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Design optimization of roll cage for formula one vehicle by using finite element analysis

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ABSTRACT

In this article, AISI-1020 tubular steel roll cage of a formula one car has been designed and optimized. CATIA software has been employed for designing whereas ANSYS software used for Finite element analysis (FEA). The design of the roll cage has been optimized for maximum load bearing capacity and manoeuvrability conditions. For this purpose, various impact tests have been performed under different conditions in order to determine the level of safety. The effects of different loading conditions on the structural members are studied and discussed. It has been found by the analysis from the front and rear impact tests that less deformation is developed at a higher value of stress. Moreover in case of front rollover and side-impact test, it has been observed that higher stress produces higher deformation. The results show that employed AISI-1020 tubular steel may lead the development of a lighter and safer roll cage design as compared to a conventional Formula-1 roll cage material.

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1. Introduction

In the name of formula one car, the term "formula" refers to a set of rules to which all participants and cars must be followed. There are several fundamental design parameters that determine a race car's performance including mass, the center of gravity height, static load distribution, engine power and aerodynamic forces. A sensitivity analysis is performed on these and other parameters to determine their effect on vehicle performance. The results further provide an insight into the differences between high-speed cars effected by aerodynamics and low-speed cars where aerodynamics makes little or no difference to performance [1]. Formula One cars are the fastest road course racing cars in the world due to very high cornering speeds and amounts of aerodynamic down force. Currently, Formula one car race at speeds of up to 360 km/h (220 mph) with engines, limited in performance to a maximum of 15,000 RPM. The cars are capable of lateral acceleration in excess of five 'G' in corners. The performance of the cars is very dependent on electronics control and other driving on aerodynamics, suspension and tyres. Nowadays most of the research on the energy absorption of composite materials has been limited to the axial compression of tubular structures [2–6]. Only a few models have been proposed to predict the energy absorption characteristics of tubular structures [7,8]. The cornering speed of Formula One cars is largely determined by the aerodynamic down-force that they generate, which pushes the car down onto the track with the help of "wings" mounted at the front and rear of the vehicle. The fundamental principle of Formula One aerodynamics is to create the maximum amount of down force for the minimal amount of drag. The most common research in this area seems to focus on car design optimization, with numerous examples, including automobile valve-train optimization, structural automobile design [9].

Mostly modern Formula One cars have mid-engine open cockpit, open-wheel single-seat on the chassis made by carbon fibre composites including the engine. Europe is the most sport's traditional base in all countries and hosts about half of each year's races and has expanded significantly by increasing the number of Grand Prix. Grand Prix racing began in 1906 and became the most popular type internationally in the second half of the twentieth century. The Formula One Group is the legal holder of the commercial rights [10]. This is more significant for annual spending totaling billions of pounds for economically investment and creation of jobs. Due

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to which Its high profile and popularity have created a major merchandising environment has resulted in great investments from sponsors due to which Since 2000 the sport's spiraling expenditures have forced several teams, including manufacturers' works teams, into bankruptcy. Here we describe the use of a genetic algorithm to optimize 66 setup parameters for a simulation of a Formula One car and demonstrate performance improvements (faster lap times) better than all other methods tested [11]. Genetic algorithm has also utilized to optimize 66 different setup parameters for a simulation of a Formula One car and demonstrate performance improvements better than all other methods tested [12]. If the construction of the car is lighter than the minimum, it can be ballasted up to add the necessary weight. It has disc brakes and the principle of braking is slowing an object by removing kinetic energy from it. Since 2009 teams have had the option of harnessing the waste energy generated by the car's braking process and reusing it via an Energy Recovery System (ERS) to provide additional engine power, which can be made available to a driver in short bursts to help facilitate overtaking. The Energy Recovery Systems (ERS) which form an integral part of an F1 car's power unit with the concept of KERS with a performance effect around ten times greater. A racing car takes a corner in three stages and individual drivers may also use their personal technique with the fundamental principle of efficient cornering is the 'traction circle' ideally keeping the car right on the edge of the traction circle through an acute sense of balance. The power unit of F1 consists of six separate elements the engine, the motor-generator unit-kinetic (MGU-K), the motor-generator unit-heat (MGU-H), the energy store (ES), turbocharger (TC) and control electronics (CE). A chassis is the under-part of a motor vehicle, consisting of the frame of the strong tubular backbone that connects the front and rear suspension attachment areas. Monocoque is a structural skin that supports loads through an object's external skin. Commercial car bodies are almost never monocoques instead modern cars use of unitary construction or unit body or Body Frame Integral construction [13]. Body-on-frame is an automobile construction method which mounted a separate body to a rigid frame that supports the drive train which was the original method of building automobiles and continues to this day. In particular, the cars are subjected to a number of tests, both static and dynamic due to which there are four types of impact are requested for the survival frontal, rear, side and steering column that absorb a high amount of energy. It is much more difficult to find data regarding impact tests. Starting with the 2014 Formula 1 season the engines have changed from a 2.4-litre naturally aspirated V8 to turbocharged 1.6L V6 "power-units". Engines run on unleaded fuel closely resembling publicly available petrol. The oil which lubricates and protects the engine from overheating is very similar in viscosity to water.

Keeping these facts in minds, in the present research article an AISI-1020 tubular steel roll cage of a formula one car has been designed and optimized by using Finite element analysis (FEA). Thereafter, to determine the maximum load bearing capacity and manoeuvrability conditions various impact tests have been performed under different conditions.

