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Crashworthiness Analysis of a Shell Eco-Marathon Prototype Car

Chinedum Ogonna Mgbemena[1]; Samod Oyedele Ogunbunmi[1];
Chika Edith Mgbemena[2]
[1]*Department of Mechanical Engineering, Federal University of Petroleum Resources, Effurun, Delta State, Nigeria.*
[1]*Department of Industrial and Production Engineering, Nnamdi Azikiwe University, Awka, Anambra State, Nigeria*
E-mail: mgbemena.ogonna@fupre.edu.ng

Abstract
Vehiclesare designed such that they can absorb some level of energy on impact to protect its occupant from injury or death. Thus, the need for a crashworthiness test. This paper describes the crashworthiness analysis of a Shell Eco-Marathon Prototypecar. The analysis was carried out on the vehicle body, roll bar, and the crumple zone to determine the level of deformation during vertical and horizontal impact on the vehicle, thereby indicating the level of safety of the vehicle upon various degrees of impact. SolidWorks and ANSYS software were used to design the car and simulate the vertical and horizontal impact on the body and the roll bar. Results indicate that the design was strong enough to withstand the applied load, as stated in the rules of the competition. It also showed that the deformation experienced by the car upon impact is significantly low to cause any harm to the driver.

Keywords: Crashworthiness, crumple zone, roll bar, safety seat belt

1. Introduction

Crashworthiness is the ability of a structure to withstand a crash and protect its occupants during an impact(*Crashworthiness - Wikipedia*, n.d.; Littell, 2020; Pavlovic et al., 2017). It is a measure of a vehicle's structural ability to protect its occupants from significant injury or death in the occurrence of an impact on a specific part. Though the structure is bound to experience plastic deformation, yet maintains a sufficient survival space for its occupants. Crashworthiness is carried out when investigating the safety of a vehicle or an aircraft.

In 1994, the National Safety Council of the United Statesrecorded a high rate of vehicle crashes, which led to substantial financial losses to the society and an increased death rate. Thus, the quest for vehicle safety began inorder to protect lives and properties. In the process of achieving vehicle safety, automobile manufacturers introduced many crash avoidance devices like a turn signal, windshield wipers, headlamps and seat belts(Beyene et al., 2014; Leiss, 2014; Littell, 2020; Pavlovic et al., 2017).

Radu & Cofaru (2015)studied the different types of crash tests that are performed in recent times. The crash test includes a frontal impact test; side impact test and rear impact test, which were applied in different situations. The various crash tests reveal injuries that can happen to both the occupants and the vehicle during various degrees of impact.

Levick & Grzebieta (2007),in their study, conducted an evaluation of the predicted safety performance of three USA prototype ambulance vehicles and analysed it using existing and established automotive safety principles. The crash test was conducted at a speed of 44miles/hr. The van was able to withstand a high level of impact. This is due to the nature of the attachment of the box to the chassis and its potential rigidity.

Newstead et al. (2011) investigated the relationship between vehicles crashworthiness and both the year of manufacture and the year of first registration in New Zealand of vehicles manufactured from 1964 to 2011 and crashing from 1991 to 2011. Injury severity (of injured drivers) and injury risk (drivers involved in crashes) were used to measure crashworthiness. The analysis result shows a significant improvement in crashworthiness of New Zealand light passenger vehicles over the years of manufacture studied.

This paper describes the crashworthiness analysis of shell eco-marathon prototype vehicle using SolidWorks and ANSYS software to design and simulate the vehicle under appropriate load specification as stated by the event organisers. The paper will assist the young engineers to focus on energy-absorbing techniques in the design and construction of a prototype car to protectthe occupants during crashes. The methodology presented here focuses on the car body design and production, safety seat belt and the roll bar construction as a means to improve the crashworthiness of the shell eco-marathon prototype car which satisfies the shell eco-marathon global rules 2019th edition. Figure 1 shows the sectional view of the vehicle design, while figure 2 shows the view with the drivers positioning in the vehicle.

Figure 1. Sectional view of the vehicle design.

