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Analysis of a Lightweight Aluminum Vehicle Chassis in a Simulation-based Design Approach

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Abstract- This study investigates different chassis designs through a simulation-based design approach. The inherent aluminum ductility and softness could make chassis a daunting modification if not analyzed properly. Structural finite element analysis is comprehensively performed on a vehicle chassis for static loading cases up to 1G in equivalent acceleration. The analysis of the vehicle chassis of both A36 steel and 6061 aluminum for the scenarios of bump, front impact, side impact and a rollover. The von Mises stresses and displacement results showed that the steel chassis possessed higher safety factor in all load cases. The safety factors for an aluminum clone of the steel chassis in some load cases are below 1.0, hence indicating that the failure criterion has been triggered and failure would occur under the 1G load. The original aluminum chassis deformation is far more severe than steel reaching as high as 9.88 mm for the bump loading. A modified aluminum chassis is proposed, by optimizing the wall thickness of the rectangular bars. The slight increase in weight resulted in overcoming the deficiency of aluminum in load-carrying capacity. An evaluation matrix procedure is implemented to analyze the tradeoffs between cost, weight and safety factor for the three chassis materials.

Keywords: chassis design; finite element analysis; simulation.

I. Introduction

Most of the automotive manufacturers worldwide currently require that all new and modified manufacturing system designs be verified by simulation analysis before they are approved for final equipment purchases [1]. Studies performed in the past are indicators of how useful simulation could be in the design and operation of production systems of all kinds, including chassis manufacturing. Simulation is an essential stage of any chassis development to ensure proper functionality and safety under the anticipated loads. The objective of this paper is to develop a reliable chassis design according to standards and regulations in a simulation-based design approach [2, 3].

A chassis is the structural backbone of any vehicle. The chassis of a vehicle performs vital functions of protecting the driver and components within, as well as being a foundation to mount and assemble various drive systems on the vehicle. When a vehicle is in motion, it is subjected to stresses and vibrations induced by the roughness of the road, harsh weather conditions and the components within it. The design process of a vehicle chassis undergoes continuous modifications to full meet the requirements.

The chassis analyzed in this study is a small-sized chassis for a participating team within the Global Hybrid Electric Challenge (GHEC). The GHEC is the latest international collegiate competition promoting education, energy efficiency, and environmental consciousness [4]. The race is generally an efficiency race attempting to answer the question of “which team can drive the maximum distance given the same amount of energy?”. There are many factors that go into the equation of “maximum distance”, such as aerodynamics, acceleration, speed, tire conditions, driving style, and most importantly the overall vehicle weight. The weight of the A36 steel chassis currently in operation is around 12 kg. Considering the lightweight nature of the vehicle being around 70 kg in total excluding the driver, cutting a few kilograms from the chassis while maintaining stiffness will reap a lot of dividends.

This study investigates a lighter-weight alternative to the current chassis A36 steel which can withstand the high stress bump and collision scenarios. By using 6061 aluminum, the weight of the chassis is expected to reduce significantly to approximately one third of the current weight. The weight reduction saves energy, minimizes brake wear, improves steering, and cuts down emissions. However, the inherent aluminum ductility and softness could make it a daunting modification if not analyzed properly. Finite Element Analysis (FEA) is used to provide a reliable method for analyzing the effect of various load cases on the deformation and stress limits of the chassis structure by replacing the steel material with aluminum [5, 6].The scope of the study is to perform a structural FEA on the chassis body for static loading with up to 1G in equivalent acceleration. The analysis is based on linear elastic behavior of the vehicle chassis of both A36 steel and 6061 aluminum for the scenarios of bump, front impact, side impact and a rollover.

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II. Finite Element Analysis

a) Chassis 3D Model

A detailed 3D model of the chassis is developed in the ABAQUS software. A wire feature is used to represent the bars of the chassis, while assigning the corresponding profiles to each bar. Figure 1 below shows the model of the vehicle chassis with the assigned section profiles.

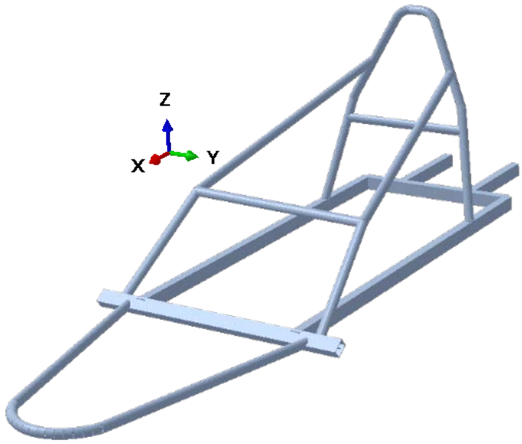

Figure 1: The 3D model of the vehicle chassis.

The rectangular and circular section profiles are shown in Figure 2 (a) and (b), respectively.

