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Design and Analysis of an Effi-Cycle Frame Structure by Using Different Grades of Steel

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Abstract

This research paper provides a detailed overview of the design of a efficycle frame structure using 3D CAD software CATIA V5. The research follows all the norms of the SAE Efficycle rulebook 2022. The study analyzes the impact resistance of different grades of steel, including (1020), (4130), (4340), and (6150), using ANSYS 2022 through Frontal, Side, and Roll Over Tests. In this research paper, we go through a detailed examination of the frame structure to determine the maximum stress, overall deformation, and safety factor for each material. After the detailed study and analysis, our testing results reflected a positive result for the AISI 4340 which has been identified as the optimal material choice for the Efficycle Frame, considering the results during the tests and its higher yield strength and strength-to-weight ratio. Over the detailed study, we come to the conclusion that the frame is safe for front, side, and rollover impacts, with a satisfactory Factor of Safety (FOS) of above 2. The paper represents the importance of material selection with an optimization of the strength, safety, and weight, which can give a detailed study analysis for advanced applications in the automotive industry and beyond. The research's limitations are that we use a single-vehicle model designed in CATIA v5 and a limited number of impact environments.

Keywords: ANSYS, CATIA V5, Design, Effi-Cycle, Steel Grades

1.0 Introduction

Efficycle is a competition organized by SAE for UG engineering students so that they can participate and test their skills in design and fabrication. The vehicle is designed with a roll cage to protect the passengers from any accident. Steel is very popular for designing of roll cages due to its properties, and availability in the market. Roll cages are very important in racing competitions and their design is very unique. Different grades of steel can be used while fabricating and designing the roll cage but it depends on its application. Low-carbon steel is popular due to weldability and ductility and it finds its application in various construction applications. Medium-carbon steel is very popular in machinery and automotive parts because of its higher strength and hardness. High-carbon steel is used for cutting tools and other applications that require high strength and wear resistance. The frame structure of the Efficycle is designed to protect the passenger during the collision of efficacy. It's very important that the frame can sustain its shape during collision and for that we have performed using FEA software ANSYS Workbench. Loading-taking tests such as Front Impact and Side Impact are conducted to determine the strength requirements for the frame. Finally, it is important to balance the strength-to-weight

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ratio in the design of the Efficycle. Therefore, reducing weight is a crucial factor in the design process as there is a limit to the weight of the efficacy in the competition.

The design and analysis of vehicles have been of interest among researchers and engineers in the past. Several studies have been conducted to explore the various aspects of vehicle performance and design. In this research paper, we aim to analyze the design and performance of an electric hybrid Efficycle. Swain and Kumar[1] and Tiwari, Singh, and Jaswal[2] discussed the design and manufacturing of the lifecycle focusing on weight reduction and increased efficiency. Krishna, Shetye, and Mallapur[3,4] examined the Static structural analysis of the chassis for BAJA vehicles using the software.

This paper states the frame's behavior under different loading conditions, giving useful information into the performance of the frame. Gaffney and Salinas[5] and Gopalakrishnan and Mahendran[6,7] provided insights on the different suspension systems in electric vehicles. These papers used simulation techniques to compare the performance of different suspension designs. Aphale and Lachake[3] performed the FEA analysis of the roll cage for an efficycle, focusing on the importance of a roll cage in ensuring the safety of passengers in case of an accident. Saleh, Abdallah, Azab, and Kassab[6] utilized FEA and genetic algorithm techniques to optimize the design of a composite drive shaft, leading to a reduction in weight and increased performance. Finally, Mahapatra, Rout, and Rautray[8] have focused on the design and analysis of a solar-powered electric vehicle, considering the challenges of solar energy combined with automobiles.

Overall, the research papers that have been reviewed in this literature review have given valuable information into the design, analysis, and optimization of various automobile components, focusing on the importance of performance, weight reduction, and efficiency in the design process. The Findings of this research will help in a better understanding of vehicle dynamics and will help in the advancement of efficycle.