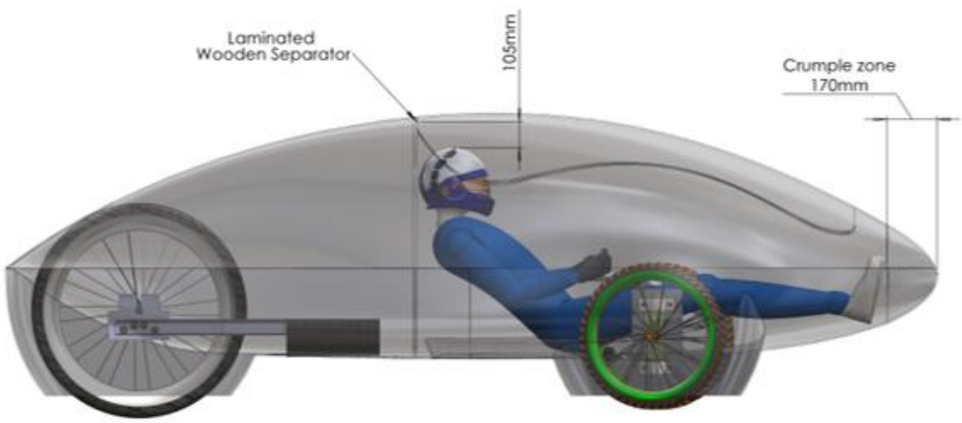

Figure 2.Unobstructed view of the vehicle with the driver.

Shell Eco-Marathon (SEM) competition is a unique competition that challenges students around the world to design, build and drive energy-efficient cars which are highly efficient, specialized and optimal for the event. Though the competition focuses on energy efficiency, the safety of the drivers and the cars are paramount to the organisers, that is why all cars must meet the requirements of the shell eco-marathon competition technical inspection checklist which guarantee optimum safety of the cars and drivers during the competition. In addition to obtaining an energy-efficient body design, the SEM 2019 global ruleswere reviewed to obtain the specifications for the vehicle design. According to the SEM 2019 global rules, the vehicle chassis should be long and wide enough to offer the driver adequate protection in the case of any collision or rollover, and the roll bar used must be capable of withstanding a static load of 700N in a vertical, horizontal or perpendicular direction without deforming. The dimensions for the PROTOTYPE chassis category were considered and are outlined below:

a) The maximum vehicle height must be less than 100cm.

b) The vehicle track width must be at least 50cm, measured between the midpoints where thetyres of the outermost wheels touch the ground.

c) The ratio of maximum height divided by track width must be less than 1.25.

d) The vehicle wheelbase must be at least 100cm.

e) The maximum total vehicle width must not exceed 130cm.

f) The maximum total length must not exceed 350cm.

g) The maximum vehicle weight, without the Driver, is 140kg(*Shell Eco-Marathon Global Rules Chapter 1*, 2019).

2. Essential Parts to Consider During the Body Design

2.1 The Crumple Zone

The crumple zone is situated at the front of the vehicle in order to absorb the impactofan opposite collision. However, the crumple zone could be located on other parts of the vehicle as well. The crumple zones work by managing crash energy as it prevents intrusion of the crash into the passengers' compartment. The crumple zone must be capable of absorbing more energy while keeping the impact forces low to the barest minimum for humans to handle(Dvorak, 2003; Raiciu, 2017).

Mathematically, the crumple zone spread out the total change in velocity across time;thus, the acceleration is reduced.

$$F \times (\Delta T) = m \times (\Delta V) \qquad (1)$$

Where F is the impact force, ΔT is the change in time, m is mass of the vehicle, and ΔV is the change in velocity.

2.2 Roll Bar

The roll bar is a part that separates the driver's compartment from the engine compartment. It must be strong enough to withstand a vertical load of 700N. The importance of the roll bar is to protect the driver and the car from vertical impact, and when the vehicle summersaults, it prevents the driver's head from hitting the ground. The angle of elevation of the roll bar will determine the sitting posture of the driver.

2.3 Safety Seat Belt

The seat belt or vehicle safety belt is a vehicle safety device designed to secure the driver or a passenger of a vehicle against harmful movement that may result during a collision or a sudden stop. It restrains the forward movement of the occupant under the sudden deceleration of the car. The seat belt also distributes the forces of rapid deceleration over more significant and stronger parts of the body, shoulder, chest, and hip.The organizers of the competition recommend the five-point pin safety belt. The lap portion is connected to a belt between the legs, and there are two shoulder belts, making a total of five-point of attachment to the seat. Figure 3 shows a pictorial representation of the arrangement of the belt.