2. Methodology

The procedure adopted in the present research article has been divided into three phases, as shown in Fig. 1. In the first phase, roll cage model of AISI-1020 tubular steel has been designed by using CATIA V5 software. Initially a tubular frame is designed according to the specifications of SAE. The Primary Structure is comprised of the following Frame components viz. main hoop, front hoop, roll hoop braces and supports, side impact structure, front bulkhead, front bulkhead support system and all the frame members, guides and supports which transfer load from the Driver's Restraint System. In the second phase, finite element analysis of designed roll cage model under different loading conditions has been carried out by using ANSYS software. During FEA it has been considered that the main hoop must be constructed by a single uncut piece, continuous, closed section steel tube. In the present study, the side view of the vehicle on the portion of the main roll hoop that lies above its attachment point to the major structure of the frame kept within ten degrees (10°) of the vertical. In the front view of the vehicle, the vertical members of the main hoop considered 380 mm (15 in.) apart (inside dimension) at the location where the main hoop is attached to the major structure of the frame. The front hoop is constructed by closed section metal tubing. The front hoop is extend from the lowest frame member on one side of the frame, up, over and down to the lowest frame member on the other side of the Frame. In the third and last phase, optimization of designed roll cage has been performed on the basis of FEA analysis.

3. Design of roll cage

The first step to designing a vehicle frame, or any other structure, is to understand the different loads acting on that structure. Some important loading conditions for a vehicle chassis are shown in Figs. 2–5. Fig. 2 visually depicts the deformation in the structure

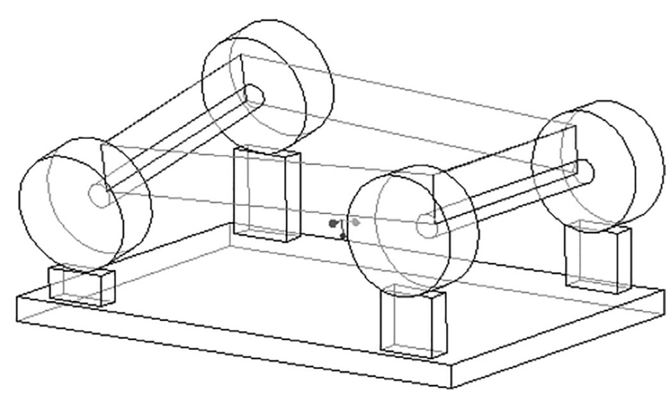

Fig. 2. Longitudinal Torsion Deformation Mode.

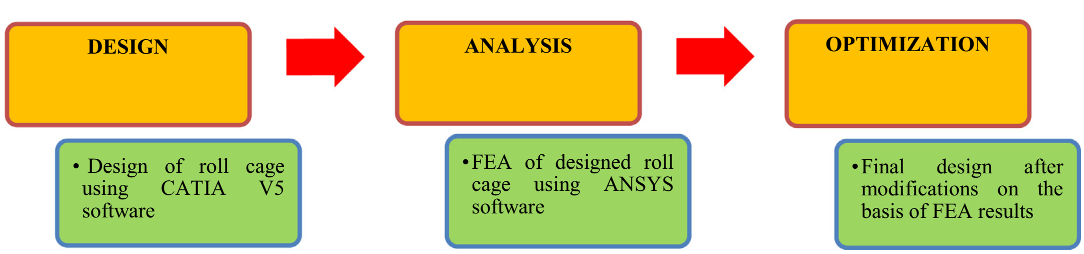

Fig. 1. Phase diagram of proposed methodology.

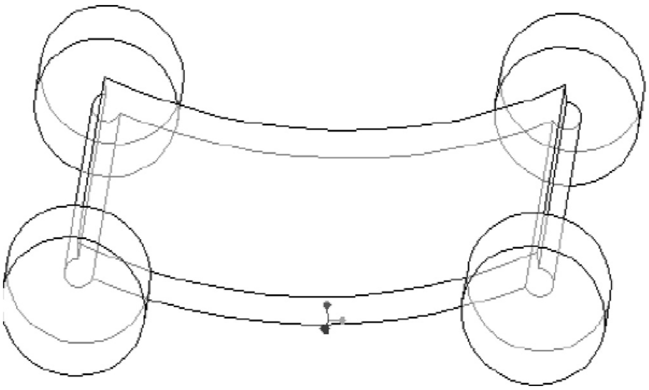

Fig. 3. Vertical Bending Deformation Mode.

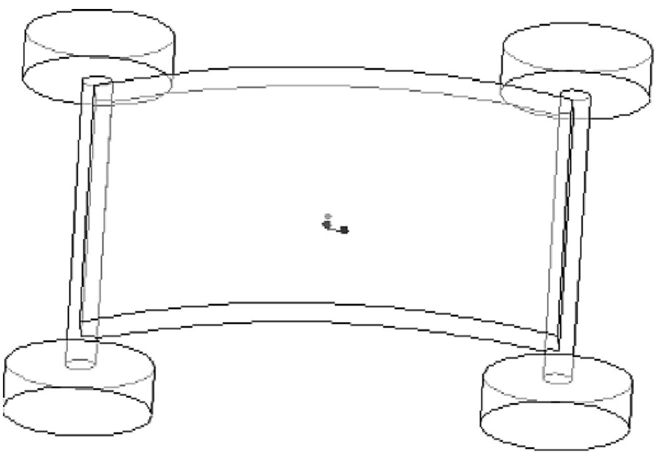

Fig. 4. Lateral Bending Deformation Mode.

