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DESIGN, FABRICATION AND TESTING OF A PROTOTYPE VEHICLE CHASSIS FOR ECO-MARATHON CHALLENGE

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ABSTRACT
A vehicle chassis refers to the main support structure of the vehicle to which all components and automobile systems are attached. The chassis gives shape and rigidity to the vehicle and aids in supporting the various loads applied to the vehicle. Firstly, the detailed design and finite element analysis of a prototype go-cart for the eco-marathon challenge were documented. Secondly, Analytical method is used to calculate the shear forces (SF) and bending moment (BM) of the chassis and their corresponding SF and BM diagrams are provided. The maximum SF and BM value calculate are 528.96 N and 310 N.m respectively. In addition, aluminum alloy profiles were objective selected over the conventional steel, because it's lightweight coefficient which is significant for racing vehicle overall performance. The strength and durability of chassis are determined by engineering design principles. The vehicle was constructed from available local materials and welding as the major joining process. Finally, all other parts of the vehicle were attached to the chassis including the body and it was tested extensively for functionality and safety before going to compete at the Shell eco-marathon challenge. This work also delivers an indigenous technology and engineering template for prototype vehicle chassis design for young engineers in the field of eco-marathon and motorsports in general that may have technology and facilities constrain.
Keywords: *Chassis design, Shell eco-marathon, Prototype vehicle, Energy efficient and FEA.*

INTRODUCTION
A vehicle chassis refers to the main support structure or backbone of the vehicle Patil, *et al.* (2013) to which every component of the vehicle is mounted and all automobile systems are attached. It is the most important structural member of any automobile Mahadeokar and Choudhary, (2014). It can also be referred to as the foremost component that acts as the frame to support an automobile body Sanjay, *et al*. (2014). All vehicle bodies have two parts - the chassis and bodywork or superstructure Karaoglu and Kuralay, (2002). The heavy framework of chassis is the main place for all the components of the vehicle, including the vehicle body that is being mounted and fastened with screws to the chassis Srinivasan, (2007), Naveen and Kumar, (2014). The chassis gives shape and rigidity to the vehicle and aids in supporting the various loads applied to the vehicle. A wide range of chassis design selection has been employed over the years to meet customer need and payload application Nora, *et al*. (2012) which is not the focus here. In this work, emphasis is on the detail design of the chassis of a prototype go-cart specifically designed for the Shell eco-marathon annual challenge. According to Kumar and Deepanjali (2016) the chassis of vehicles need to possess high strength with a good factor of safety. This is necessary because, in most applications, these vehicles are subjected to higher stresses beyond their design limit.

Vehicle design mostly involves a trade-off between performance and safety Veloso, *et al.* (2009) to obtain a good chassis design with an excellent performance features such as economy of operation, durability, strength, low centre of gravity, stability and load clearance must be considered closely Narang, (2009):

To ensure that the above criteria are conform to, a lot of time and resources is put by automobile into the design, analysis and material selection for automobile chassis using the V-shape method. The design of the chassis frame should be as light as possible to obtain a good efficiency in fuel consumption Mat and Ghani, (2012). In addition to resist the distorting forces is critical Narang, (2009); some of the undesirable forces are weight of the components and that of the automobile user which results in sagging due to bending effects and horizontal forces caused by road irregularities Upward twisting forces caused by road shocks due to torsional effect

These dynamic forces may induce stresses that may cause members to fail Topac *et al.*(2009). To make up for the bending and torsional effects, the need arises to consider the chassis section. The most common chassis sections used are – channel, tubular and box sections. Channel section provides a good resistance to bending but poor in torsion, while box sections provide a good resistance to torsion and bending forces Babu and Singh, (2014). As stated by Wright, (2014) "The US automotive industry is the steel makers' second most important market, but they face a growing challenge from aluminum manufacturers". With the combination of favorable properties found in aluminum, modern day automobile manufacturers are increasingly turning to aluminum for use in the fabrication of automobile chassis.

Moaaz and Ghazaly, (2014), argued that, finite element stress analysis plays an important role in the design stages of a truck chassis and the vehicle structure is of fundamental importance to the overall vehicle performance and functionality. Hence, for the structural integrity of the vehicle chassis not to be compromised, finite element analysis method is used to analyzed chassis structure and validated with the analytical calculations.

MATERIALS AND METHOD

In the overall design of the prototype vehicle chassis, the main design factors considered based on their importance to the overall vehicle performance are the strength, safety, durability, efficiency, cost, maintainability, and ease of assembly.

The materials selected for the chassis will determine the strength of the system and its limits before failure may occur. Therefore, the material must be selected by adequate objective material selection method, proven equations and computer aided design simulation method. These are to ensure that the optimal material fit for purpose is chosen. A3-D model of the chassis was developed using INVENTOR® and finite element analysis (FEA) was conducted to investigate the principal stresses and deformation. Material selection for the chassis was done using the formalization of design procedure as used by Charles and Crane, (1989) considering all the above-stated design criteria. Aluminum alloy was selected and a hollow box section was used for the fabrication by the means of arc welding as the major joining process. The Aluminum arc welding process was possible with the used of special Aluminum electrode and expert welders. Analytical calculations of stresses, strain and deformation were done for chassis design and the resulted values were used for the validation of FEA results.