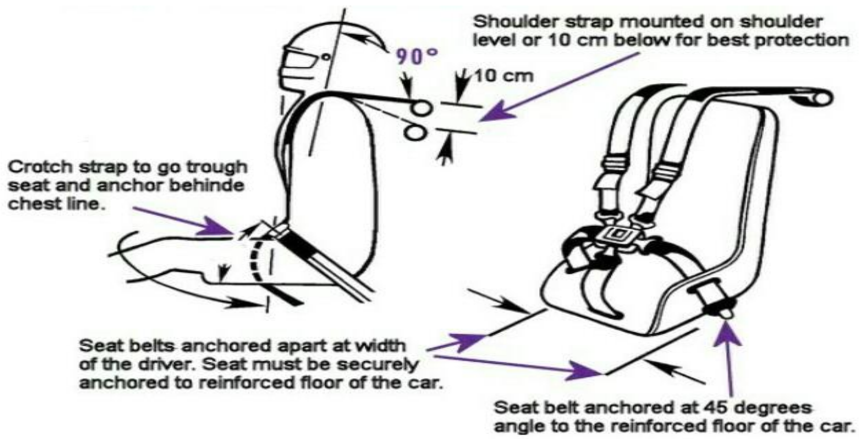

Figure 3. Pictorial Presentation of Safety seat belt installation

3. Materials and Method

The analysis on the entire body and roll bar (laminated wooden separator) of the vehicle was done to assess the integrity of the roll bar in ensuring safetyby predicting if the design can withstand a static load of 700N (70 kg) applied perpendicularly and horizontally on the body of the vehicle targeting the roll bar without failure. The design and simulation were done using Solidworks.The vehicle body is made up of carbon fibre reinforced polyester resin. The traditional hand lay-up method was used in the development of the vehicle body.

3.1 Design Assumptions

The CAD model was prepared using Solidworks, and the following assumptions were made and used to run the simulation:

- A perpendicular force of 700N was applied on the body of the vehicle targeting the roll bar
- The base of the tire outlets was used as fixtures to provide more accurate results

Table 1 shows the material properties of the Carbon Fibre used for the vehicle body, while Table 2 shows the material properties of the Balsa wood used as a separator.

Table 1. Mechanical Properties of the Carbon Fiber used for the Vehicle body

Property	**Value**	**Unit**
Elastic modulus	2.1e+11	N/m^2
Poisson's ratio	0.28	
Shear modulus	7.9e+10	N/m^2
Mass density	1600	Kg/m^3
Tensile strength	60000000	N/m^2
Yield strength	60000000	N/m^2
Coefficient of Thermal Expansion	2.1e+11	/K
Thermal conductivity	50	$W/(m.K)$
Specific heat	460	$J/(Kg.K)$

Table 2. The Mechanical Properties of the Balsa Wood as Separator

Property	**Value**	**Unit**
Elastic Modulus	2999999232	N/m^2
Shear Modulus	299999910.5	N/m^2
Mass Density	159.989899	Kg/m^3
Yield Strength	19999972	N/m^2
Thermal Conductivity	0.05	$W/(m.K)$