Table 1. Details of Frame Structure

State	Fully Defined
Width	1000 mm
Height	970 mm
Length	1200 mm
Outer Radius	10.65 mm
Inner Radius	8.35 mm
Pipe Thickness	2.3 mm
Volume(approx.)	0.0041 3
Surface Area	3.4108^2 Kg
Mass (approx.)	**32**
Analysis Type	3D

2.0 Details of Materials

As a part of safety, major responsible factors of consideration that play a vital role are performance, dependability, and safety in eco-cycle material. At the time of material selection for the Effi-cycle frame, the Number of parameters can vary including Cross section and sizes. Where the vehicle's weight is a completely dependent variable which may vary according to the weight of the material. The Effi-cycle material is extremely strong because of its strength and weight, where it has a low carbon content, and can easily welded. Parallelly the Cost plays a significant role in the decision-making process at the time of material selection. To facilitate the procedure, a material selection decision matrix was created via material properties[9].

Provides the physical properties of four different types of steel: 4340, 1020, 4130, and 6150.

1. Density: it is the mass per unit volume of the material. All four types of steel have the same density of 7.85 g/cm^3.
2. Young's modulus: it is the stiffness of the material and its ability to resist deformation under stress. The 4340, 1020, and 4130 steel have the same Young's modulus of 205 Gpa, while the 6150 steel has a slightly lower value of 200 Gpa.

Table 2. Physical properties for selected steel grades.

Sr no	Properties	Units	Steel 4340	Steel 1020	Steel 4130	Steel 6150
1	Density	g/cm^3	7.85	7.85	7.85	7.85
2	Youngs modulus	Gpa	205	205	205	200
3	Poissen's ratio		0.29	0.29	0.29	0.29
4	Ultimate strength	mpa	745	394.72	560	670
5	Yield strength	mpa	470	294.74	460	415
6	Bulk modulus	Gpa	140	140	140	140
7	Shear modulus	Gpa	80	80	80	80

3. Poisson's ratio: it is the ratio of transverse strain to axial strain when a material is subjected to uniaxial stress. All four types of steel have the same Poisson ratio of 0.29.
4. Ultimate strength: it is the maximum stress that the material can withstand before it breaks. The 4340 steel has the highest ultimate strength at 745 MPa, followed by the 6150 steel at 670 MPa, the 4130 steel at 560 MPa, and the 1020 steel at 394.72 MPa.
5. Yield strength: it is the stress at which the material starts to deform plastically. The 4340 steel has the highest yield strength at 470 MPa, followed by the 4130 steel at 460 MPa, the 6150 steel at 415 MPa, and the 1020 steel at 294.74 MPa.
6. Bulk modulus: it is the resistance of a material to compression. All four types of steel have the same bulk modulus of 140 Gpa.
7. Shear modulus: it is the resistance of a material to shear deformation. All four types of steel have the same shear modulus of 80 Gpa.

Overall, the physical properties of the different types of steel vary, with the 4340 steel having the highest ultimate and yield strengths, making it more suitable for applications requiring high strength and toughness. The 1020 steel, on the other hand, has the lowest ultimate and yield strengths, making it less suitable for applications requiring high strength and toughness. The other two types of steel, 4130 and 6150, fall somewhere in between interms of their physical properties.

3.0 Details Of Software

3.1 Catia V5

CATIA is a very popular software among designers to design any CAD/CAE drawing. Using CATIA V5, we have successfully in modeled the Efficycle frame according to the SAE effi-cycle 2022 rulebook[9]. Dimensions for Primary, as well as Secondary members, were provided in the Rulebook 2022. Two Cross Bracing members with a Diagonal Bracing member (DBM) were provided to strengthen the frame structure. First LCM was connected with the outer OHPMs at the topmost point of their bend portion behind the driver's head. The second LCM was provided at one of the following locations, Figure 1 shows the Efficycle Frame Structure (Steel) rendered image from CATIA V5(Left), CATIA V5 Work- bench (Right)