Materials

Material selection

According to Charles and Crane, (1989), the choice of material is to be made with the economy of time and effort, with the assurance that no design factor is overlooked, and taking cost into consideration.

The material selection for the vehicle chassis was done by paying attention to the design considerations of this project. Thus, the material used for the chassis must be the lightest material that will accommodate the maximum loads with minimum deflection and adequate strength to withstand the accompanying stresses. The data for the different alternatives was obtained from the American Society of Metals (ASM) materials data sheet, ASM (2016).

From the ratings obtained from the objective material selection procedure, the aluminum alloy had the highest overall rating and was employed for fabrication of the chassis. Thus, Aluminum-6061 material with element definition hollow-square-pipe of $30\ \text{mm} \times 30\ \text{mm}$ with a thickness of 3 mm. The thickness of the hollow Aluminum square-pipe aids the use of aluminum-arc welding for joining process.

Method

Method development

The 3-D model was developed using INVENTOR® and in accordance with the Shell eco-marathon global rules 2016, Shell (2016). The wireframe and part designs are depicted in Figure 1 and 2.

Table 1: Alternative materials and their properties

Alternatives	**Yield stress σ_{YS} (MPa)**	**Fracture toughness $K_C(MPa.m^{\frac{1}{2}})$**	**Density $\rho(g/cm^3)$**	**Modulus of elasticity $E(GPa)$**
Aluminium alloy	648	28	2.800	71.7
Magnesium alloy	285	20.7	1.800	42
Mild steel ASTM – A36	250	50	7.850	200
Titanium	880	75	4.430	113.8

MatWeb (2016)