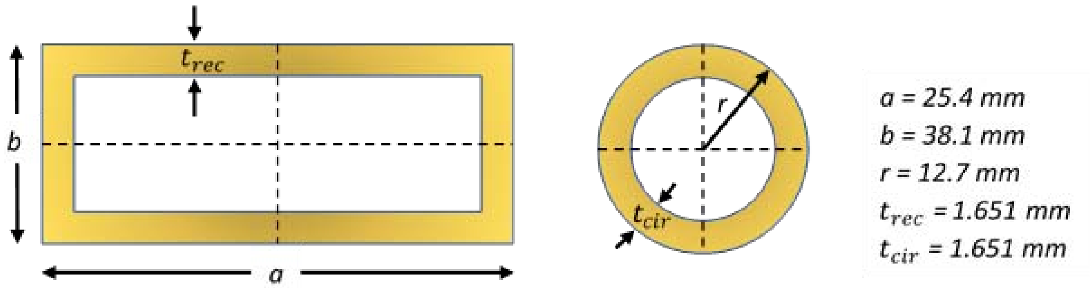

Figure 2: Original steel and aluminum chassis design section profiles (a) rectangular and (b) circular.

b) Material Definition

The mechanical response of the A36 steel and 6061 aluminum are listed in Table 1.

Table 1: Mechanical properties of A36 steel and 6061 aluminum [7, 8].

Property	A36 steel	6061 aluminum
Young's Modulus	200.0 GPa	68.9 GPa
Density	7,850 kg/m^3	2,700 kg/m^3
Poisson's Ratio	0.26	0.33
Yield Strength	250.0 MPa	55.0 MPa
Ultimate Tensile Strength	400.0 MPa	124.0 MPa

c) Original Design - Analysis

The structural FEA is performed on the two chasses with static loading. Each analysis is carried out for both A36 steel and 6061 aluminum. Several impact scenarios are simulated, which are: bump, front impact, side impact and rollover. The load cases for each scenario is defined as per the following:

i. *Bump (torsional test):* Fix rear and one front wheel, apply vertical load at third wheel (1G) [9].The vehicle speeds are fairly low, on the order of 45 kph, and the races are generally held on a smooth racetrack with flat run-off areas, so the 1G bump is a reasonable load. Figure 3 (a) below shows the bump loading conditions. The torsional stiffness/rigidity of the chassis is often an important measure of how much the chassis will twist under the loads transferred to it from the suspension.

ii. *Front impact:* Fix the wheels and apply 1G longitudinal load at bumper apex. The vehicles are of a comparable mass, and if they collide, the vehicles will slide with a tire/ground friction force that is less than 0.8G equivalent acceleration. Therefore, a 1G front impact force is adequate. Figure 3 (b) below shows the front impact loading conditions.

iii. *Side impact:* Fix the wheels and apply 1G lateral load distributed across 10 – 15 cm. This value is selected based on the same reasoning of the front impact load case. Figure 3 (c) below shows the side impact loading conditions.

iv. *Rollover (roll hoop) impact:* Fix the frame and apply a 1G vertical load on the roll hoop apex. This is based on the regulations that dictate a 1G load to be applied at the apex of the roll hoop. Figure 3 (d) below shows the rollover loading conditions.

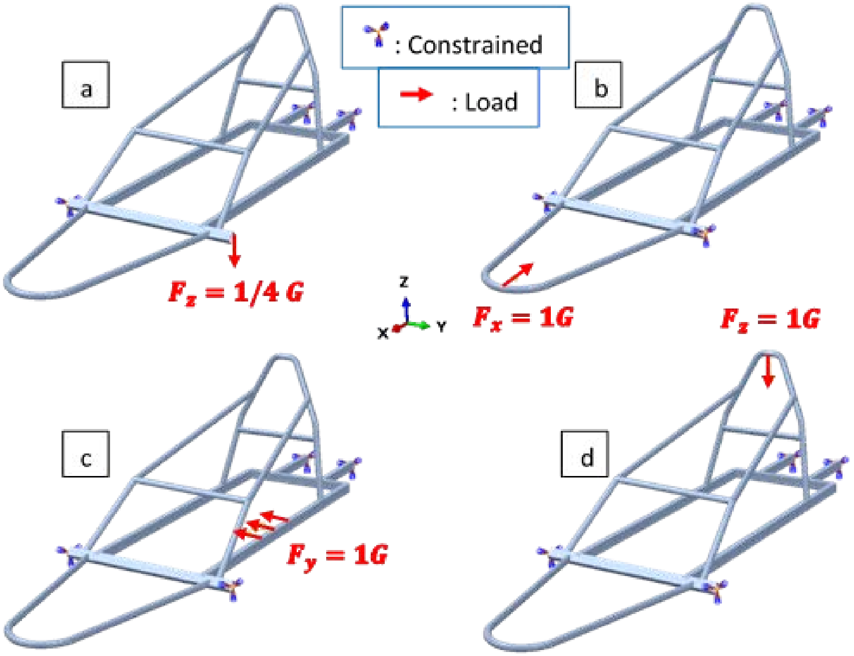

Figure 3: FEA loading conditions of the a) bump b) front impact c) side impact d) rollover.

d) Original Design - Results

The chassis models made of steel and aluminum weigh 11.9 kg and 4.1kg, respectively. The weight reduction advantage of using aluminum over steel is significant, resulting in a final mass that is 35% of the initial steel chassis mass.

The von Mises stress distributions as a result of the bump/torsional load for A36 steel and 6061 aluminum are shown in Figure 4.