- 24-inch (609.6 mm) forward to rear LCM.
- Within 2

3.2 Meshing of Efficycle Frame in ANSYS 2022

Mesh creation is very important while performing any type of simulation in FEA software. The tetrahedral element meshing method is used to mesh the Efficycle frame in ANSYS 2022 R1. To obtain accurate results,

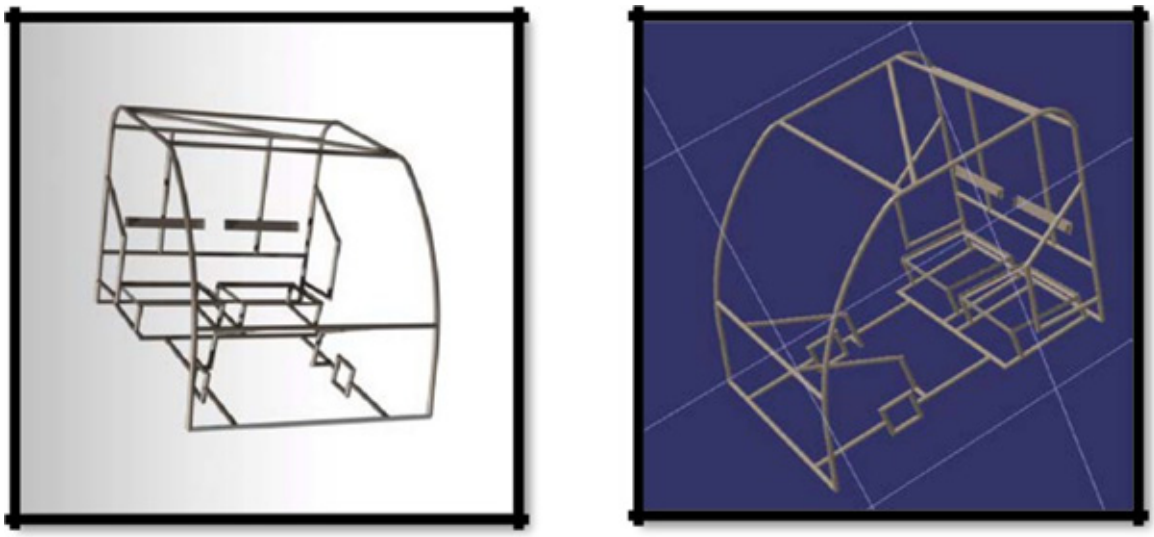


Figure 1. The efficycle frame structure (steel) rendered image from CATIA V5(left), CATIA V5 work- bench (right).

elements are restricted to a minimum size of 8.5 mm with resolution 1 and Adaptive Settings ON. Much finer meshes can be created, but doing so will just result in more nodes and elements to solve, taking longer overall. Also, it was discovered that sometimes a CPU time limit error will occur when element sizing is decreased further. Figure 2 shows the Meshed Model.

Element size: 8.5 mm

Physics preference: Mechanical Analysis Type: Static Structural Number of Nodes: 328942 Number of Elements: 83009

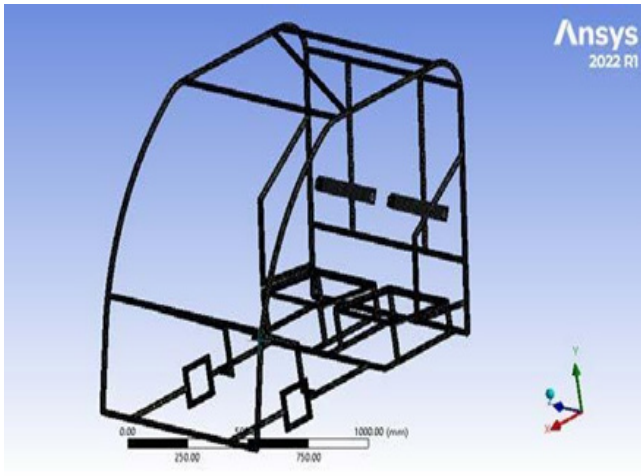


Figure 2. Meshed model.