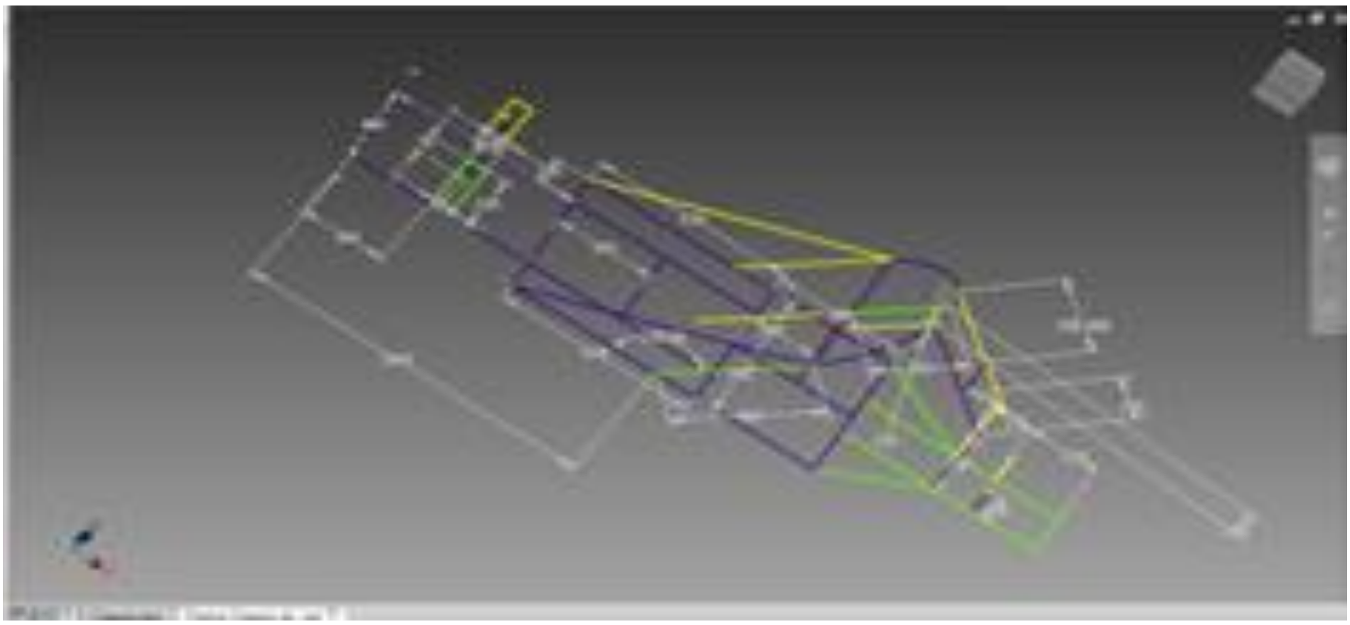

Figure 1: Wireframe of chassis

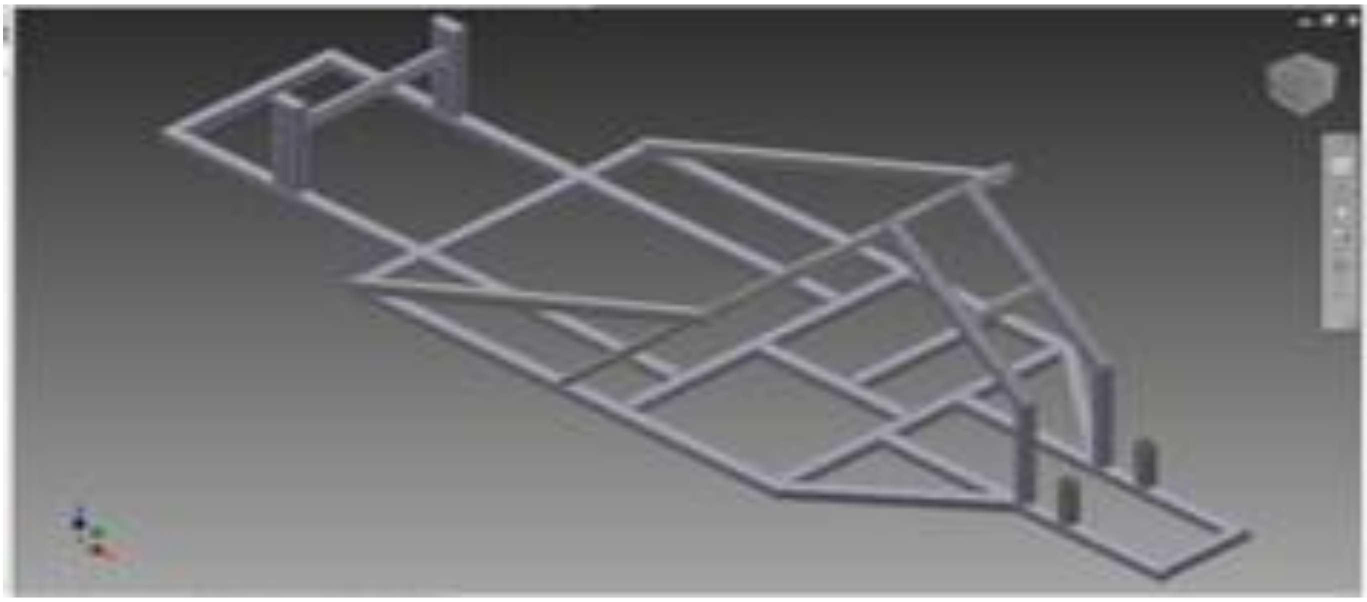

Figure 2: Part design of chassis

Analytical Calculations
Bending Stress

The bending stress of a member is the resistance offered by the internal stresses to resist bending. Correspondingly, the shear stress of a member is the resistance offered by the internal stresses provided to resist shear. Figure 3 shows a cross-section of the square beam.

where, L_o = length of outer cross-section and L_i = length of inner cross-section, the moment of inertia, I is given as:

$$I = \frac{Lo^4 - Li^4}{12} \quad (1)$$

where, $Lo = 0.03\text{m}$, and $Li = 0.024$.

Therefore, $I = \frac{Lo^4 - Li^4}{12} = 3.985 \times 10^{-8}\text{m}^4$.

In order to calculate the maximum bending moment of the chassis, we assume the chassis is a simple strength beam supported at both ends with central load acting on it as show in Figure 4.

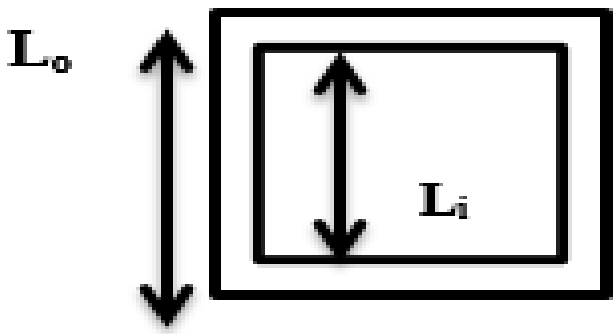

Figure 3: Square box section

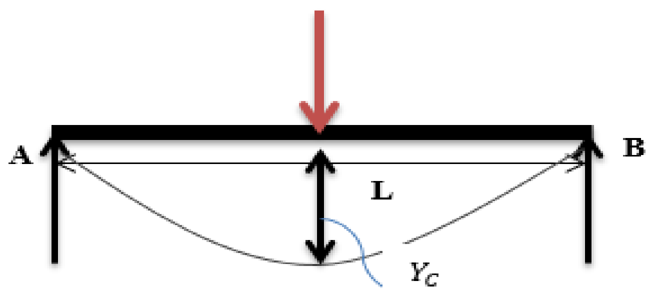

Figure 4: Beam pivoted at both ends with a central load

where, P = Total load on chassis and L = total length of chassis. The Maximum bending moment of the beam is the maximum force that tends to bend the beam. For a beam pivoted at both ends with a central load the Maximum bending moment M_{max} is given as:

$$M_{max} = \frac{PL}{4} \quad (2)$$

The bending stress σ_b of the chassis can then be determined from the basic bending equation, which is:

$$\frac{M}{I} = \frac{\sigma_b}{Y} = \quad (3)$$

where, $M_{max} = M$, I = Moment of inertia, Y = distance from center axis to the stressed surface, R = radius of gyration, and E = Modulus of Elasticity.

Given that total load P, on chassis as can be seen in the shear force diagram (SFD) and bending moment diagram (BMD),
$P = 568.98 + 269.78 + 338.445 = 1177.21$ N
From equation (2) Maximum bending moment,

$$M_{max} = \frac{PL}{4} = 676.89 \text{ Nm}.$$

where, L=length of chassis = 2.3 m.