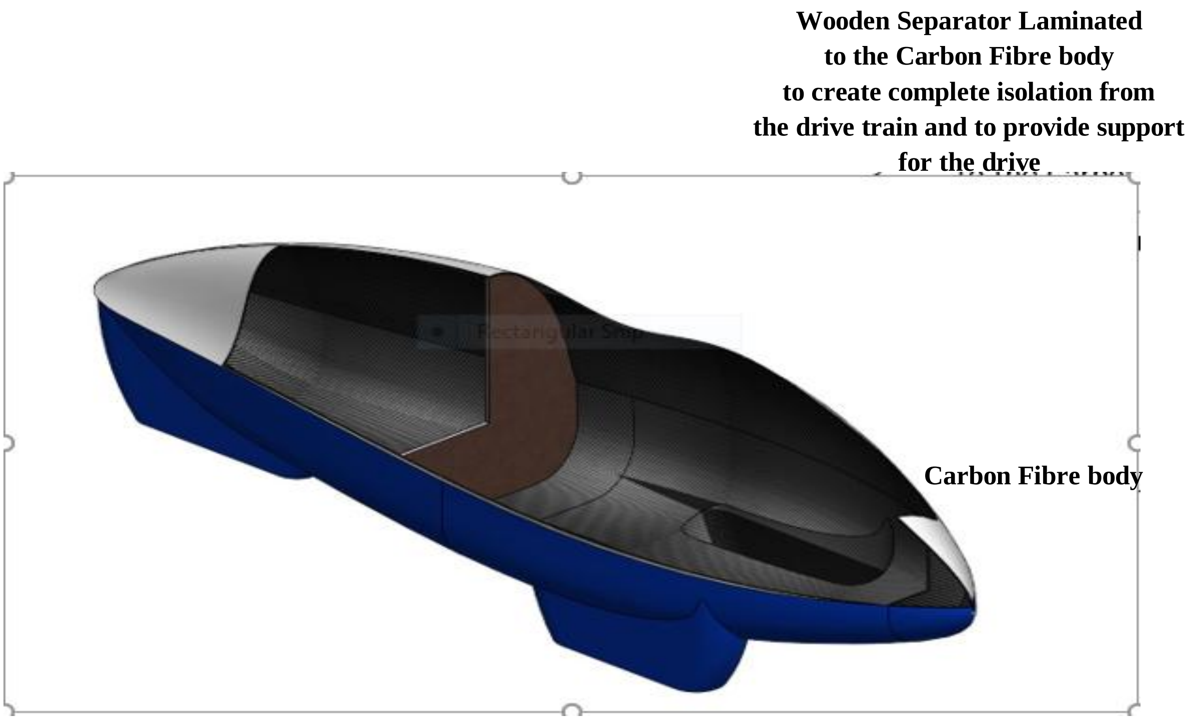

Figure 4. The sectional view of the vehicle showing the body and the roll bar.

3.2 The Prototype Car Model and Geometry

The prototype car has a weight of 202.815 N, a mass of 20.6954 kg, volume of 0.0128866 m^3, and density of 1605.97kg/m^3. The geometric model developed in SolidWorks was imported in ANSYS R18 for crashworthiness evaluation. Figure 5 is a meshed model of the car with a total of 17820 nodes and 8719 elements

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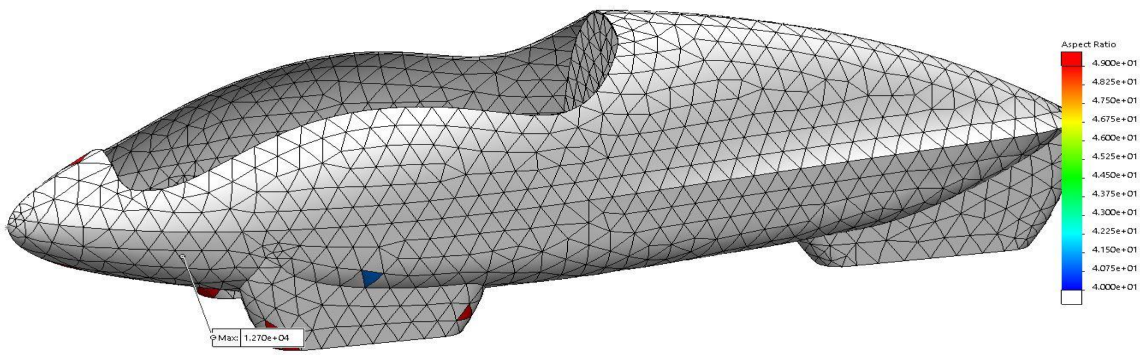

Figure 5. A meshed model of the prototype car

3.3 Failure Analysis and Crashworthiness

The classical failure theory implemented to analyse the crashworthiness is the Distortion Energy Theory (DET), otherwise called Hencky von Mises stress(Ihueze & Mgbemena, 2016; Mgbemena et al., 2016;Mgbemena et al., 2017). It is expressed mathematically as:

$$\tau_0 = \frac{1}{3}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]^{1/2} \quad (2)$$