4.0 Calculations of Force

- Front Impact Test:

  The used equation is F= M.(dV/dT) where,

  F is the force exerted,

  M is the vehicle's mass i.e 220 kg,

  dV/dT is the velocity change rate.

  After a frontal collision with the wall of the car, traveling at a top speed of 25 kmph. The assumed velocity is zero for 0.5 seconds[1,2].

  The calculated force is obtained at 3055.55 N.

- Side Impact Test:

  The calculation process is the same as the front impact test. Therefore, it is an exception for total momentum change with time and assumed to be 1 second in this instance and the vehicle is hit by an identical vehicle moving at a speed of 25 kmph.

  The calculated force is obtained at 1527.78 N.

- Roll Over Test:

  The least amount of force is necessary to rotate the body around its wheels for the rollover test[3]. The formula used was F* h = ((N *w)/ 2) where,

  F = applied force, N = normal reaction, w = track width.

  The calculated force is obtained at 1111.34 N.

5.0 Static Structural Analysis

During the static structural analysis, the displacement, stress, strain, and force in a structural component are calculated as a function of the load. Assuming the load doesn't have damping and inertia. In other words, both the loads and the structures change gradually over time under a steady load along its response circumstances.

Using ANSYS, a static structural load is performed, and for stress analysis, the FEA tool ANSYS-Workbench is utilized.

5.1 Boundary Conditions for Static Structural Analysis

During attaining the solutions, boundary conditions are applied. The following boundary conditions are:

5.2 Front Impact Test

- The suspension mounting points of the frame members are acting as fixed supports.
- The applied force is towards the frontal members of the frame.

5.3 Side Impact Test

- The lower suspension mounting points of the frame members are acting as fixed supports.
- The applied force is towards the right-side SPM (Side Protection Member) of the frame.

5.4 Roll-Over Impact Test

- The Right-side Bottom Suspension members of the Frame are acting as fixed supports.
- The applied force is towards the Top left side OHPM (Over-Head Protection member) and DBM (Diagonal Bracing member) of the frame.

6.0 Comparison of Impact Data on Efficycle Frame

6.1 Front Impact Test

The front members of the efficycle frame are subjected to impact force during the test. The fixed supports from the rear members and the trailing arm is mounted of the frame.

The total deformation and safety factors of various steel grades are displayed in the table below.

- The Front member of the efficycle frame is represented by the red colour contrast and having the greatest deformation.
- The Rear members of the frame structure is represented by the blue colour and having the least amount of deformation.

During performing the front impact test, the Steel 4340 is having the highest Factor of Safety i.e., 2.2954 and represent the best performing steel among the various tested steel grades. Table 3 shows the Represents the Total Deformation and Factor of Safety

6.2 Side Impact Test

The right-Side protection members of the efficycle frame are subjected to impact force during the test. The maxi- mum stress and total deformation along its safety factor of various steel grades are displayed in the Table 4.

- The side protection member of the efficycle frame, is represented by the red colour contrast and having the greatest deformation.
- The rest of the frame structure shown by the blue color and having the least amount of deformation.