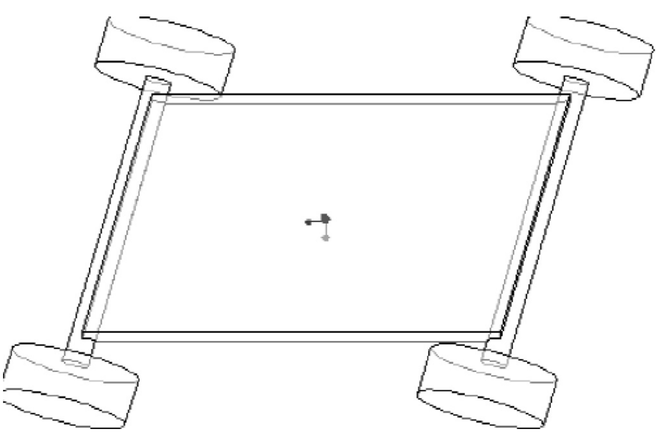

Fig. 5. Horizontal Loading Deformation Mode.

due to longitudinal torsion loads. In this condition, applied loads act on the one or two opposite corners of the vehicle or its suspension parts and effect the balancing. Apart from this, bending loads also affect vehicle performance as shown in Figs. 3 and 4. Moreover, forward and backward forces applied at the opposite wheels also cause deformation. These forces tend to distort the frame into a parallelogram shape as shown in the Fig. 5.

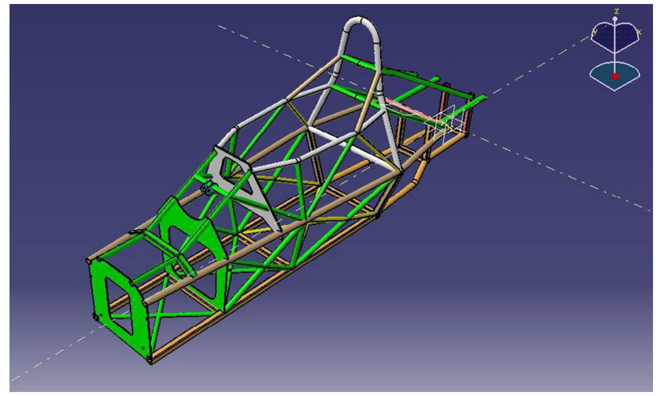

Fig. 6. Roll Cage Model of Vehicle Designed in CATIA.

In the present work, CATIA V5 R20 CAR software has been used in the development of chassis design. In this phase, roll cage design has been started by including the necessary elements like the roll bar and the constrained dimensions of the vehicle. Moreover, support points have been also added for the main vehicle body and the driver compartment. The front part of the frame has been also extended forward to make it able to mount the necessary tow hook. In design, the front and rear axles have also consisted of tubing cubes to create mounting points, whereas the rear is made capable to mount the engine, gearbox, and the rear suspension. In the final phase of the design of the frame involve more polygons due to it is the basis which everything else has been mounted. Therefore, it should be strong and able to hold all of the required components. Moreover, the vehicle must be open-wheeled and open-cockpit due to a formula style body with four wheels but not in a straight line as shown in Fig. 6. The main hoop and front hoop of the vehicle have been also designed with required conditions and are shown in Figs. 7 and 8.

All parts have been designed by AISI-1020 tubular steel having dimensions outer diameter of 25.4 mm and the wall thickness of 3 mm, which is best suited for making roll cages. As the vehicle has been designed to ensure optimum results under different test conditions and safety parameters, therefore, some changes have been made in the designed vehicle as compared of Mercedes F1 W05, which are tabulated in Table 1.

To maximize the manoeuvrability of the vehicle under extreme cornering conditions some decrement has been also made in the length and width of the vehicle. Moreover, ground clearance has been also increased to ensure maximum safety of the driver and exposed parts of the vehicle (Fig. 9).

Thereafter, in the next phase, designed chassis has been evaluated analyzed under different loading conditions by using ANSYS software. To determine the stiffness and strength of the proposed frame and chassis design before construction, a finite element model has been developed. The first boundary condition has been tested to clamp the front of the rear suspension bay and to observe its effect on the stiffness of the frame. It increased the overall frame stiffness by several hundred foot-pounds per degree. This is due to that the entire rear bay of the car was virtually unloaded and barely deflecting. These discrepancies in the results raised the question that which model is more accurate. Therefore, once the need to model the suspension is decided than research began on the best way to model the various suspension components. It has been observed that the a-arms, pull-links and several other components which transmit the tensile and compressive forces without generation of bending effects. Therefore, these parts have been modelled in ANSYS as the link members. Table 2 contains the types

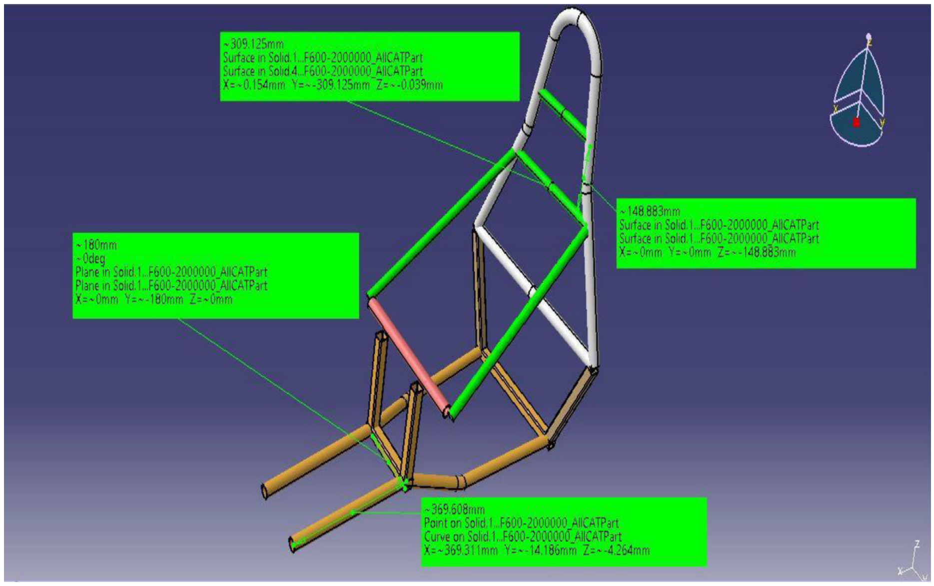

Fig. 7. Main Hoop of Vehicle.