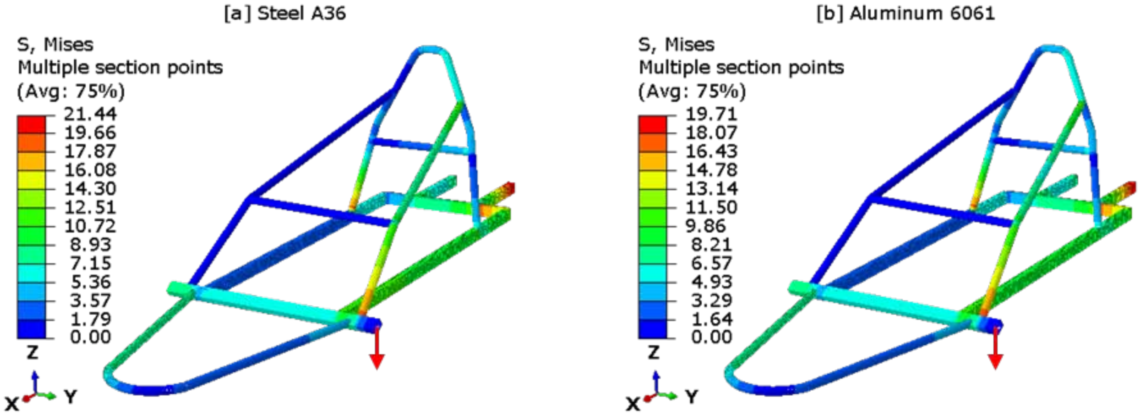

Figure 4: The von Mises stresses of the torsional test for a) A36 steel b) 6061 aluminum.

The von Mises stress distributions of the front impact for A36 steel and 6061 aluminum are shown in Figure 5.

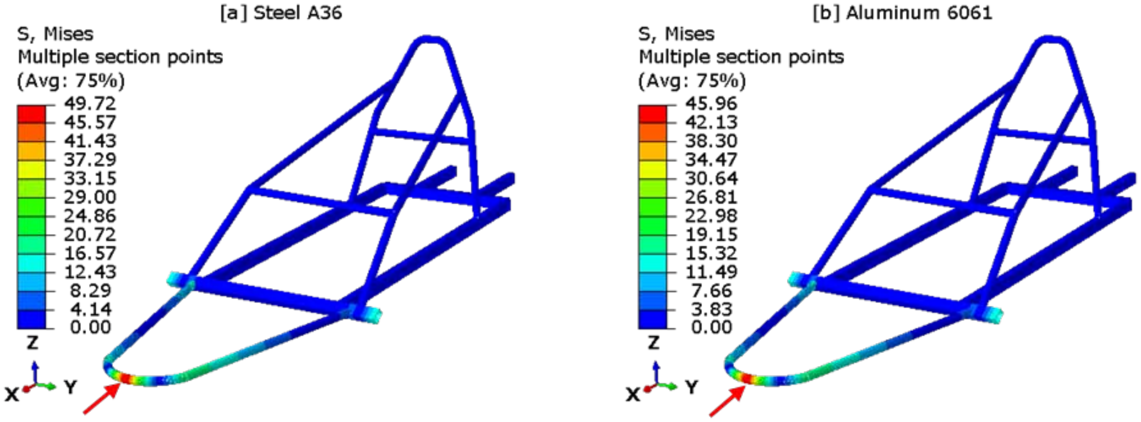

Figure 5: The von Mises stresses of the front impact test for a) A36 steel b) 6061 aluminum.

The von Mises stress distributions of the side impact for A36 steel and 6061 aluminum are shown in Figure 6. The stress in this case exceed the yield strength of 6061 aluminum ($\sigma_y = 55$ MPa) and hence will cause chassis plastic deformation/failure.

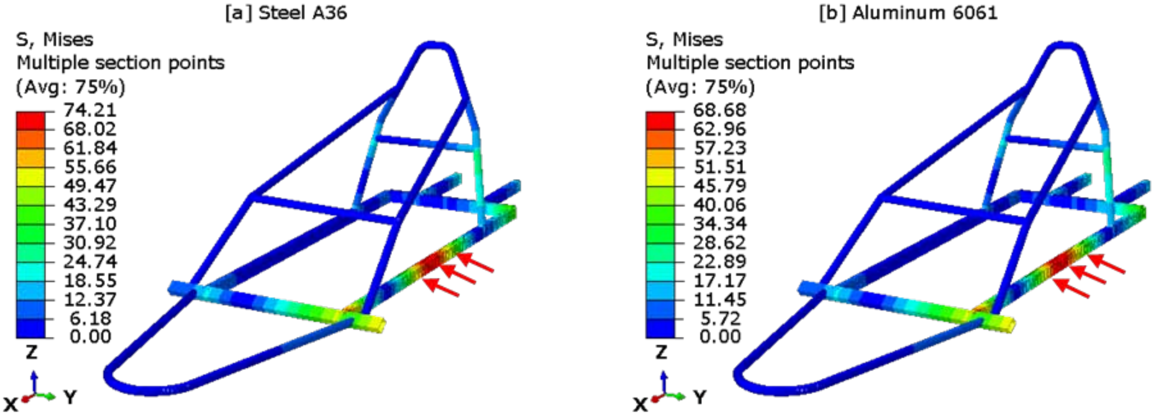

Figure 6: The von Mises stresses of the side impact test for a) A36 steel b) 6061 aluminum.