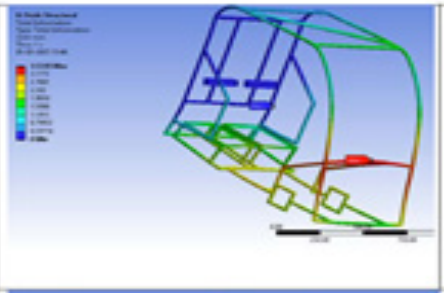
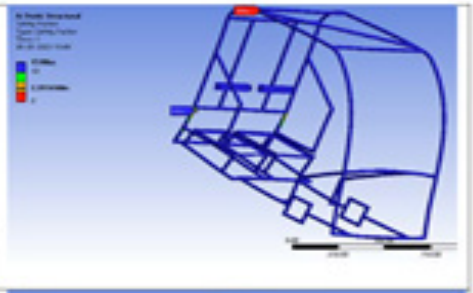
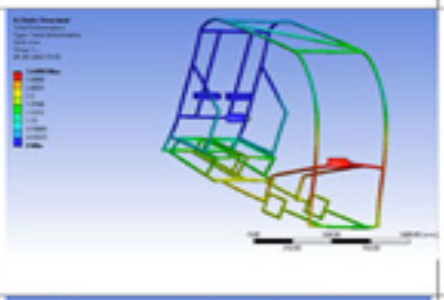
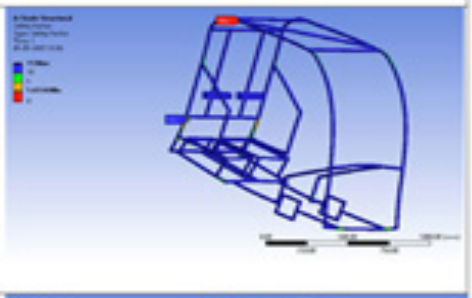
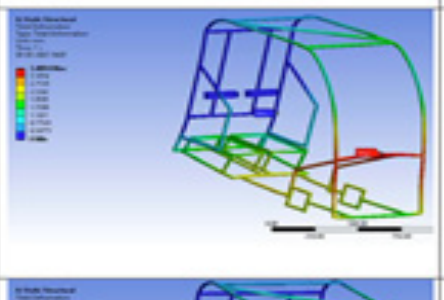
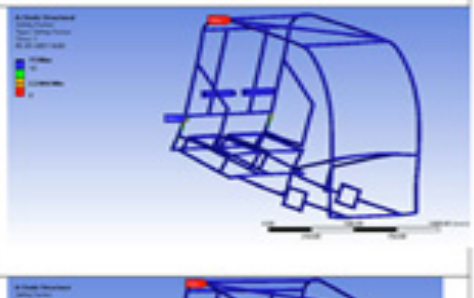
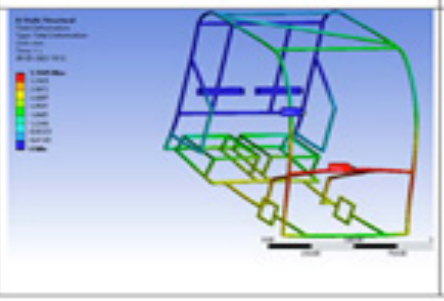
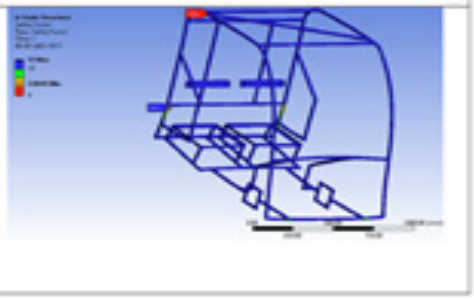
During performing the side impact test, the Steel 4340 is having the highest Factor of Safety i.e. 2.04 and represent the best performing steel among the various tested steel grades.

6.3 Roll Over Test

The front parts of the efficycle frame are subjected towards force during the test. The total deformation and safety factors of various steel grades are displayed in the Table 5.

- The Over Head Protection member (OHPM) and Diagonal Bracing Member (DBM) of the efficycle frame, is represented by the red colour contrast and having the greatest deformation.
- The opposite side lower members of the frame structure are represented by the blue colour and having the least amount of deformation.