Equation (2) can be re-expressed in terms of the orthogonal component stresses as:

$$\tau_0 = \frac{1}{3}\left[\left(\sigma_x - \sigma_y\right)^2 + \left(\sigma_y - \sigma_z\right)^2 + (\sigma_z - \sigma_x)^2 + 6\left(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2\right)\right]^{1/2} \quad (3)$$

The limiting value of the octahedral shear stress is expressed as:

$$\tau_0 = \frac{\sqrt{2S_y}}{3} \quad (4)$$

Re-expressing Equation (4) in terms of principal stresses and factor of safety,

$$\frac{S_y}{n} = \frac{3}{\sqrt{2}}[\tau_0]lim = \frac{1}{\sqrt{2}}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]^{1/2} = \sigma' \quad (5)$$

The distortion energy at yielding is obtained as:

$$U_d = \frac{1+v}{3E}(\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - \sigma_1\sigma_2 + \sigma_2\sigma_3 + \sigma_1\sigma_3) \quad (6)$$

Where $\sigma_1, \sigma_2, \sigma_3$ are the ordered principal stresses; $\sigma_x, \sigma_y, \sigma_z$ are the orthogonal stresses in the x, y, z directions; $\tau_{xy}, \tau_{yz}, \tau_{zx}$ are the orthogonal shear stresses, S_y is the yield stress; U_d is the distortion energy; ν is the Poisson's ratio; E is the elastic modulus; n is the factor of safety; σ' is the von Mises stress.

In this study, SolidWorks and ANSYS R.18 were used to evaluate the yield stresses obtained as von Mises stress, and the displacement on the roll bar and the vehicle body

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3.4 Vehicle crashworthiness simulation using ANSYS software

A slab made of concrete with and the dimensions are 968mm X 800mm X 200mm and set at a distance to 500mm from the car was used to conduct the crashworthiness. A velocity of 50m/s was used to simulate because it is safe and efficient for the driver to drive at the optimum speed to prevent accidents and also to meet the stipulated time target by the organizers of the competition, which is 25minutes to travel 9.6km.

4. Results and Discussions

The failure analysis of the prototype car was conducted using SolidWorks to evaluate the von Mises stress, and displacement of the car. However, the ANSYS R18 was used in conducting the crashworthiness of the car.

4.1 von Mises Stress

The von Mises stress around the roll bar was obtained using SolidWorks as 6890 N/m^2 for the minimum value on node 1423 and the maximum value obtained as 19,360,000N/m^2 on node 3437 as shown in Figure 6.