Consequently, the bending stress is obtained by making σ_b subject in Equation 3.
where, $M_{max} = M$, and Y = 0.015 m.

$$\sigma_b = \frac{M \times Y}{I} = 254789209.50 \text{ N/m}^2$$

Shear Stress
The shear stress is obtained from the basic twisting moment equation, which is given as:

$$\frac{T}{J} = \frac{\tau}{r} \quad (4)$$

where, T = Torque provided by the car engine, J = polar moment of inertia, τ = shear stress, and r = distance of mid-point of the cross-section to the surface being stressed.

We know from fundamental strength of material that Polar moment,

$$J = I_{XX} + I_{YY} \quad (5)$$

For square hollow pipe $J = \frac{Lo^4 - Li^4}{6}$ (6)

From Equation 6 the polar moment of the square hollow section of the chassis is given as:

Polar Moment, $J = \frac{Lo^4 - Li^4}{6}$

$$J = \frac{Lo^4 - Li^4}{6} = \frac{0.03^4 - 0.024^4}{6}$$

$$J = 7.97 \times 10^{-8} \text{m}^4$$

where, Torque (T) provided by the engine is10.3 Nm. Making τ subject in Equation 4.

Given that r = 0.015 m

$$\tau = \frac{Tr}{J} = \frac{10.3 \times 0.015}{7.97 \times 10^{-8}}$$

$$\tau = 1938422.16 \text{N/m}^2$$

Deflection of Chassis
Deflection is a very important factor to be considered in load bearing structures such as beams and cantilevers. Whenever a beam or a cantilever is loaded, it is observed to deflect from its original position. The deflection of beams and cantilevers depends on two important design criteria: strength and stiffness. The beam should have an adequate strength and stiffness not to deflect to an unsafe extent under the action of the load.

Deflection of chassis =

$$\frac{W \times (b-X)}{24EI}[X(b-X) + b^2 - 2(C^2 + a^2) - \frac{2}{b}[XC^2 + a^2(b-X)]] \quad (7)$$

where, wheel base = b, front overhang = a, rear overhang = b, and weight on chassis,

$$W = \frac{\text{Total weight on chassis}}{2} \quad (8)$$

In order to calculate for deflection, we make use of Equation 7.
From Equation (8), Weight of chassis, $W = \frac{1177.205}{2} = 588.60$ N

$$X = \frac{\text{Length of chassis}}{2} = \frac{2.3}{2}$$

$$X = 1.15\text{m}$$

Deflection of chassis =

$$\frac{W \times (b-X)}{24EI}\left[X(b-X) + b^2 - 2(C^2 + a^2) - \frac{2}{b}[XC^2 + a^2(b-X)]\right]$$

Deflection of Chassis = 0.0156 m

Failure Criterion
The failure criterion used in this case is the Von Mises Stress Criterion. According to Kumar, et al., (2008), the Von-Mises Stress is given as;

$$\sigma_v = \sqrt{\sigma_b{}^2 + 3\tau^2} = 254816149 \text{ N/m}^2$$

Von-Mises Stress, $\sigma_v = 255$ MPa

Shear Force and Bending Moment Diagrams of Chassis
The shear force and bending moment diagrams are very important, as they give details of how the shear force and bending moment varies at each section of the chassis. Assuming the vehicle chassis is a simple beam, containing the appropriate loading effect, the shear force and bending moment were calculated numerically at every section as presented below.

Determination of Reactions
Chassis was considered as a simple beam supported at B and E corresponding to the front and rear wheel axles respectively. Let,
R_B = reaction at front wheel B
R_E = Reaction at rear wheel E, [Figure 5].

The condition for equilibrium of the beam is as stated below;
Total upward forces = Total downward forces

$R_B + R_E =$ total downward force on chassis
$= 1117.21$ N

Taking moment about E:
$R_B \times 1.72 + 147.15 \times 2.01 \times 0.145 = 568.95 \times 1.06 + 147.15 \times 2.01 \times 1.005 + 269.78 \times 0.33$
$R_B = 571.63$N
$R_E = 605.57$N

Calculations for Shear Force
$F_A = 0$N
$F_B = 0 - (147.15 \times 0.29) + 571.633 = 528.96$N
$F_C = 528.959 - (147.15 \times 0.66) - 568.98 = -137.14$N
$F_D = -137.140 - (147.15 \times 0.73) - 269.78 = -514.34$N
$F_E = -514.340 - (147.15 \times 0.33) + 605.572 = 42.67$N
$F_F = 0$N

Calculations for Bending Moment
$M_A = 0$N
$M_B = -147.15 \times \frac{0.29^2}{2} = -6.19$ Nm
$M_C = -147.15 \times \frac{0.95^2}{2} + 571.633 \times 0.66 = 310.88$ Nm
$M_D = 571.633 \times 1.39 - 568.98 \times 0.7 - \left(147.15 \times \frac{1.68^2}{2}\right) = 171.56$ Nm
$M_E = -147.15 \times \frac{0.29^2}{2} = -6.19$ Nm
$M_F = 0$ Nm

The shear force and bending moment were then plotted as ordinate, with all positive values plotted above the abscissa and negative values below the abscissa, and the position of the beam taken as the abscissa. The SFD and BMD are as shown Figure 5.