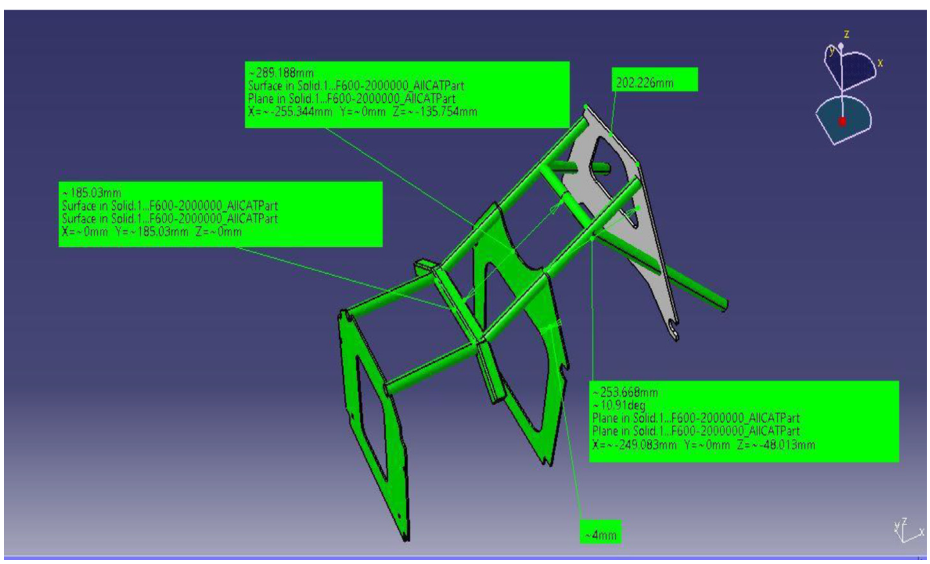

Fig. 8. Front Hoop Vehicle.

Table 1
Modifications in designed vehicle.

Parameters	Mercedes F1 W05	Designed Vehicle
Overall width	1800 mm	1530 mm
Overall length	4800 mm	4675 mm
Ground clearance	120 mm	150 mm

of different elements which has been used in the modelling. By using these five elements, a model for every load carrying component of the chassis is developed. All of these effects mean that the ANSYS model is for the approximation of the real car and will have to be considered when comparing the results to the experimentally determined values. The complete finite element chassis model is shown in Fig. 10. During FEA, model of roll cage is subjected to different kind of loads &their impacts. Mass of each subsystem has been considered as per Table 3. All tests have been performed on ANSYS WB 14.0 software (Table 4).

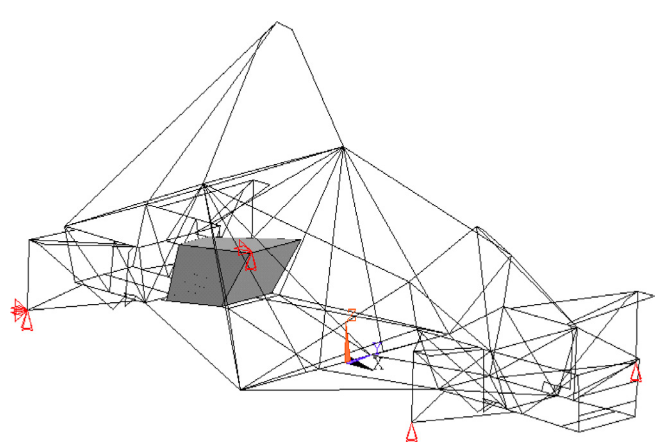

Fig. 9. Five Element Chassis Model.

Table 2
ANSYS Element Type and Use.

ANSYS Element Type	Numbers	Use
Beam	4	Round and Square Tubes, gussets, tabs
Link	8	Tension/Compression links such as pull links or a-arms
Combine	7	Joint for rocker
Combine	14	Spring in suspension (can handle damper as well)
Solid	45	Solid block used for engine

4. Result and discussion

4.1. Impact test analysis

During impact test analysis, four types of impact viz. front, rear, front roll over and side impact have been carried out. Front impact refers to front collision with a stationary object. A value of 10 G's, here G refers the gravitational force, is set as the goal point for an extreme worst case collision in case of front impact. Force values for different impacts are calculated by using Newton's 2nd law of motion i.e.

$$F = m \times a \tag{1}$$

This force is applied on 4 nodes of front members of vehicle and finds front impact total deformation and maximum stress shown in Figs. 10 and 11 so from Eq. 1.

Force $F = 249.27 \times 10 \times 9.81 = 24452.99$ N

Therefore front impact force applied on each node = 24452.99/4 = 6113.25 N

A rear impact is most likely to occur with the vehicle hit by another vehicle at the rear end and from Eq. 1. Calculation forrear impact total deformation and maximum stress are shown in Figs. 12 and 13

Force $F = 249.27 \times 10 \times 9.81 = 24452.99$ N

Table 3
Mass of Each Subsystem.

