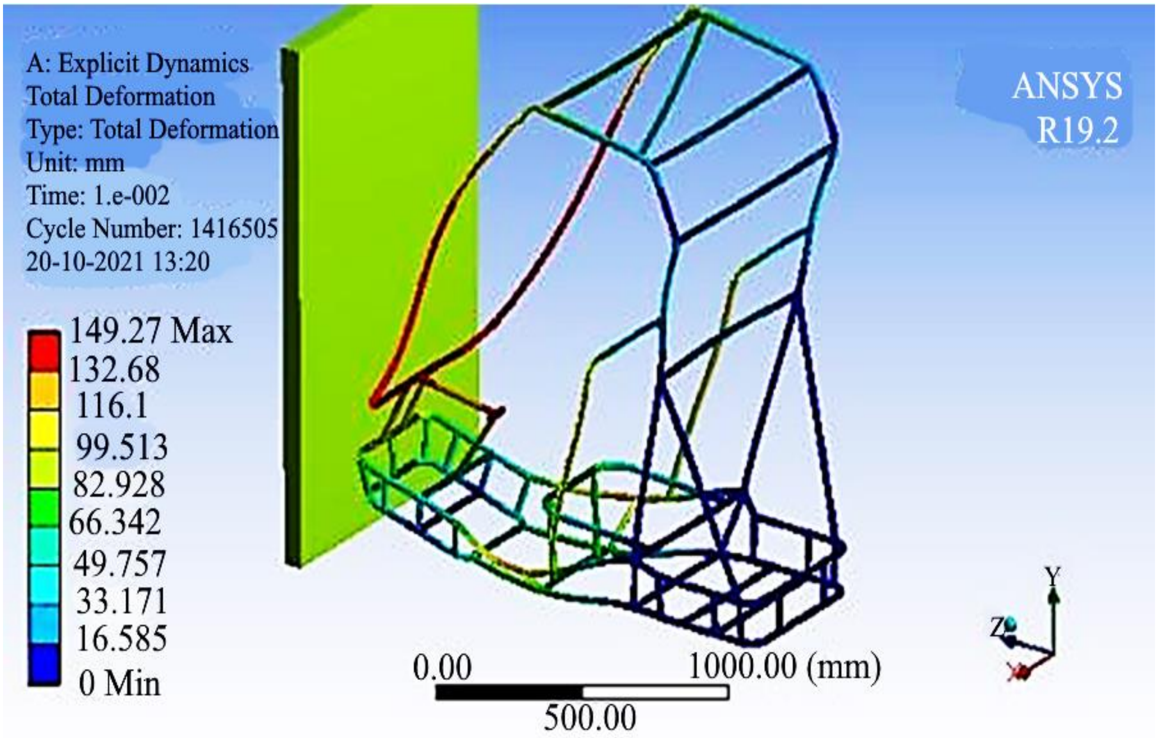

Figure 2. Result – front-impact analysis.