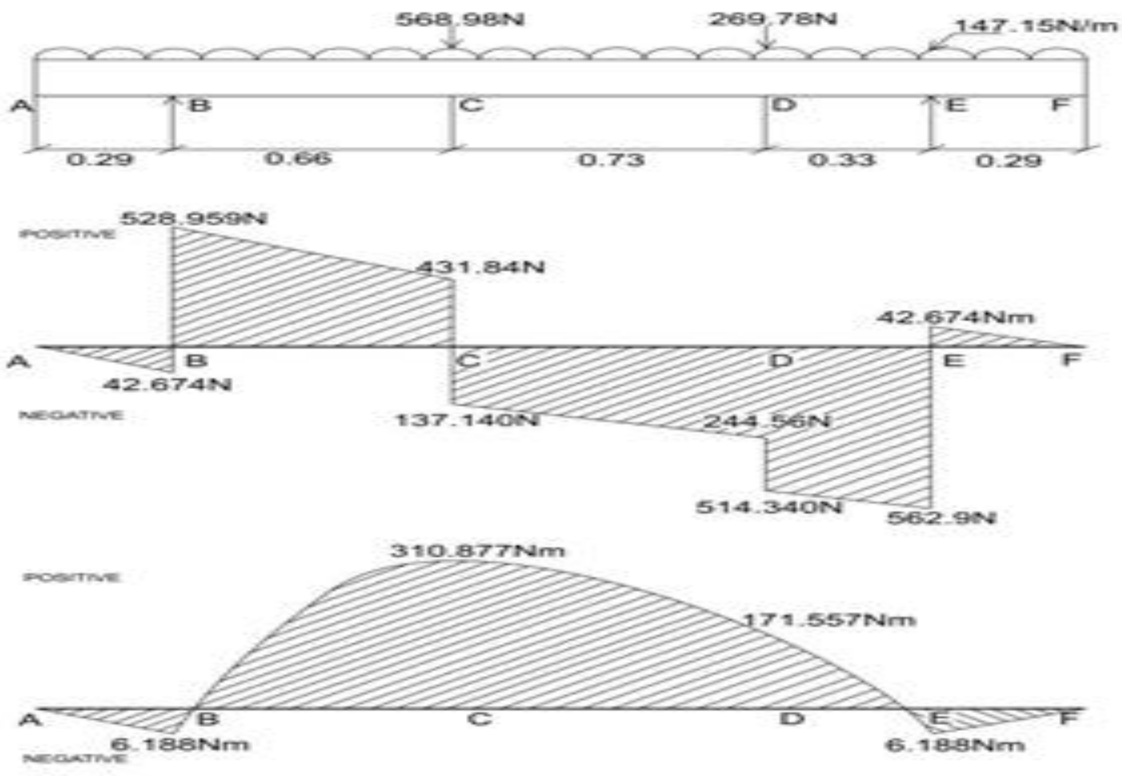

Figure 5: SFD and BMD of chassis

Finite-Element Analysis of Vehicle Chassis
The Finite element analysis (FEA) method is applied to predict how the chassis will respond to real-time forces, vibrations, and other accompanying stresses it is designed to withstand. This analysis is aimed at determining if the chassis will be able to withstand the forces for which it was designed for or if it will end up yielding to these stresses and forces. Thus, the result obtained from this analysis will be used to predict what will happen when the chassis becomes operational and if it is safe to develop. The model used for the analysis is as found in Figure 2 in section 2.2.

Meshing and Boundary Conditions
The point loads applied to the body includes the maximum weight of the driver, the weight of the battery and the engine, which sums up to 838.755 N. The weight of the car body is considered as a uniformly distributed load of 147.15 N/m and is applied to the chassis as a remote load. For the mesh setting, the average element size used is 0.1, minimum element size 0.2 and the maximum turn angle is 60°. The part with the applied constraint and the selected faces with their corresponding forces are show in Figure 6.