The von Mises stress distributions of the rollover impact for A36 steel and 6061 aluminum are shown in Figure 7. The stress in this case exceed the yield strength of 6061 aluminum ($\sigma_y = 55$ MPa) and hence will cause chassis plastic deformation/failure.

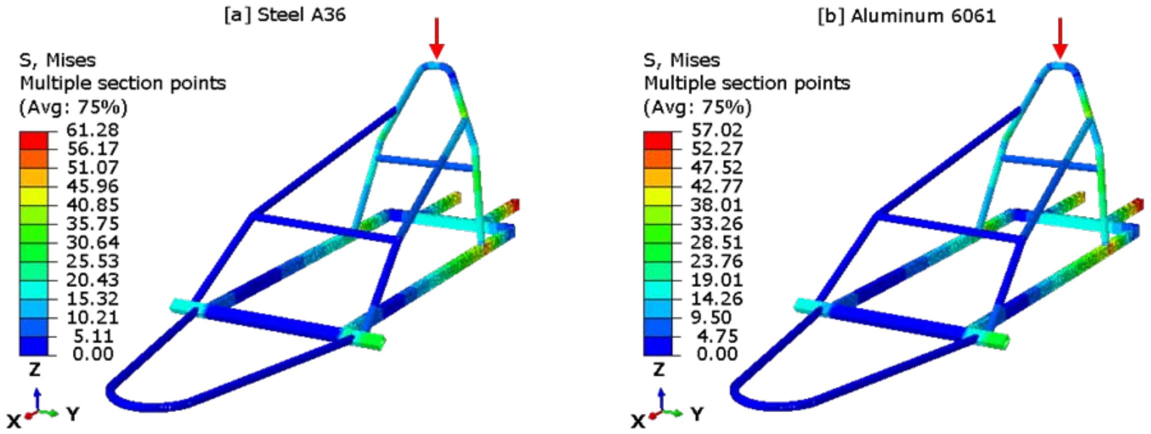

Figure 7: The von Mises stresses of the rollover impact test for a) A36 steel b) 6061 aluminum.

The 1G equivalent acceleration force applied to the steel chassis is calculated as follows:

$$F = m_{total\ ,\ steel} * g = 100\ kg * 9.81 m/s^2 = 981.0\ N \tag{1}$$

The 1G equivalent acceleration force applied to the aluminum chassis is calculated as follows:

$$F = m_{total\ ,Aluminum} * g = 92.2\ kg * 9.81\ m/s^2 = 904.5\ N \tag{2}$$

The displacements due to the bump/ torsional load for A36 steel and 6061 aluminum are shown in Figure 8. The deformation is visually scaled by 10. Both deformations of steel and aluminum are high. The aluminum deformation is far more severe than steel reaching up to 9.88 mm.

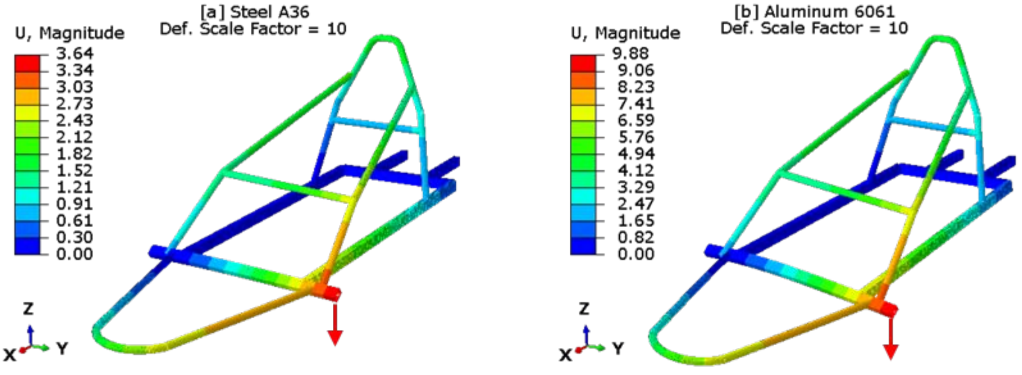

Figure 8: The displacements of the torsional test for a) A36 steel b) 6061 aluminum.

The displacements due to the front impact for A36 steel and 6061 aluminum are shown in Figure 9. The deformation is visually scaled by 10. Minimal deformations are shown in the front impact test (less than 1 mm).