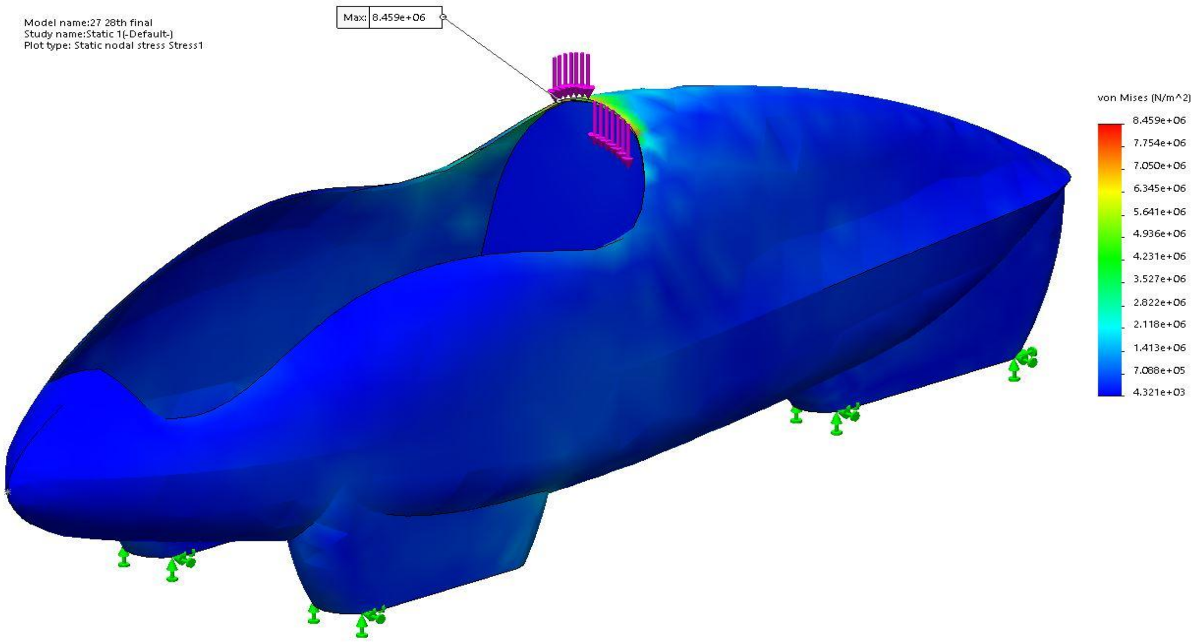

Figure 6. von Mises stress values on the roll bar

4.2 The Displacement

The displacement was obtained as 0.0001106m on node 10887, as shown in Figure7.The valuewas found to be negligibly small, and it occurs around the roof of the car. This is an indication of the sturdiness of the prototype car.

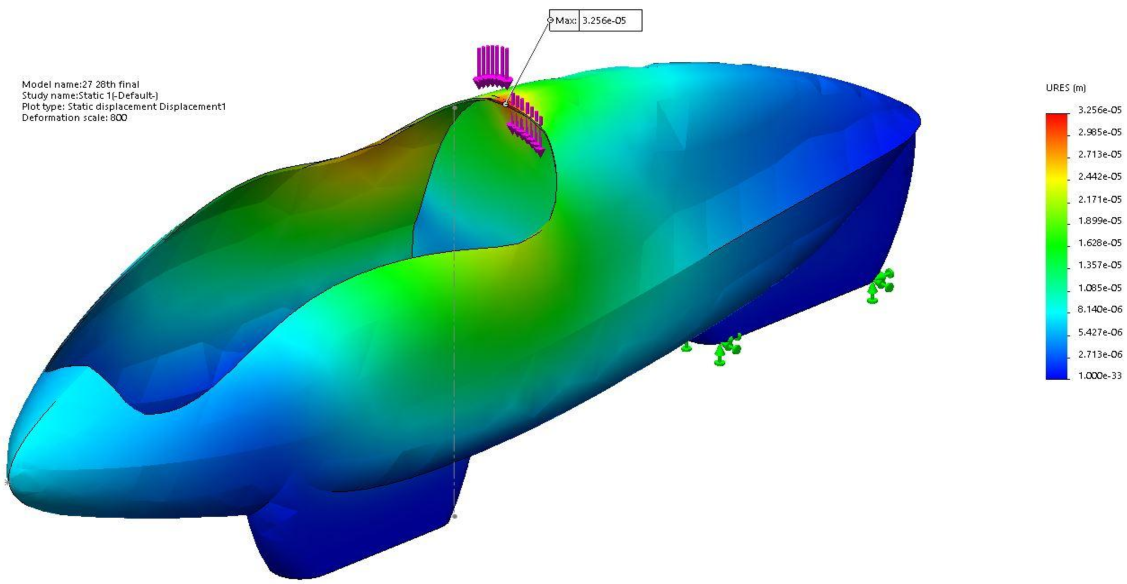

Figure 7. The displacement in the prototype car

4.4 Vehicle crashworthiness simulation using ANSYS software

Figure 8 typifies the set up used to analyse the crashworthiness of the prototype car. The meshed model has 3138 nodes and 2807 elements. The maximum values obtained for the directional deformation along X-axis and the total deformations is 0.15047m as shown in Figures 9 and 10, respectively.