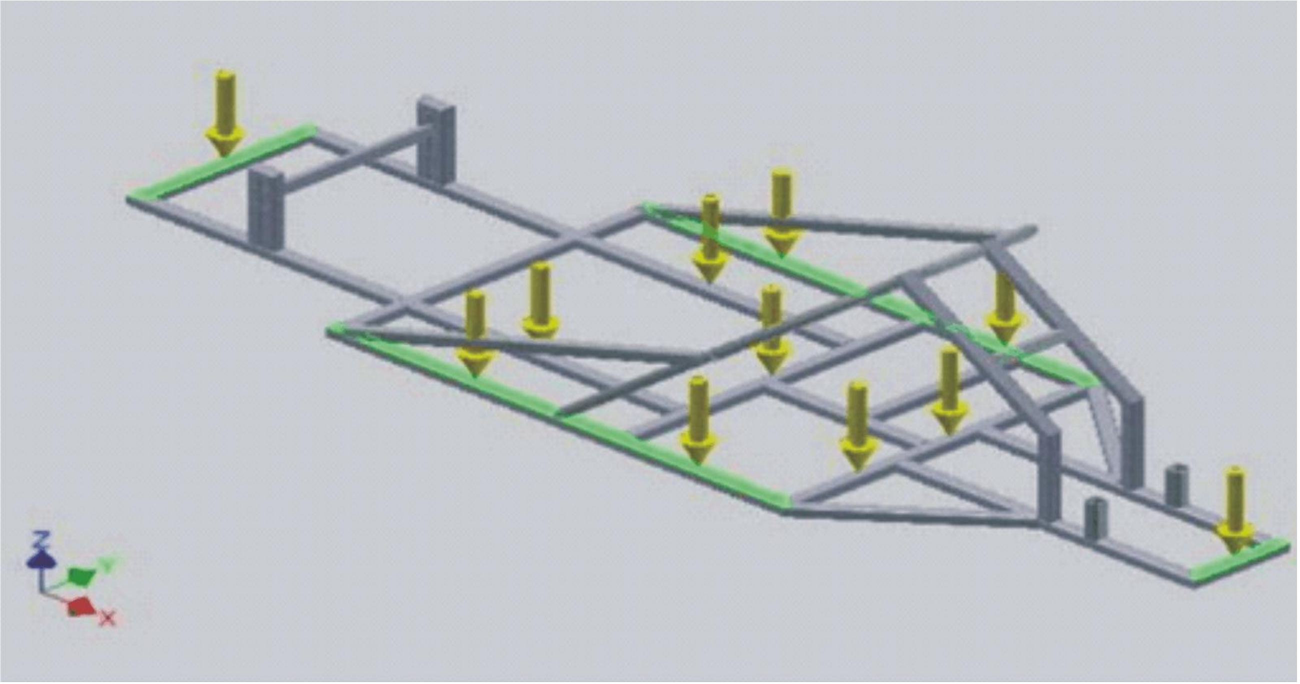

Figure 6: Fixed constraint and forces with their corresponding faces

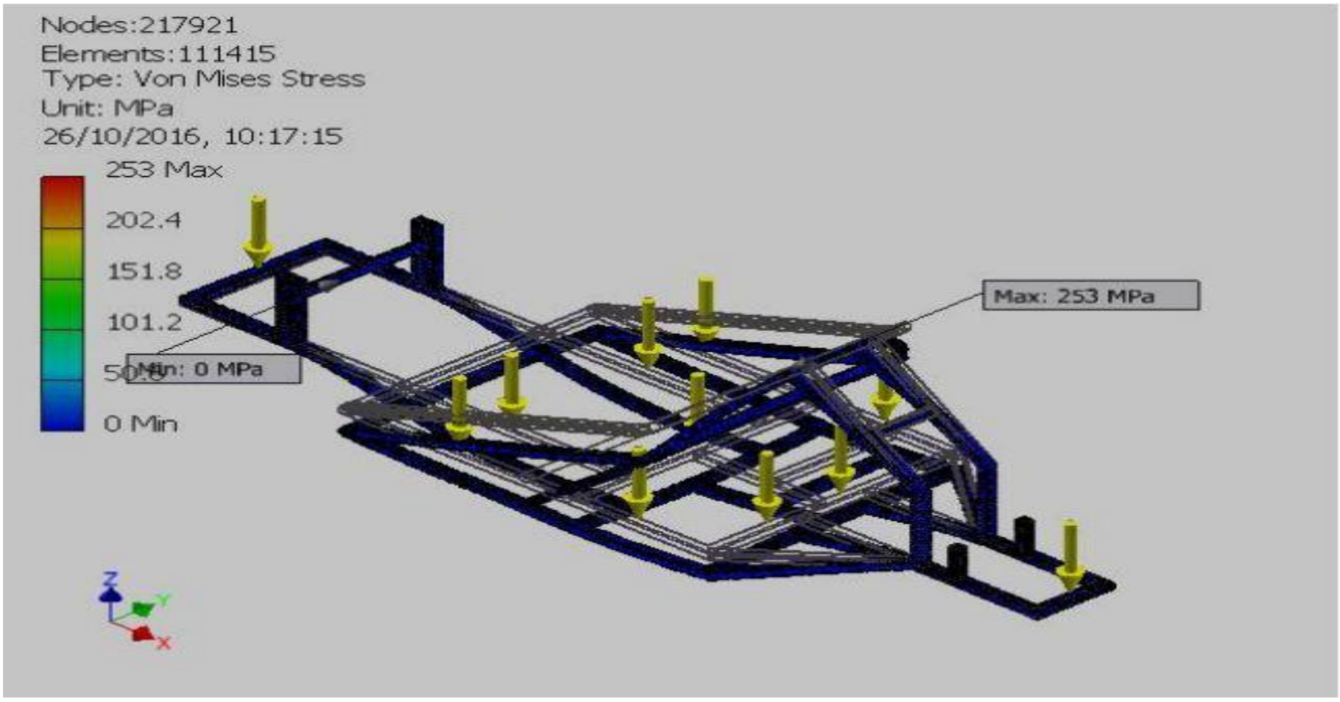

Figure 7: Contour plots for von mises stress distribution

Stress Analysis of the Vehicle Chassis
The type of stress analysis carried out on the chassis is of the static type. From the coordinates chosen, the z-directional load was applied on the square box cross-section of the vehicle chassis. The contour plots for the Von Mises stress distribution, displacement and equivalent strain of the chassis are show in figures 7, 8, and 9.