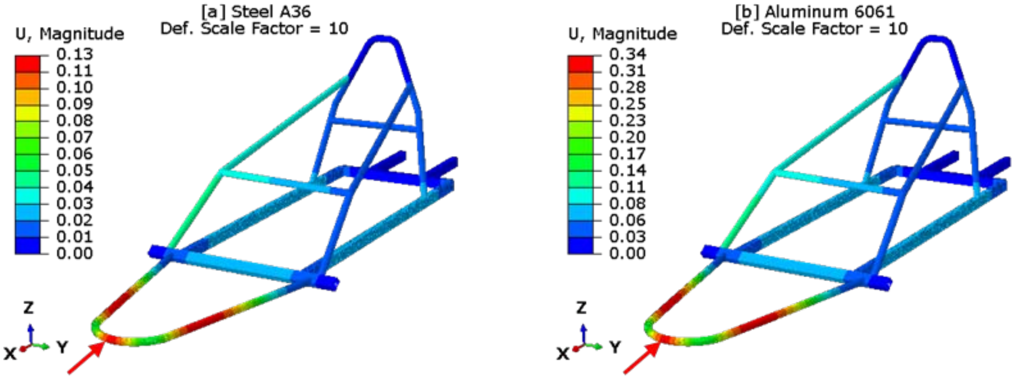

Figure 9: The displacements of the front impact test for a) A36 steel b) 6061 aluminum.

The displacements due to the side impact for A36 steel and 6061 aluminum are shown in Figure 10. The deformation is visually scaled by 10. Intermediate deformations are shown in the side impact test, reaching up to 5.36 mm in the aluminum frame.

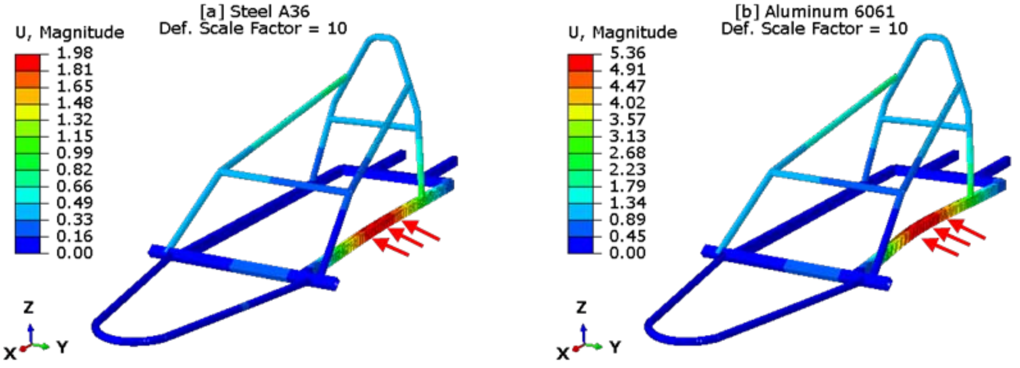

Figure 10: The displacements of the side impact test for a) A36 steel b) 6061 aluminum.

The displacements due to the rollover for A36 steel and 6061 aluminum are shown in Figure 11. The deformation is visually scaled by 10. Intermediate deformations are shown in the rollover test, reaching up to 6.53 mm in the aluminum frame.

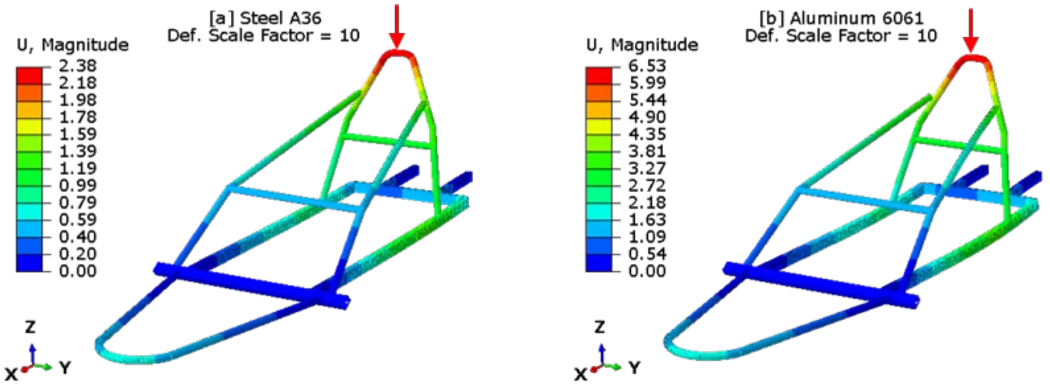

Figure 11: The displacements of the rollover test for a) A36 steel b) 6061 aluminum.

e) Modified Design – Analysis

Since the von Mises stress in the cases of side impact and rollover exceeded the yield strength of 6061 aluminum, additional material is added to the thickness of the rectangular tubes of the same aluminum model. The modified aluminum design section profiles are shown in Figure 12, at which the thickness of the rectangular tube is increased to 3.175 mm. This addition shall add to the chassis load-carrying capacity under the specified load cases, accompanied with a slight increase in weight. Similar load cases to those presented in Section 2.3 are applied to the modified aluminum chassis design.