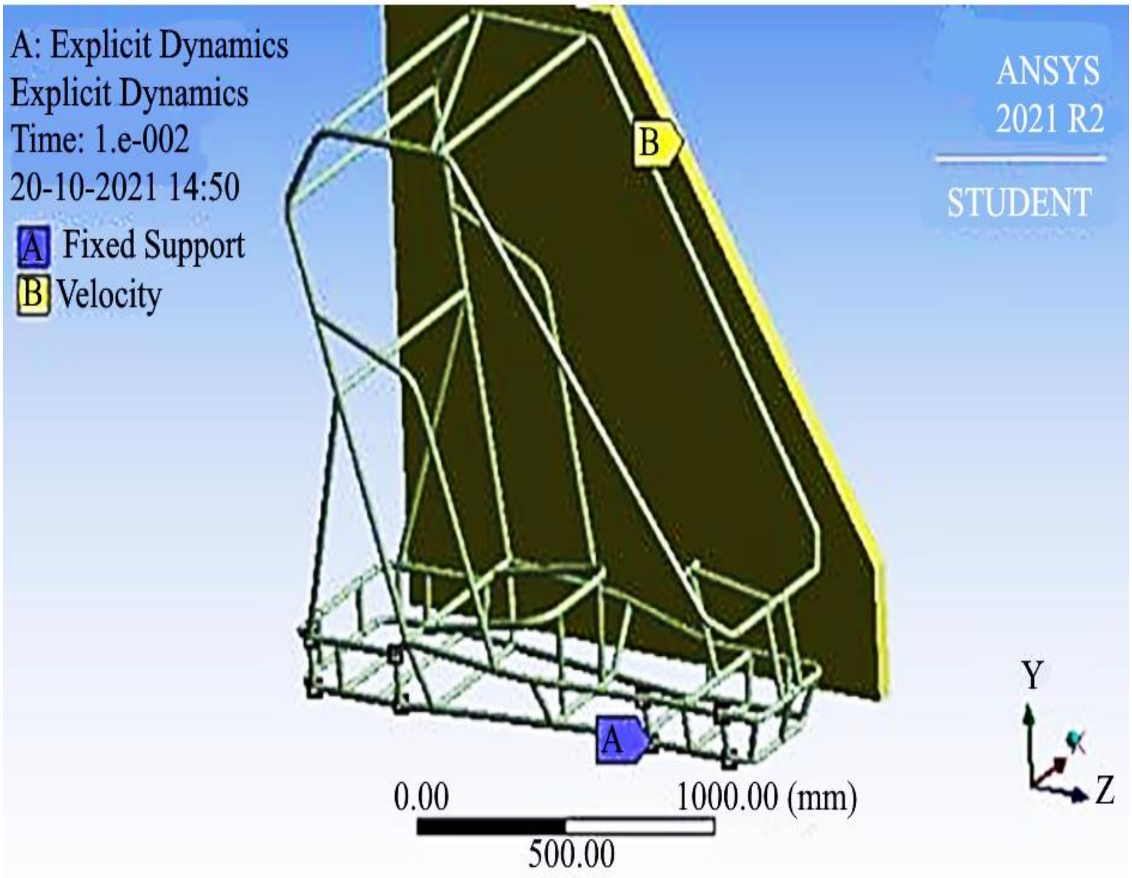

Figure 3. Boundary conditions for side impact analysis.

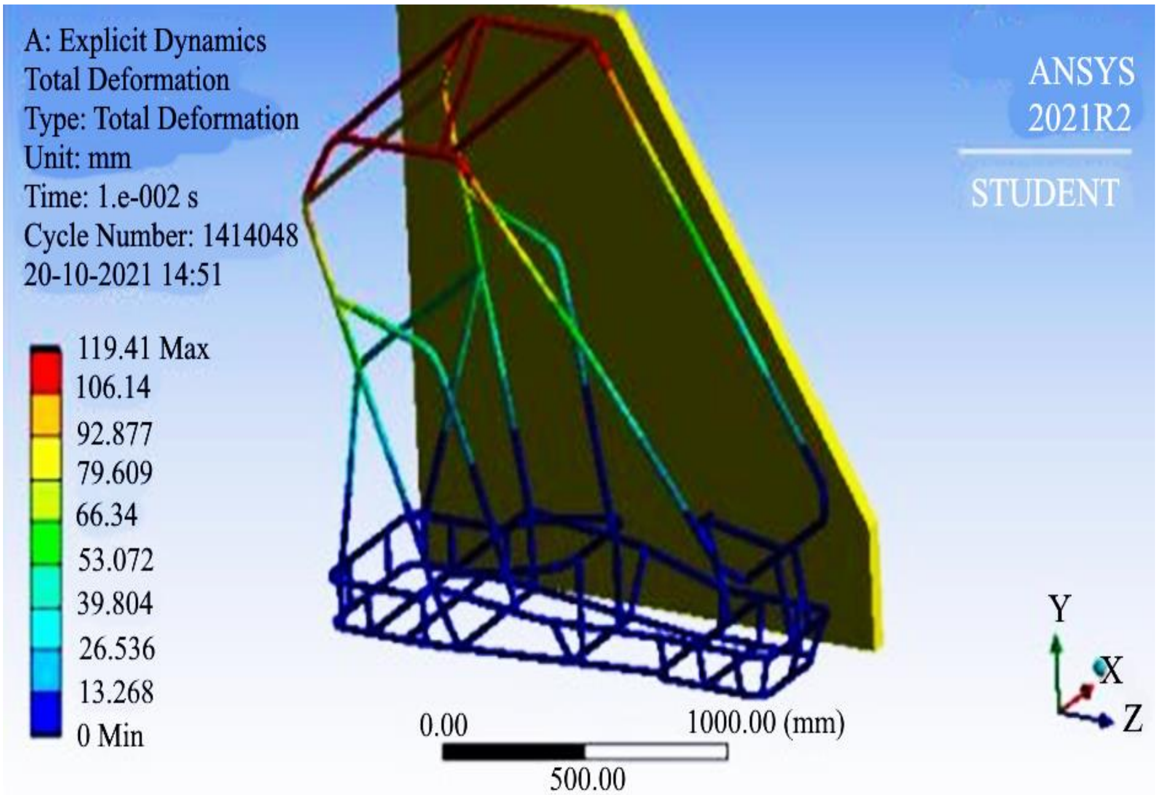

Figure 4. Results – side impact analysis.