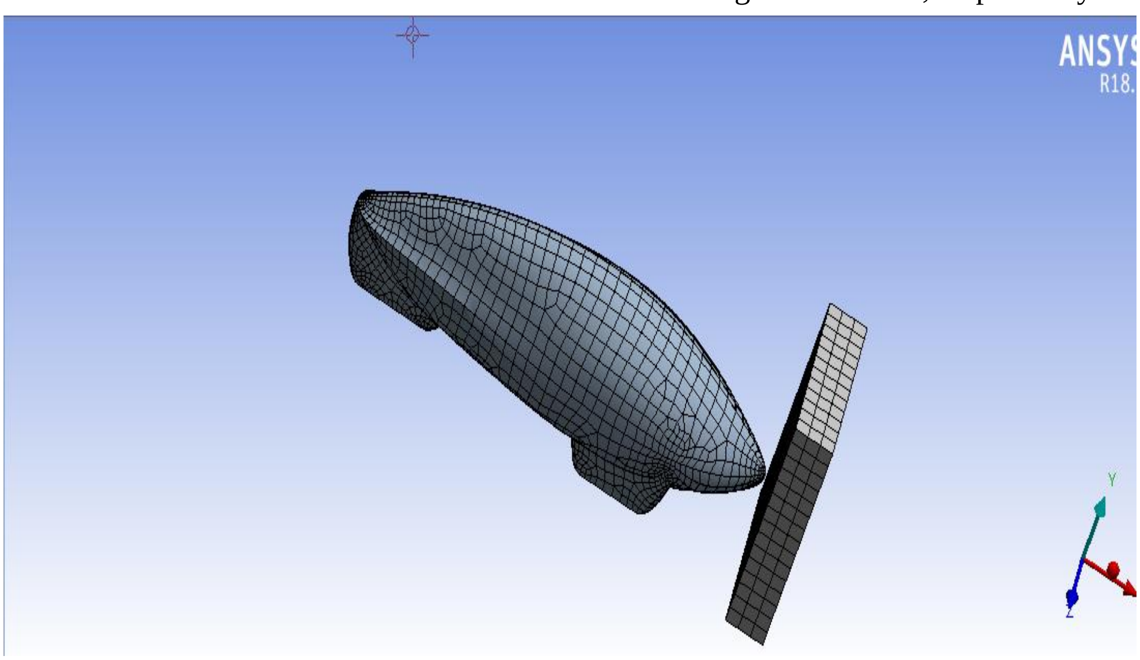

Figure 8. A meshed model of the crash set up

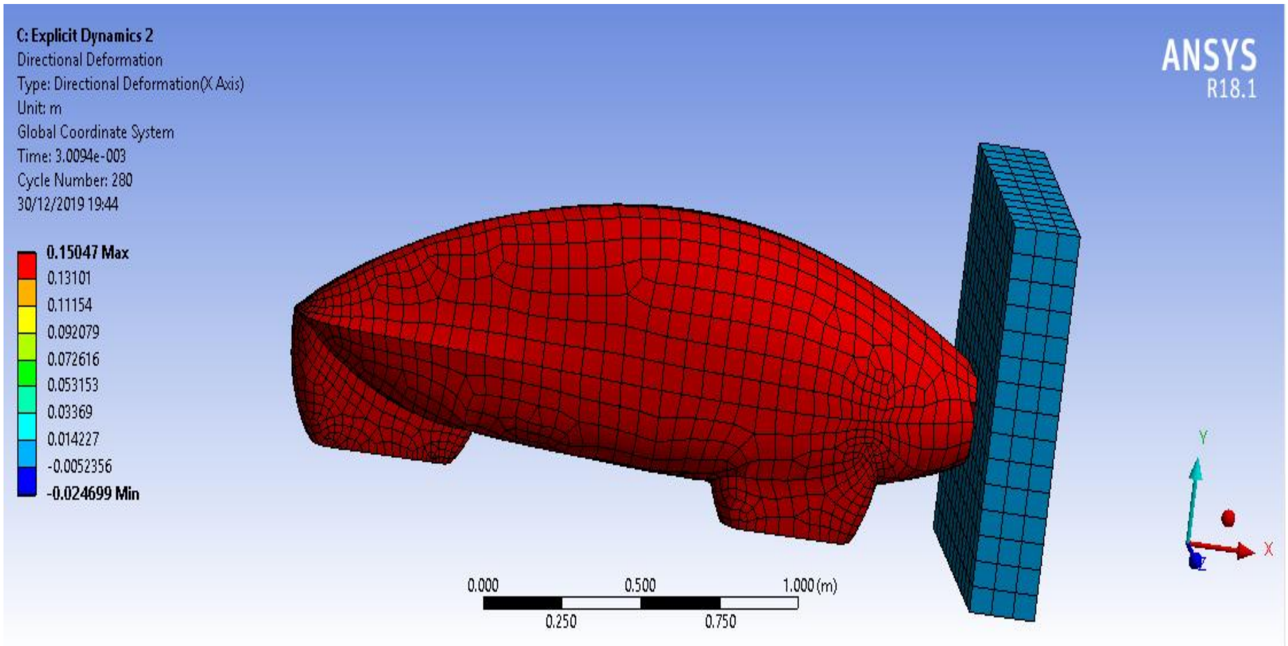

Figure 9. Directional deformation along the x-axis

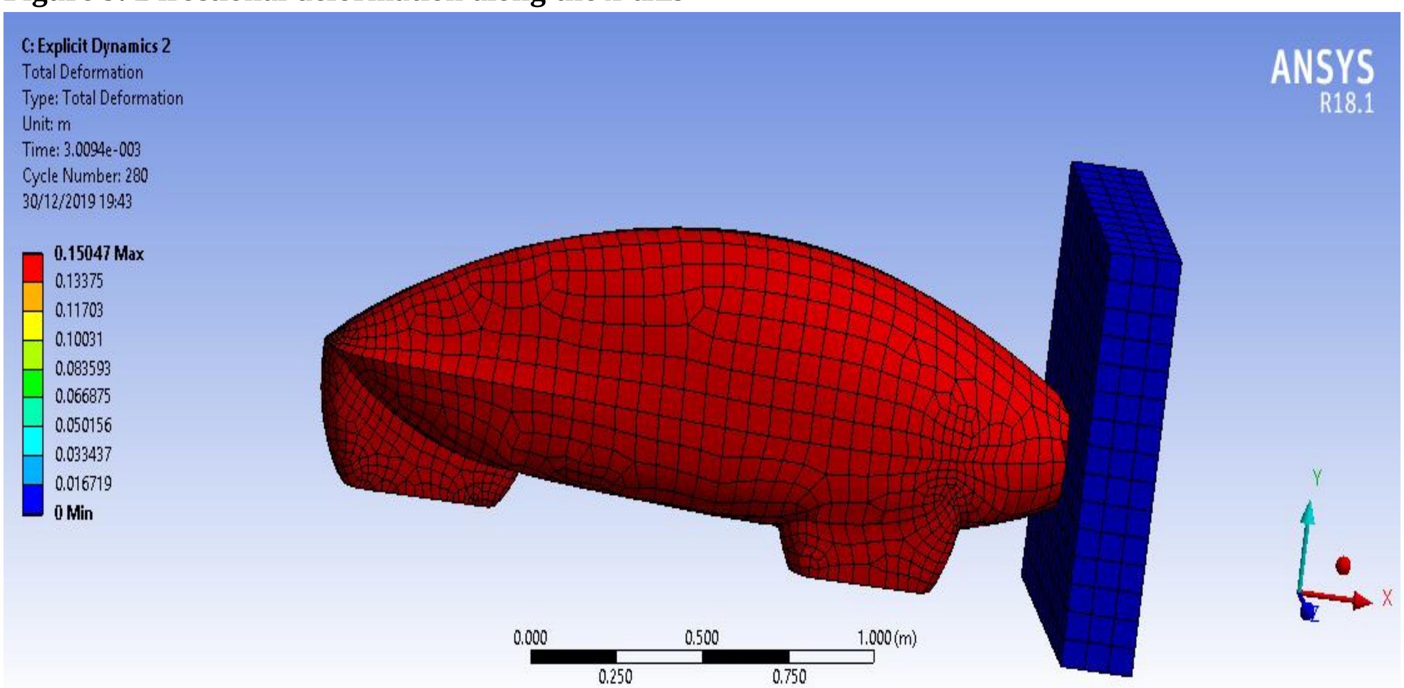

Figure 10. Total deformation

5. Conclusions

The following were conclusions made from this study:

1. The Maximum stress experience due to loading condition was obtained as 1.936e+07 N/m^2 . Moreover, the total deformation obtained as 1.106e-04 m, which is negligible.

2. The maximum stress on the roll bar and the body when a static vertical load of 70kg (700N) was applied on the car, is less than the yield strength of the car.
3. Also, the total deformation experienced is negligible, thus indicating that the driver is safe.
4. The distance of 105mm was obtained, as the gap between the driver's helmet and roll bar after the simulation. Hence, providing the necessary protection needed by the driver in the cause of any crash.

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