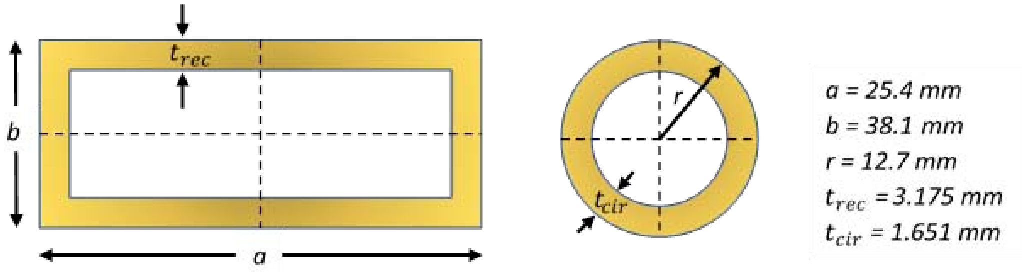

Figure 12: Modified aluminum chassis design section profiles (a) rectangular and (b) circular.

f) Modified Design –Results

The modified aluminum chassis model weighs 5.85 kg. This little compromise in weight (increasing from 4.1 kg) is expected to add the necessary stiffness to maintain a stress value below the yield strength of aluminum in all load cases. The mass of this modified aluminum chassis is around 50% of the original steel chassis mass. The von Mises stress distributions as result of the bump, front impact, side impact and rollover for the modified 6061 aluminum are shown in Figure 13 (a), (b), (c) and (d), respectively.

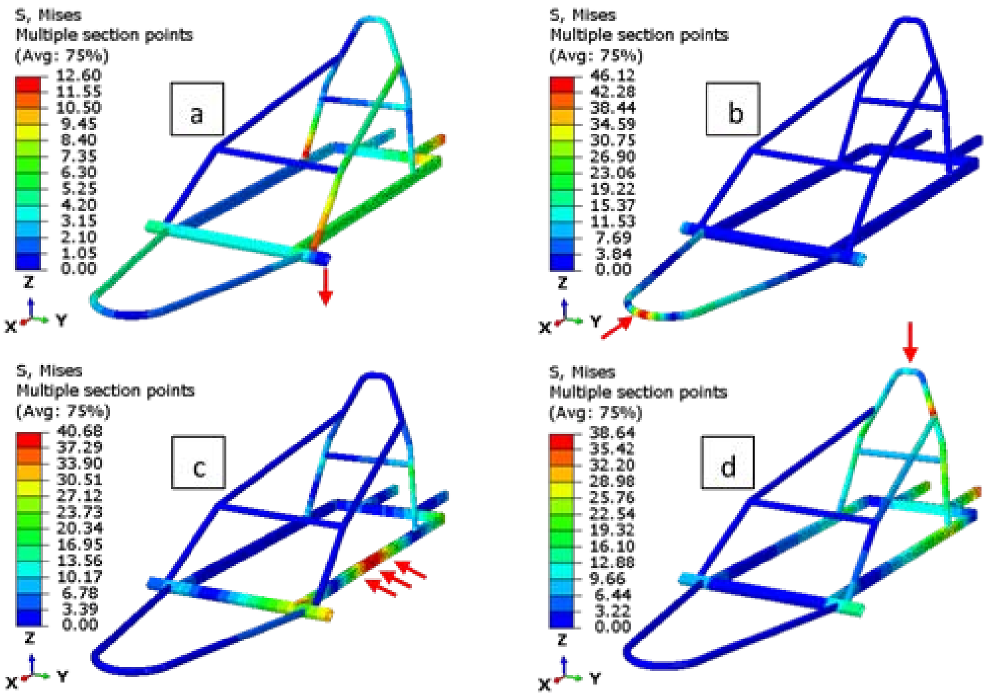

Figure 13: The von Mises stresses of the modified chassis during a) bump b) front impact c) side impact d) rollover.

The displacements as result of the bump, front impact, side impact and rollover for the modified 6061 aluminum are shown in Figure 14 (a), (b), (c) and (d), respectively. The deformations are visually scaled by 10. The modified aluminum chassis deformation is less severe than that of the original steel and aluminum.