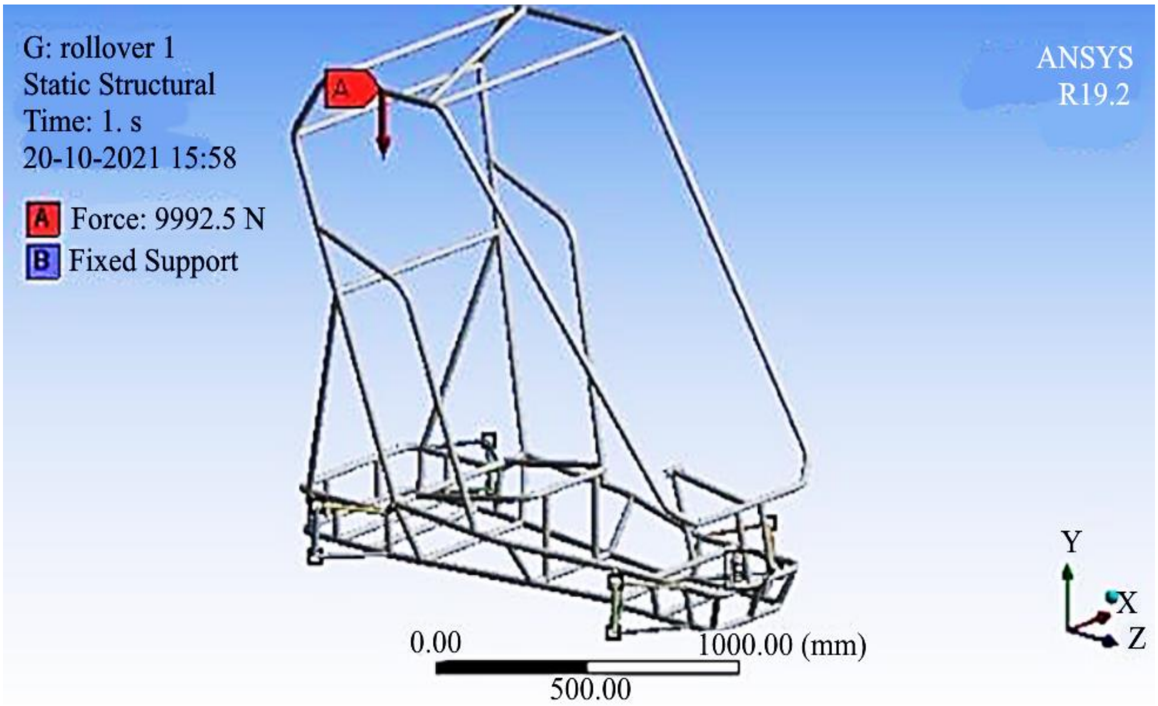

Figure 5. Boundary conditions for torsional analysis.

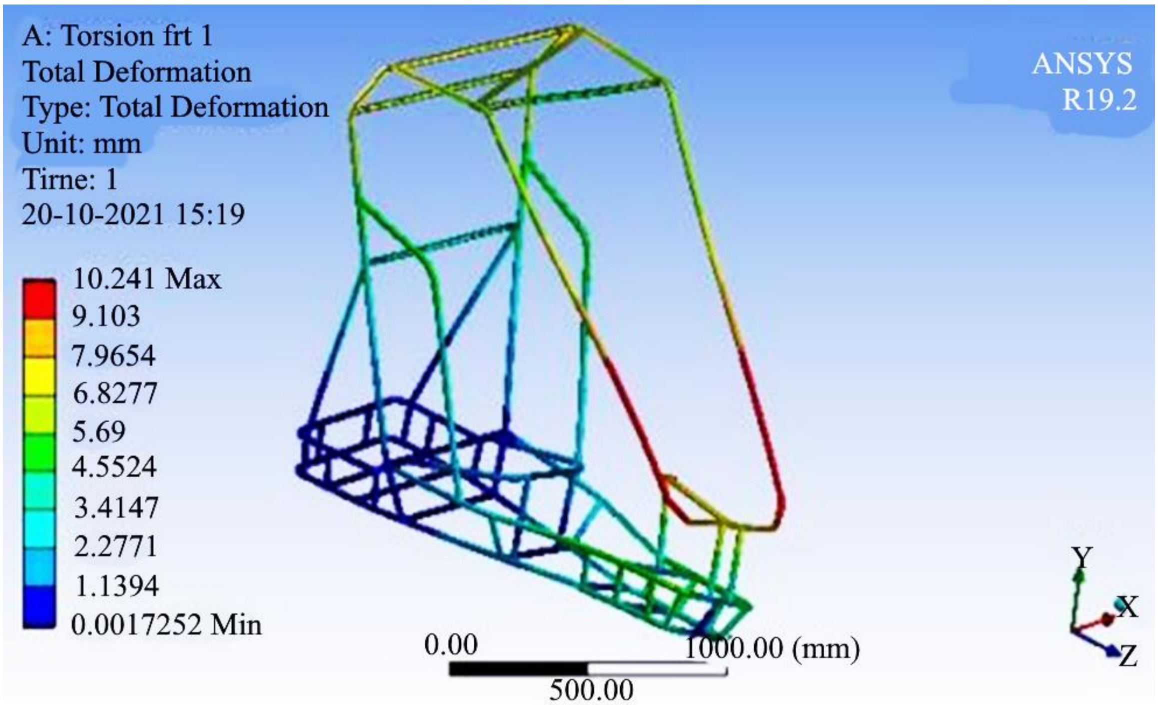

Figure 6. Result – torsional analysis.

CONCLUSION

This study successfully demonstrated the effectiveness of CAE analysis in optimizing the chassis design of a 4-wheel Efficycle. Among the three materials considered, AISI 1018 proved to be the most suitable, balancing strength, ductility, cost, and weldability. Future work could include fatigue analysis and dynamic load simulations for real-road conditions. The integration of virtual simulation and strategic material selection offers a robust framework for vehicle development in student competitions and low-cost vehicle projects.

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