Table 3. Represents the total deformation and factor of safety

Material	Total Deformation	Factor of Safety
Steel (4340)		
Steel (1020)		
Steel (4130)		
Steel (6150)		

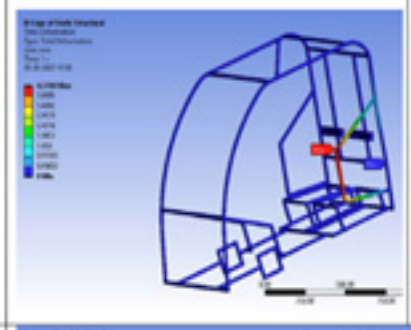
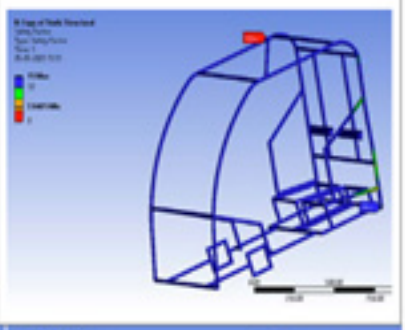
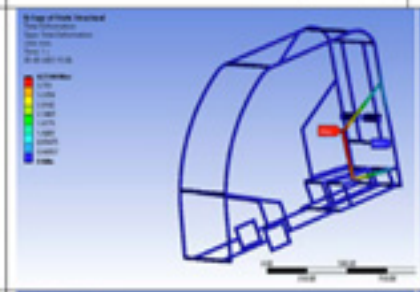
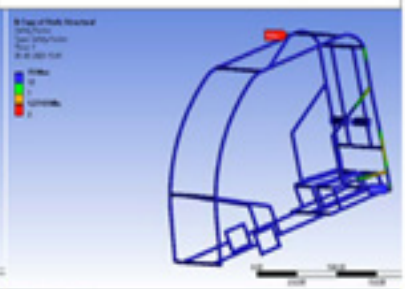
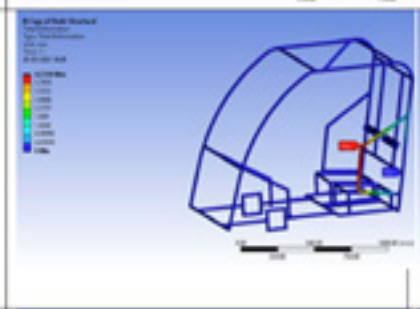
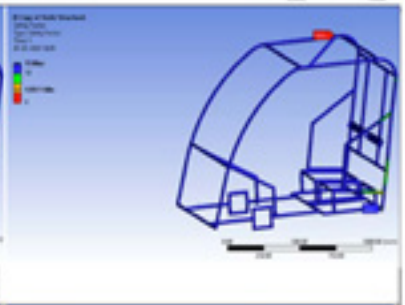
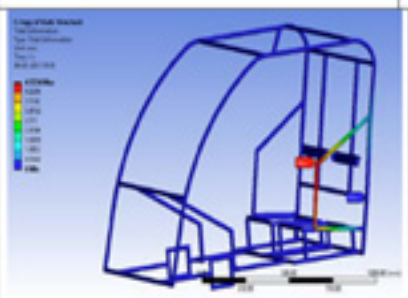
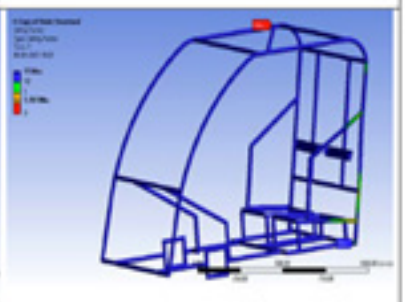
7.0 Result and Discussion

7.1 Front Impact Test

After measuring the deformation, equivalent stress, and factor of safety, the maximum resistance of each material was to be tested.

Maximum deformation was measured in (mm). The results show that the 1020 steel had the lowest deformation at 3.4499 mm, while the 6150 steel had the highest deformation at 3.7045 mm. All four types of steel had equivalent stress of 199.44 MPa. Highest FOS was observed in steel 4130 which was 2.2219 followed by the 4340 steel at 2.2702 and the 6150 steel at 2.0045. The 1020 steel had the lowest FOS at 1.4177. According to the tests 4130 and 4340 steels is supposed to be more suitable for high-impact resistance, because of their higher FOS. Steel 4340 had the best performance with respect to other steel grades.