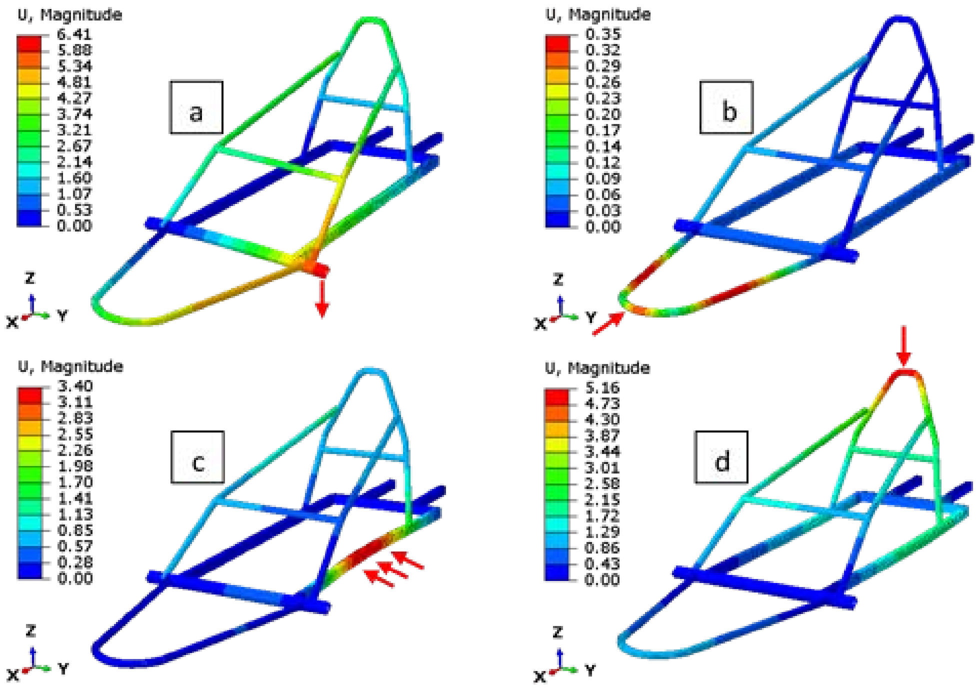

Figure 14: The displacements of the modified chassis during a) bump b) front impact c) side impact d) rollover.

III. DISCUSSION

To identify failure occurrence, a conservative failure criterion is used, the material will fail (yield) when the maximum von Mises stress exceeds the yield strength σ_y of each material. The safety factor for each of the impact scenarios for each material is calculated using the formula $SF = \sigma_y / \sigma_{VM,max}$ and the results are summarized in Table 2. Within the table, the green-colored numbers indicate no failure ($SF > 1.0$), while red-colored numbers indicate failure (SF≤ 1.0). It is evident that steel possesses the higher safety factor in all load cases, and hence has a lesser likelihood of failure. However, both A36 steel and the modified 6061 aluminum' safety factors are within a safe window, indicating a minimum SF of 1.19 for the aluminum front impact scenario. Since these safety factors are above 1.0, the failure criterion has not been triggered and hence no failure occurrence on a 1G load. In contrast, the safety factors of the original 6061 aluminum chassis during side impact and rollover cases are below 1.0, which indicate failure occurrence. Figure 15 shows a bar plot of the SF for steel, original aluminum and modified aluminum under all loading scenarios.

Table 2: The safety factor (SF) for each impact load scenario for A36 steel and 6061 aluminum.

	A36 steel	6061 aluminum t_{rec}= 1.651mm	6061 aluminum t_{rec}= 3.175mm
SF for Bump	11.66	2.79	4.37
SF for Front impact	5.03	1.20	1.19
SF for Side impact	3.37	0.80	1.35
SF for Rollover	4.08	0.96	1.42

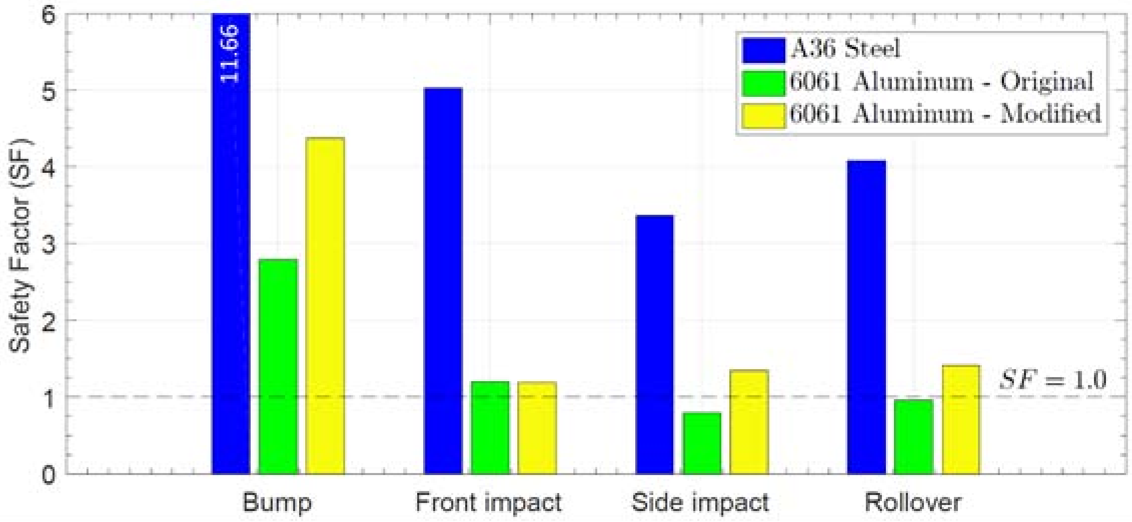

Figure 15: Bars plot of SF for steel and two aluminum chassis under the different loading scenarios.

A summary of the maximum displacements for each material and load case is presented in Table 3. It is expected that aluminum undergoes the higher strain since it is more ductile than steel.

Table 3: Maximum displacements for each material and load case.

	A36 steel [mm]	6061 aluminum t_{rec}= 1.651mm	6061 aluminum t_{rec}= 3.175mm
Max. disp. - bump	3.64 mm	9.88 mm	6.41 mm
Max. disp. - front impact	0.13 mm	0.34 mm	0.35 mm
Max. disp. - side impact	1.98 mm	5.36 mm	3.40 mm
Max. disp. - rollover	2.38 mm	6.53 mm	5.16 mm

IV. EVALUATION METRICS

Since the material selection of the chassis is a tradeoff between cost, weight, and failure safety factor, the following evaluation matrix shown in Table 4 is used. The Cost scores are based on the current local market and fabrication prices of the A36 steel and 6061 aluminum. The Weight and SF scores are extracted from the FEA results. The overall scores are generic and must always be accompanied with the explanation of the compromise of benefits.