Sub System	Mass (in kg)
Roll Cage	33
Engine	27
Tire Assembly	45
Steering	27
Brakes	90
Body Work & Auxiliary Components	250

Table 4
Final Test Result.

Test	Deformation (mm)	Stress (MPa)
Front Impact	0.83653	12.646
Rear Impact	0.734	15.581
Front Roll over	0.219	41.587
Side Impact	1.4683	67.824
Torsional Rigidity	1.0467	41.101

Therefore rear impact force applied on each node = 24452.99/4 = 6113.25 N

This simulates the situations in which vehicle may fall over on its front side as there won't be any direct forces that would cause rollover thus rollover impact was analyzed for 2.5 G's of deceleration hence taking deceleration during vehicle impact a = 2.5G. This force is applied on 2 nodes of the front Lateral Cross member (LC) so from Eq. 1, we can calculate front roll over total deformation and maximum stress as shown in Figs. 14 and 15.

Force $F = 249.27 \times 2.5 \times 9.81 = 6113.35$ N

Therefore force applied on each node = 6113.35/2 = 3056.67 N

A side impact is most likely to occur with the vehicle being hit by another vehicle as it is most likely to occur with the vehicle already in motion. This force is applied on 4 nodes on the left Side

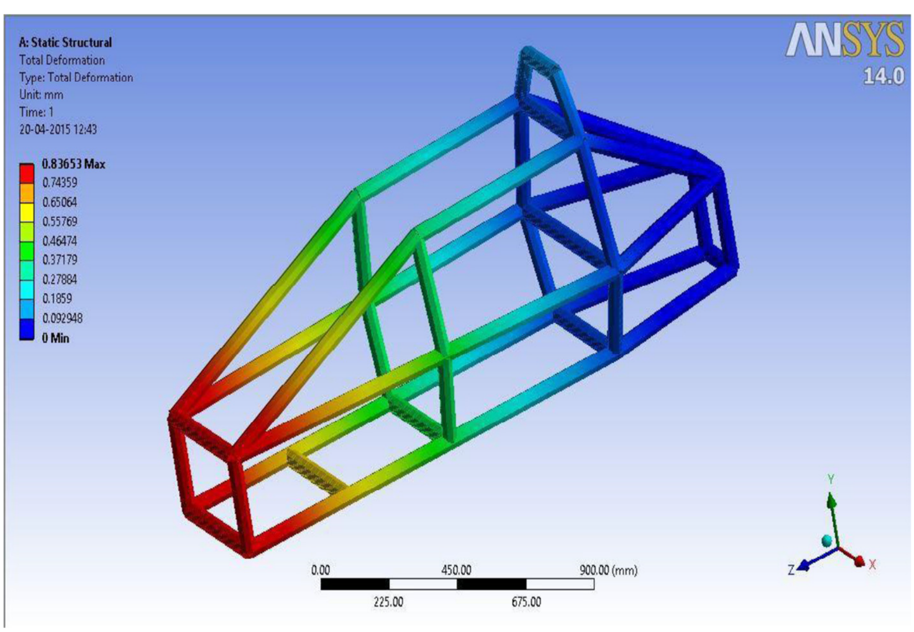

Fig. 10. Front impact -Total Deformation.

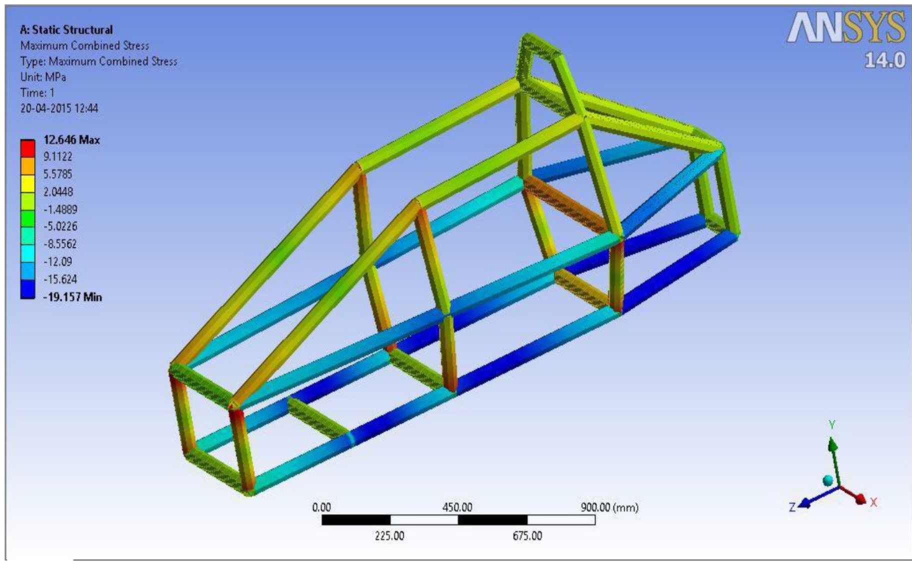

Fig. 11. Front impact -Maximum Stress.