Table 4. Represents the total deformation and factor of safety

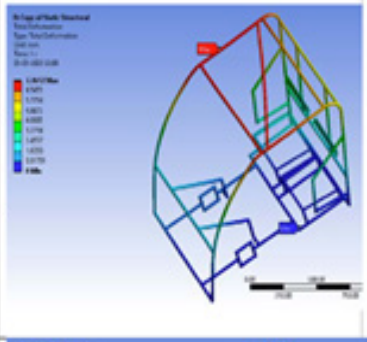
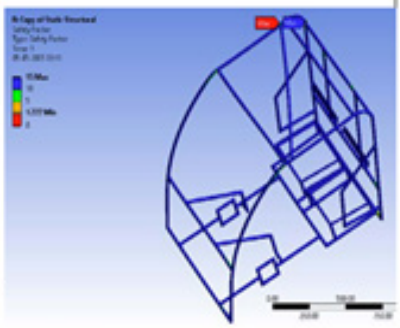
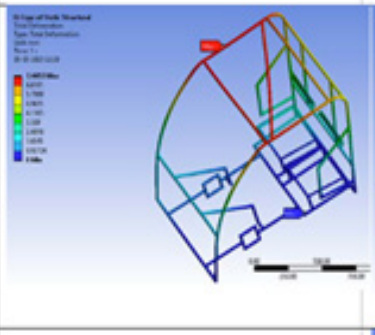
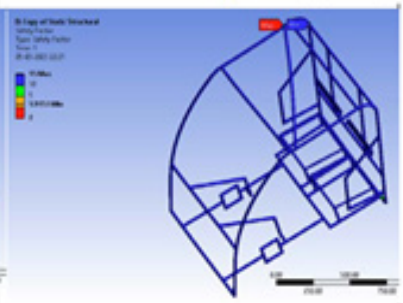
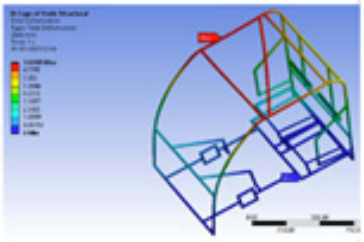
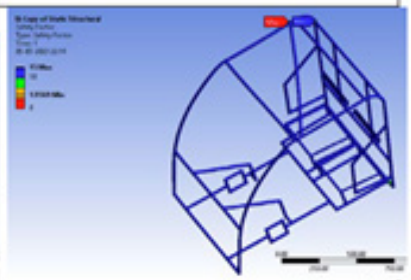
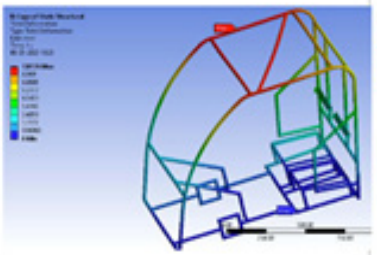
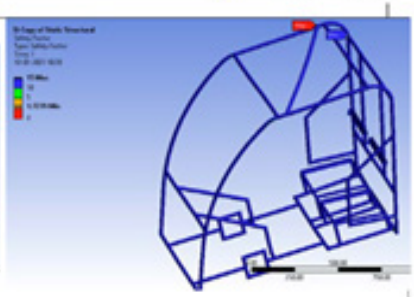
Material	Total Deformation	Factor of Safety
Steel (4340)		
Steel (1020)		
Steel (4130)		
Steel (6150)		

7.2 Side Impact Test

After measuring the deformation, equivalent stress, and factor of safety, the maximum impact resistance of each material was to be tested.