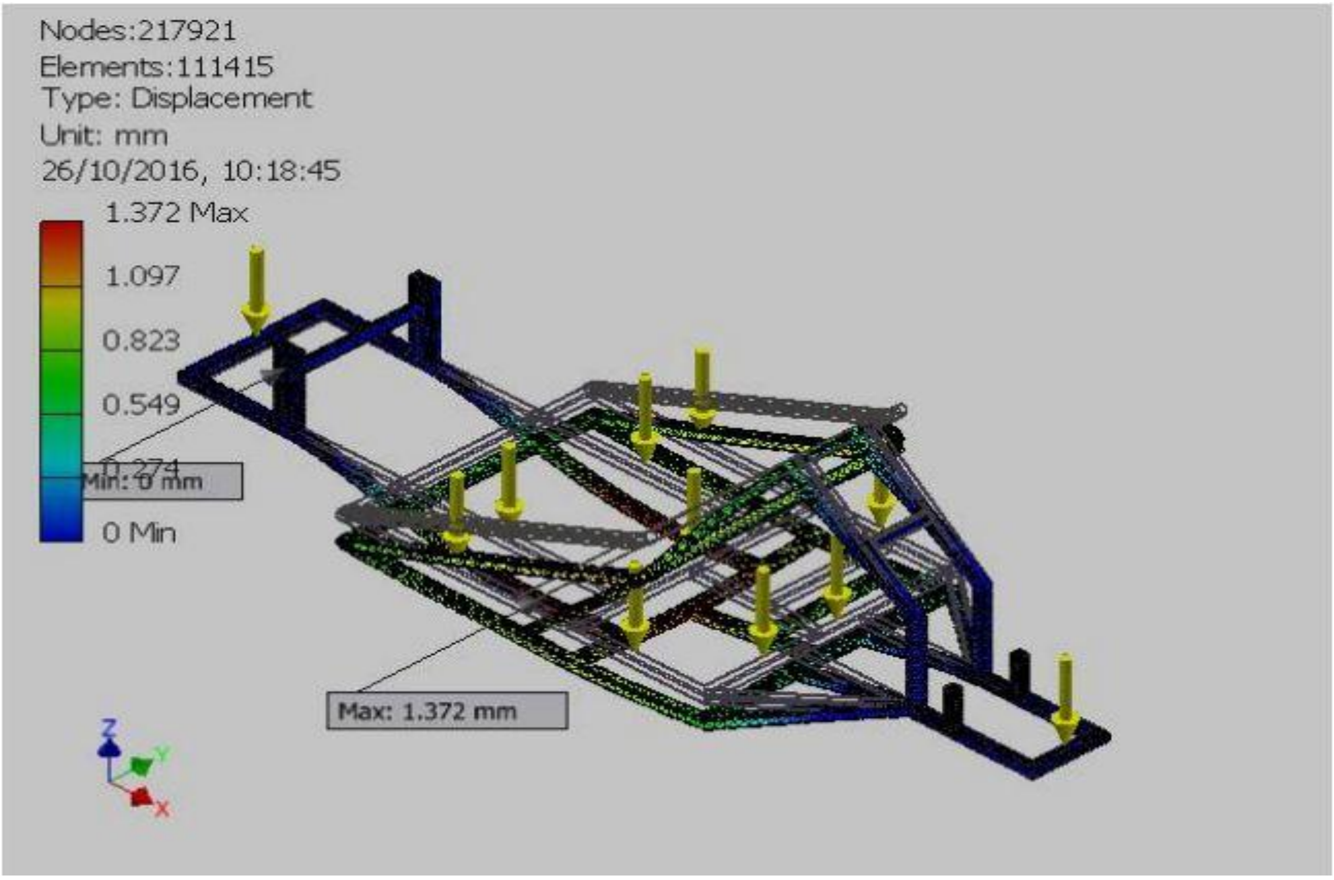

Figure 8: Contour plots for displacement

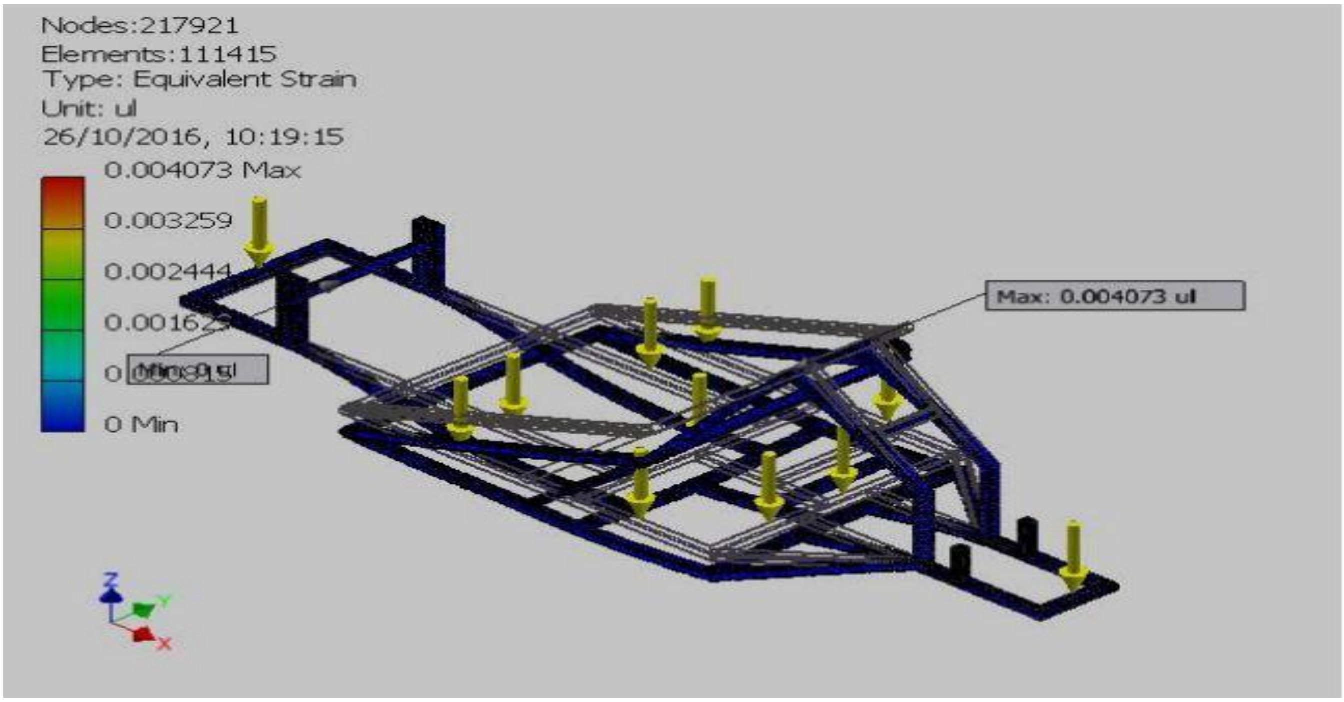

Figure 9: Contour plots for equivalent strain

Fabrication and Testing

As stated earlier, the complete chassis was fabricated from an aluminum alloy (hollow box section) using arc welding as the major joining process. The Aluminum arc welding process was possible by using special Aluminum electrode and expert welders. Other components of the go-cart were mounted on the chassis, either by riveting or with the use of bolts and nuts. The welded chassis during production and the assembly without the body during the testing of the vehicle are shown in figures 10 and 11 below. The complete vehicle on the racetrack at the Shell Eco-marathon challenge in Pretoria South Africa is shown in Figure 12 as well.

Figure 10: Chassis during fabrication

Figure 11: Complete Chassis assembly during testing FUPRE campus cricuit

Figure 12: Chassis with body (Fupre PRO) on race track - Shell Eco-marathon challenge 2016 at Zwartkops Raceway, Pretoria, South Africa

RESULTS AND DISCUSSION

The main aim of this work was to achieve a working chassis that will withstand all the stresses that may be experienced during operation and be able to successfully compete in the Shell eco-marathon challenge. This was achieved, all test driving to check the strength of chassis was done in the campus road that mimic racingcircuit of 1.2 km. The topology of the track circuit consist of about 8^o inclination upward and wavy orihentation and sharp curves. These make the campus cuicuit very suitable for chassis fuctionality test. The vehicle completed over 8 laps non-stop for the first test drive exercise. Endurance test driving was also perfomed.The welded joints were visually inspected for cracks after the test exercies but non was found. Cresh test was not conducted due to limited resources for the project.At the Shell eco-marathon challenger event 2016 the prototype energy effcient vehicle passed the rigorous and compulsory technical and safety inspections according the Shell eco-marathon global rules before vehicle can go on track to race. The prototype vehicle covered an avarage distance of 52. 