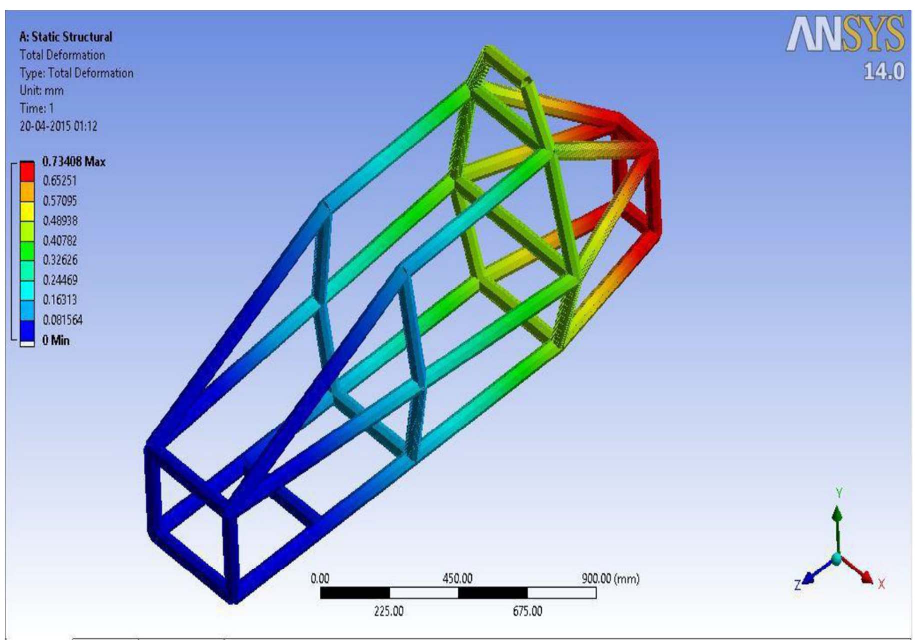

Fig. 12. Rear Impact -Total Deformation.

Impact Member (SIM) and Lower Frame Side (LFS) member so from equation no. (3) We can calculate side impact total deformation and maximum stress by keeping deceleration during vehicle impact a = 5G as shown in Figs. 16 and 17.

Force $F = 249.27 \times 5 \times 9.81 = 12226.50$ N

Therefore force applied on each node = 12226.50/4 = 3056.67 N

4.2. Torsional Rigidity analysis

Roll cage is subjected to torsional load during cornering and when one wheel goes over a bump so from Equilibrium Eq. 2We can calculate torsional rigidity for total deformation and maximum stress as shown in Figs. 18 and 19.

$$T_{max} = \frac{P_{axle} \times B}{2} \tag{2}$$

$P_{axle} = m \times g$

$P_{axle} = 249.27 \times 9.81 = 2445.34$N where track width B = 1.3 m (assuming)

$$\text{So}\, T_{max} = 2445.34 \times 1.3/2 = 1589.47\,\text{N - m as}\ T = \text{Force} \times \text{Length} \tag{3}$$

So $1589.47 = 2 \times F \times 0.325 + 2 \times F \times 0.367$

$F = 1148.46\,\text{N}$

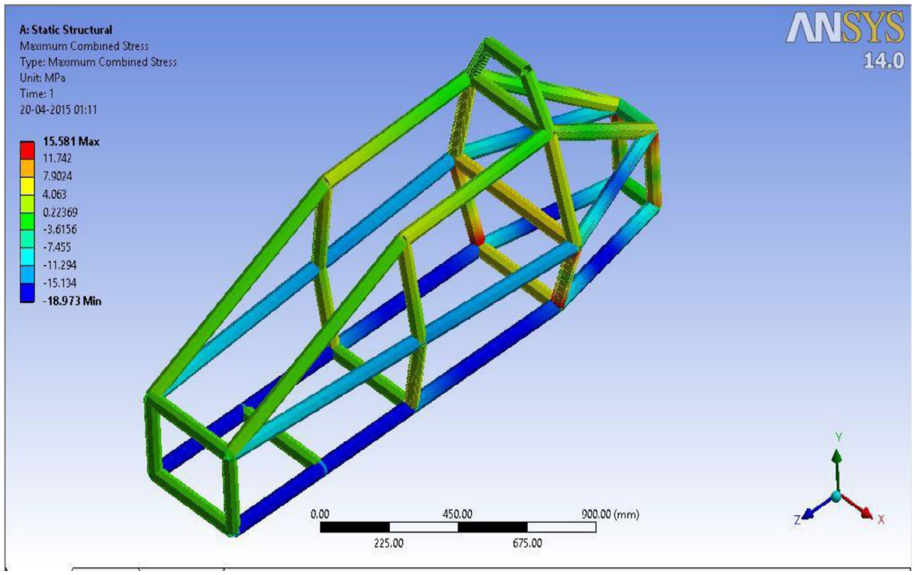

Fig.13. Rear Impact -Maximum Stress.