Maximum deformation was measured in (mm). The results show that the 1020 steel had the lowest deformation at 4.2244 mm, while the 6150 steel had the highest deformation at 4.5234 mm. All four types of steel had equivalent

Table 5. Represents the total deformation and factor of safety

Material	Total Deformation	Factor of Safety
Carbon Steel (1020)		
Carbon Steel (4130)		
Carbon Steel (4340)		
Carbon Steel (6150)		

stress of 249.51 Mpa. Highest FOS was observed in steel 4130 which was 2.0238, followed by the 4130 steel at 1.9807 and the 6150 steel at 1.787. The 1020 steel had the lowest FOS at 1.2638.

According to the tests 4130 and 4340 steels is supposed to be more suitable for high-impact resistance, because of their higher FOS. Steel 4340 had the best performance with respect to other steel grades.

7.3 Roll-Over Test

After measuring the deformation, equivalent stress, and factor of safety, the maximum impact resistance of each material was to be tested.

Table 6. Results of the front impact test

Materials	Deformation (mm)	Equivalent Stress (mPa)	Factor of safety (F.O.S)
Steel (1020) Maximum	3.4499	199.44	1.4177
Steel (4130). Maximum	3.489	199.44	2.2219
Steel (4340) Maximum	3.5745	199.44	2.2702
Steel (6150) Maximum	3.7045	199.44	2.0045

Table 7. Results of the side impact test

Materials	Deformation (mm)	Equivalent Stress (mPa)	Factor of safety (F.O.S)
Steel (1020) Maximum	4.2244	249.51	1.2638
Steel (4130) Maximum	4.2726	249.51	1.9807
Steel (4340) Maximum	4.3769	249.51	2.0238
Steel (6150) Maximum	4.5234	249.51	1.787

Table 8. Results of the roll over impact test

Materials	Deformation (mm)	Equivalent Stress (mPa)	Factor of safety (F.O.S)
Carbon Steel (1020) Maximum	7.3612	259.74	1.222
Carbon Steel (4130) Maximum	7.4453	259.74	1.9153
Carbon Steel (4340) Maximum	7.6269	259.74	1.9569
Carbon Steel (6150) Maximum	7.8176	259.74	1.7279

Maximum deformation was measured in (mm). The results show that the 6150 steel had the highest deformation at 7.8176 mm, while the 1020 steel had the lowest deformation at 7.3612 mm. All four types of steel had equivalent stress of 259.74 MPa. Highest FOS was observed in steel 4130 which was 1.9569, followed by the 4130 steel at 1.9153 and the 6150 steel at 1.7279. The 1020 steel had the lowest FOS at 1.222.

According to the tests 4130 and 4340 steels is supposed to be more suitable for high-impact resistance, because of

their higher FOS. Steel 4340 had the best performance with respect to other steel grades.

In Table 6, Due to their higher FOS steel 4340 and 4130 are suitable for resistance against the deformation of all kinds of front impact events.

In Table 7, Due to their higher FOS steel 4340 and 6150 are suitable for resistance against the deformation of all kinds of side impact events.

In Table 7, Due to its higher FOS steel 4340 is suitable for resistance against the deformation of all kinds of roll over events.

Considering all relevant factors, steel 4340 is the most suitable steel grade for different specification of problems.

It is also worth noting that the results presented in these tables may not apply to all applications and may need to be verified through additional testing.

8.0 Conclusion

We have successfully analyzed the roll cage frame of an Effi-cycle utilizing different materials and evaluated them based on their strength and safety against a variety of different collision environments. Through static structural and stress analysis, we have identified that AISI 4340 is the best material choice for the efficycle frame, also it has higher yield strength and strength-to-weight ratio as well compared to other materials in this study. The research findings give us the result that the Effi-cycle frame is deemed safe during front, side, and rollover impacts with a satisfactory Factor of Safety (FOS) of above 2 in the case of AISI 4340 steel material. The research also emphasizes the importance of material selection and optimization for weight, strength, and safety which have very important uses in the automotive industry.

The research limitations are the use of only 1 designed model on CATIA V5 and only 3 impact scenarios, and future research could add more impact tests on the frame.

9.0 References

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