4 km per litre of petrol (premium motor spirit) ontrack at Zwartkops Raceway, Pretoria, South Africa. This same chassis was adopted for the subsequent Shell eco-marathon prototype fuel efficient vehicle in Figure 13 that was show-cased by Team Fupre in the Shell eco-marathon 2017 event at the same raceway with an avarage of 57.5 km per litre of petrol on the race track. Thefit of the energy effcient prototype vehicle show in both events has validated the functionality, durability and safety of the chassis design and fabrication. The table 2 below shows a comparison between the analytical calculations and the FEA results.

Table 2: Comparison between the analytical calculations and the FEA results

Material	**Aluminum**		
		FEA result	**Theoretical calculation**
Von-mises stress (MPa)	Max	253	255
	Min	0	0
Equivalent strain	Max	0.004073	_
	Min	0	0
Displacement (mm)	Max	1.372	15.6
	MIN	0	0

Figure 13: Chassis with body (Fupre Ambassador) on race track - Shell Eco-marathon challenge 2017 at Zwartkops Raceway, Pretoria, South Africa

The FEA Von-mises stress show good agreement with the theoretical calculation. Although, there were large discrepancy between FEA displacement maximum values and the theoretical values. This could be attributed to how the loads were applied on the model corresponding faces for the analysis.

CONCLUSIONS

The chassis for every automobile is a very important structural member and the design of it has gained very great concern for reliability not to be compromised in automobiles. This work have presented a detailed engineering design and analysis of the chassis of a go-cart prodcued for the Shell eco-marathon challenge.The chassis performance meet the overall design requirements. It is important to statethat joining of aluminum materials of the chassis with the use of arc welding process provided the required technology and offer animprovement of local experties for the project.Testing of the whole vehicle for durability, endurance, safety and efficiency on local and international raceway validated the strength of the chassis design and fabrication method. This research work also delivers a indigenous technology and engineering design template for prototype vehicle chassis design for young engineers in the field of Shell eco-marathon compition and motorsports in general that may have technology and facilities constrain.

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