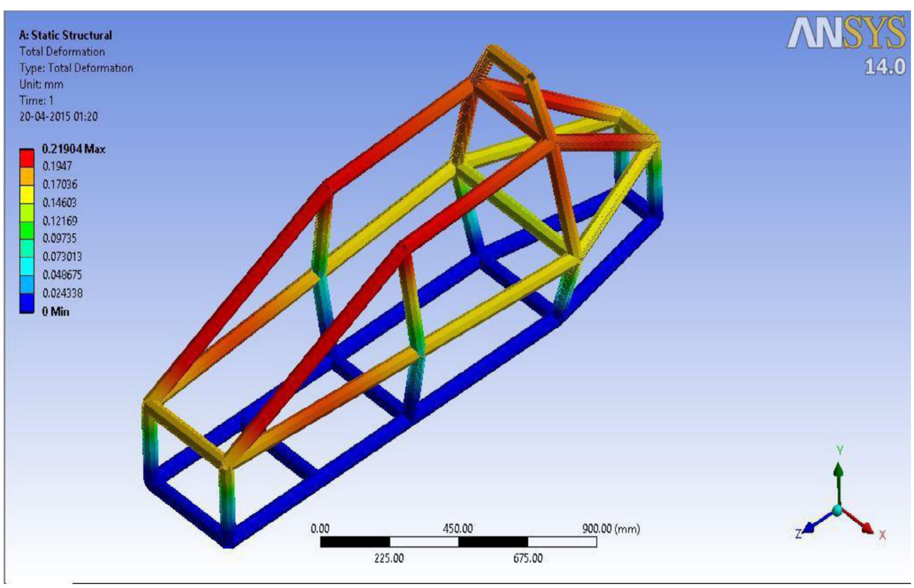

Fig. 14. Front Roll over -Total Deformation.

All tables should be numbered with Arabic numerals. Every table should have a caption. Headings should be placed above tables, left justified. Only horizontal lines should be used within a table, to distinguish the column headings from the body of the table, and immediately above and below the table. Tables must be embedded into the text and not supplied separately. Below is an example which the authors may find useful.

Different stress–strain analysis tests were performed on the roll cage for various impact scenarios with the help of ANSYS WEB 14.0 in order to determine the level of safety for the roll cage. We find the different deformation values and maximum stress with respect to different impact test as per table no. 4. The result shows that relying on light yet strong material such as AISI-1020 in tandem with design optimization lead to the development of a lighter yet more safe roll cage design as fewer members were used as compared to a conventional Fromula-1 roll cage.

5. Conclusions

In this research article AISI-1020 tubular steel has been used to design a roll cage of a formula one car. Finite element analysis has been performed to optimize the maximum load bearing capacity and manoeuvrability conditions. Following conclusions have been enumerated by the present study:

1. From the analysis of front and rear impact tests, it has been observed that less deformation is produced at a higher value of stress.
2. From the analysis of front rollover and side-impact test, it has been observed that higher stress produces higher deformation.
3. The results show that employed AISI-1020 material is able to use for the development of a lighter and highly safe roll cage design as compared to a conventional Formula-1 roll cage.

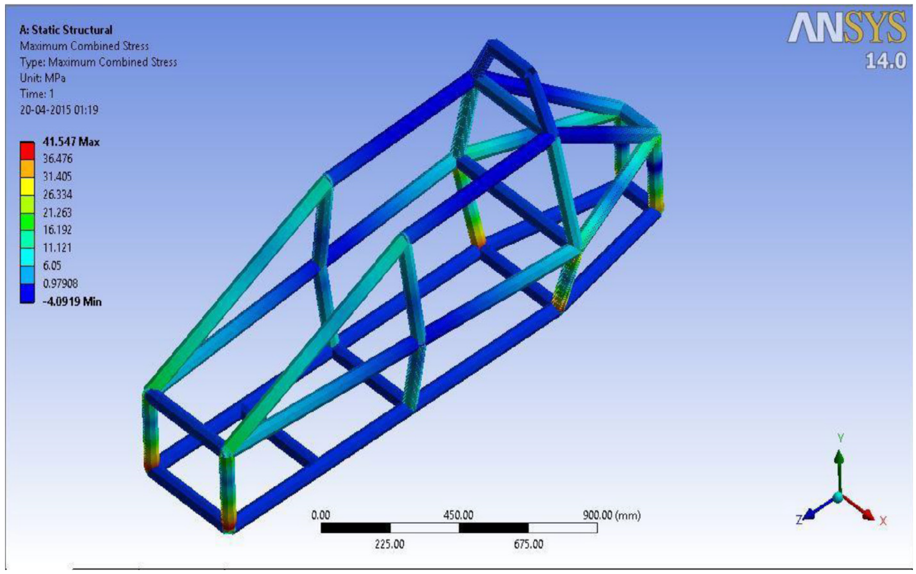

Fig. 15. Front Roll over - Maximum Stress.

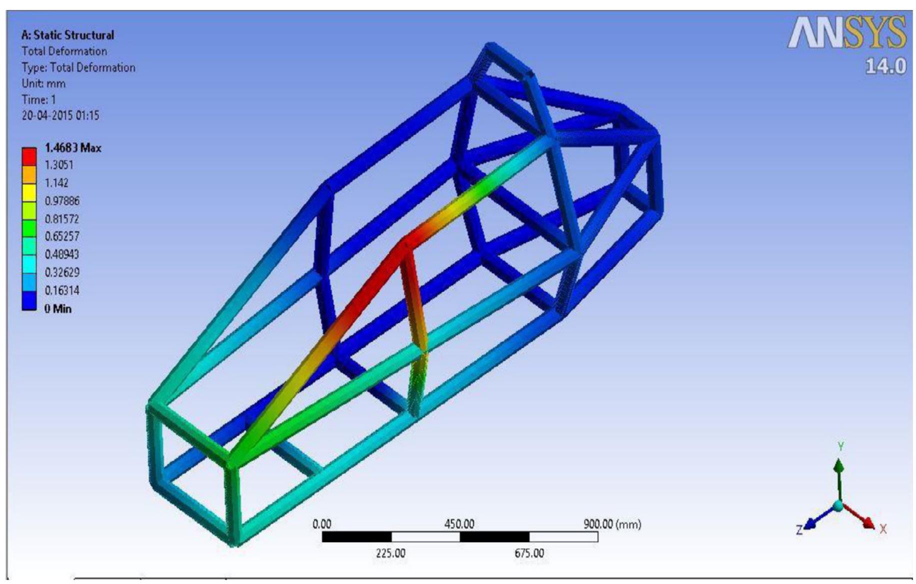

Fig. 16. Side Impact -Total Deformation.