Table 4: Evaluation Matrix for chassis material selection.

	A36 steel	6061 aluminum t_{rec}= 1.651mm	6061 aluminum t_{rec}= 3.175mm
Cost	4	5	4
Weight	2	5	4
Safety Factor (*SF*)	5	0	4
Score (out of 15)	11	10	12

For the cost criterion, the following scoring system is used:

$$Cost\ [USD]\begin{Bmatrix} Cost < 200 \rightarrow 5 \\ 200 \leq Cost < 500 \rightarrow 4 \\ 500 \leq Cost < 700 \rightarrow 3 \\ 700 \leq Cost < 1000 \rightarrow 2 \\ Cost \geq 1000 \rightarrow 1 \end{Bmatrix} \tag{3}$$

The raw material and fabrication costs for the steel, original aluminum and modified aluminum chassis are 371.00USD, 189.25USD and 210 USD, respectively. Hence, the score for steel cost is 4 points, 5 points for the original aluminum and 4 points for the modified aluminum.

As for the weight criterion, the following scoring system is used:

$$Weight[kg]\begin{Bmatrix} Weight < 5 \rightarrow 5 \\ 5 \leq Weight < 6 \rightarrow 4 \\ 6 \leq Weight < 9 \rightarrow 3 \\ 9 \leq Weight < 12 \rightarrow 2 \\ Weight \geq 12 \rightarrow 1 \end{Bmatrix} \tag{4}$$

The weights given from FEA for the steel, original aluminum and modified aluminum chasses are 11.9 kg, 4.1 kg and 5.85 kg, respectively. Hence, the score for steel weight is 2 points, 5 points for the original aluminum and 4 points for the modified aluminum.

As for the SF criterion, the following scoring system is used:

$$SF\begin{Bmatrix} SF > 5 \rightarrow 5 \\ 4 < SF \leq 5 \rightarrow 4 \\ 3 < SF \leq 4 \rightarrow 4 \\ 1 < SF \leq 3 \rightarrow 2 \\ SF \leq 1 \rightarrow 0 \end{Bmatrix} \tag{5}$$

The minimum safety factors (most severe case) are taken into consideration in the evaluation matrix. The minimum SF scores are taken from Table 2. The SF score for steel is 5 points, 0 points for the original aluminum and 4 points for the modified aluminum.

While chassis safety is one the most important aspects for the survival of the driver and the vehicle, weight reduction is a critical race-winning factor. Therefore, the decision of fabricating the chassis out of steel or aluminum cannot be simply made by accounting for the evaluation matrix numbers, especially when the score numbers are quite close (10, 11 and 12 points). Rather, factors like the difficulty and aggressiveness of the racetrack in terms of turns radii, surface roughness and berms steepness must be considered. These factors will either decrease or increase the likelihood of failure, and hence will necessitate conservative or non conservative design decisions.

V. CONCLUSIONS

The objective of this paper was to develop a reliable chassis design according to standards and regulations in a simulation-based design approach. The weight of the A36 steel chassis currently in operation is around 12 kg. Considering the lightweight nature of the vehicle being around 70 kg in total excluding the driver, cutting a few kilograms from the chassis while maintaining stiffness will reap a lot of dividends. This study investigated a lighter-weight 6061 aluminum alternative to the current chassis A36 steel which can withstand the high stress collision scenarios. By using 6061 aluminum, the weight of the vehicle is expected to reduce significantly to approximately one third of the current weight. However, the accompanied aluminum ductility and softness could make it a daunting modification if not analyzed properly. A structural FEA was performed on the chassis body for static loading up to 1G equivalent acceleration. The analysis is based on linear elastic behavior of the vehicle chassis of both A36 steel and 6061 aluminum for the scenarios of bump, front impact, side impact and a rollover.

From the static stress analysis results, it was evident that steel possessed the higher safety factor in all load cases, and hence has a less likelihood of failure. However, aluminum chassis yielded unacceptable SF, given the same cross section tubes are used to that of steel. The SF was increased for aluminum by adding more material (thickness), but that has also resulted in higher mass. Overall, the final chosen geometry yielded an optimal design which provided the lightest possible chassis while still maintaining an acceptable SF of over 1.0.

An evaluation matrix procedure was attained to analyze the tradeoff between cost, weight and safety factor for the three chassis designs. Steel scored a total of 11 out of 15 points, while the original aluminum scored of 10 out of 15 points, and finally 12 out of 15 points for the modified aluminum. Although chassis safety is one of the most important aspects for the survival of the driver and the vehicle, weight reduction is a critical race-winning factor. Hence, with a little compromise in steel SF, an advantageous weight reduction is achieved. Nevertheless, caution and care are required when exceeding the anticipated loading conditions of 1G.

In the future, factors like the difficulty and aggressiveness of the racetrack in terms of turns radii, surface roughness and berms steepness will be considered. These factors will either decrease or increase the likelihood of failure, and hence will necessitate conservative or non conservative design decisions.

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