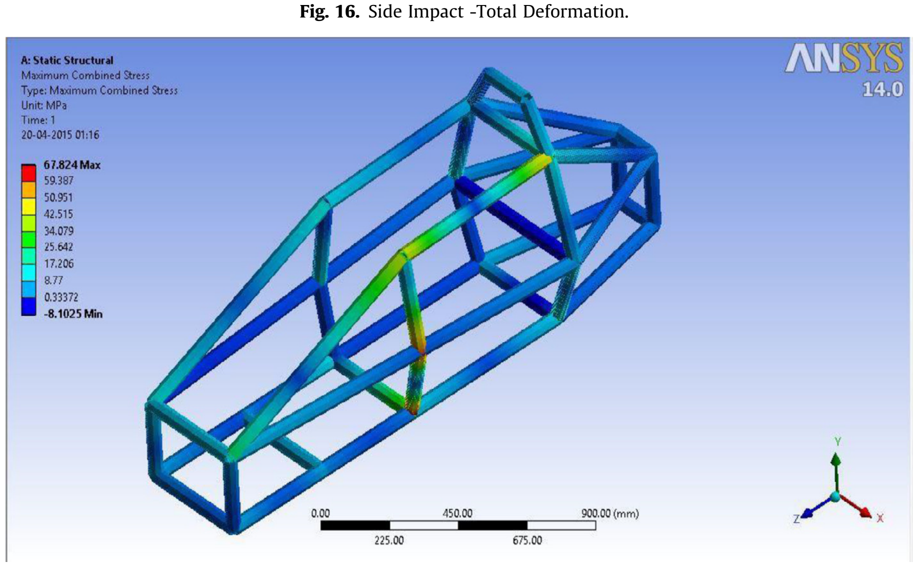

Fig. 17. Side Impact -Maximum Stress.

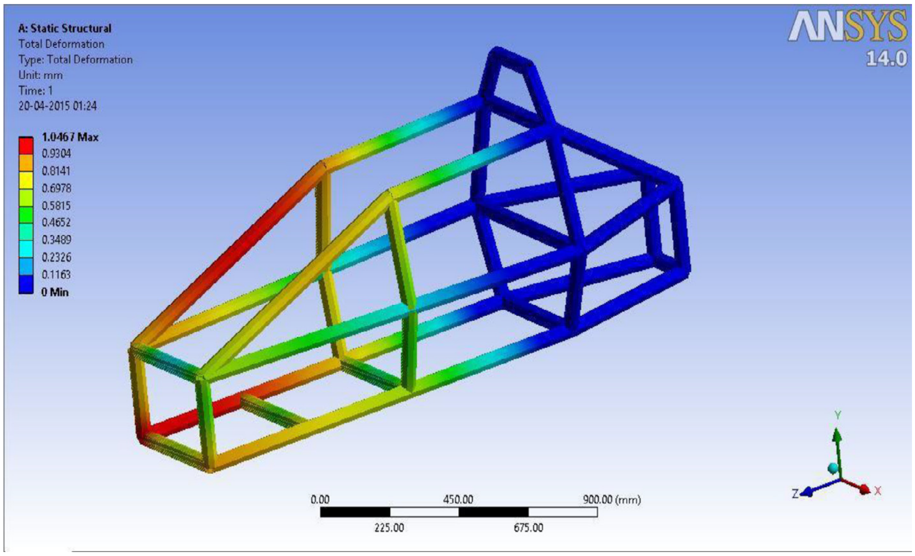

Fig. 18. Torsional Rigidity- Total Deformation.

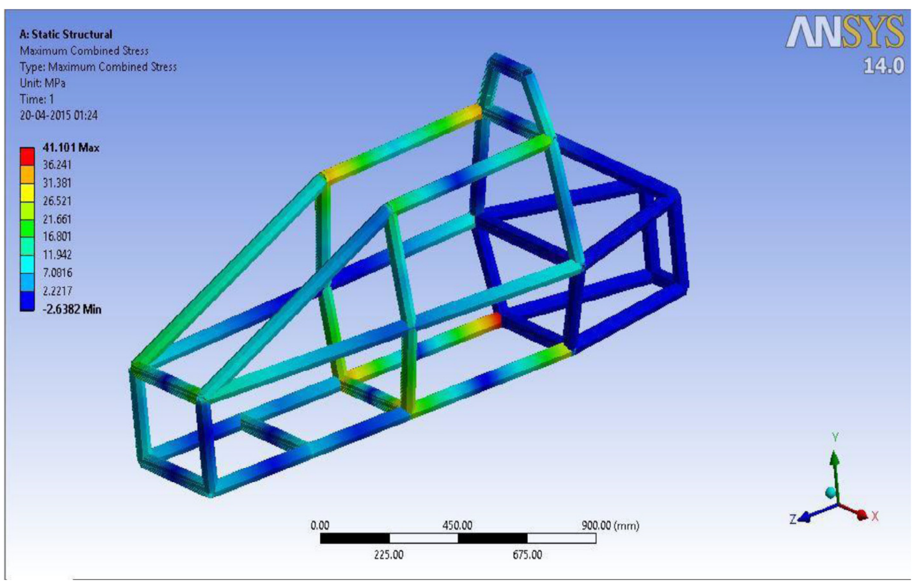

Fig. 19. Torsional Rigidity- Maximum Stress.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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