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The Design and Analysis of Multiple Monocoque Chassis for Formula Student (FS) Racecar

Research Article

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Abstract

This paper presents an initial understanding of the designing and analysis of multiple monocoque chassis formula student race carsmade of carbon fibre considering high strength to weight ratio as well as focusing aerodynamics and manufacturability. An efficient design can achieve weight reduction and manufacturing ease through achieving high torsional stiffness and strength. Hence different loading analyses on all thehybrid monocoque chassis designs and investigating the performance based on torsional stiffness, static loadings, and strength to weight ratio for the chassis selection purposes as well as meeting the FSAE competition rules and requirements.The details approach of several investigated loading scenarios highlighted in order to meet the strength/weight ratio and torsional stiffness demands with ergonomics and structural properties for the low overall weight for a race car monocoque chassis which were considered to be essential towards satisfying the performance aspects of the monocoque chassis designs, factors such as the configuration of the provided materials and implementing its properties during the finite element analysis (FEA), e.g., core thickness and some ply layups to be used for face skins for defining the weight of the monocoque chassis structure. Commercial design software CATIA V5 is used to design all the monocoque chassis for the FS caraccording to the provided SOLIDWORKS 2016 space frame model of Coventry University's FS car, hence fulfilling all the requirements of 2015-16 Formula FSAE Rules for the competition.According to the simulated result, it seems among the four design concepts, the design configuration (2) shows a prominent choice for all parameters for all chassis design considering excellent torsional and specific stiffness along with low weight factor. Other design configurations (1) and (3) Further, these analyses can be performed for other design configurations by considering engine bracket and rim stiffeners assembly with chassis during the FEA, this may increase weight factor slightly but can result in a further increase in torsional stiffness and resistance to static vertical bending.

Keywords: Formula Student (FS); Finite Element Analysis (FEA); Formula Society of Automotive Engineers(FSAE); Centre of Gravity (COG).

Introduction

The single composite monocoque was initially announced in Formula One car in 1962 made of a sandwich panel of aluminium sheet with a balsa wood core. The first carbon fibre made of carbon fibre skin with an aluminium honeycomb core was introduced in monocoque chassis on McLean MP4/1C during 1981 [19]. Still, now the carbon fibre monocoques are applying in Formula One because of the competitive behaviour of the sport, research and manufacturing information popularity held in the commercial. The racing car chassis excellently provides the dynamic forces to attain possibly highest acceleration in the required direction at all times. The main two factors that impacts on design performances are mass and torsional stiffness. During torsional stiffness analysis, the racing car chassis should be modelled as a torsional spring coincident along with x-axis. However, a feeble spring will have a significant impact on the lateral load transfer at the front and rear track, resulting in unpredictability and difficulty for drive to control and resist the different rolling moment at the front and the rear of the car [12]. The inertial forces and CoG (Centre of Gravity) can be determined by the mass of the chassis which are an important factor of braking, cornering and acceleration of the car.

The chassis body is considering as a suspension model which provide a path to connect the front and rear suspension units. The role of suspensions is to make sure that all tires continue to

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maintaindirect contact with thesurface of the ground during hard manoeuvres, yet still, a weak chassis torsional spring can reduce the chances of suspension performance optimization, causing the chassis to take over control of lateral load transfer. However, the issues can be solved by increasing the torsional stiffness [14].

The Project was completed by considering all the FSAE International Rules, hence successfully tackling the design limitations for the monocoque chassis structure and controlling the torsional stiffness and static loading by using multiple-ply layups of carbon fibre sheets and aerospace grated Nomex honeycomb core of different thickness for the weight purposes. The paper also consists of a review of previously done work, FEA and conceptual justification of material choice for chassis made of carbon fibre. It alsocovers the results of loading conditions imparted on the monocoque chassis during the ABAQUS analysis for achieving high strength and safety factor by less structural weight, hence by making changes in the design process based on structural geometry with the implementation of the carbon fibre composite properties.

Formula Sae Competition and Rules

Formula SAE is an international committee set in 1978, which organizes an engineering design competition for all University students. However, the main concept of this competition is to allow students to tackle engineering designs and project management skills by following a specific set of rules for the challenges. Students are set up a goal for this competition is to come up with a manufactured single seated race car by following the Formula SAE Rules which is later going to be scored based on its performance, manufacturing cost, design and construction aspects [15].

FSAE competition specifies a set of rules and guidelines for all the university students which are meant to be strictly considered during the designing and construction process of the race car, hence keeping the competition fair for everyone. The rules define the limitations over the designing, aerodynamics and other aspects of the vehicle for performance as well as specifying the scoring criteria of the competition. These rules are explained throughout the report. Below Figure 1 shows standard rules of chassis structure.

Conceptual Background and Review

Monocoque Chassis

The word 'monocoque' is derived from the French language, which means 'single shell'. As from the meaning itself, it explains monocoque structure as a stressed outer surface with the loads distributed over the shell surface. In 1960, Cylindrical shape monocoque structures were considered for the race cars for improving the torsional rigidity [8]. Below Figure 2 shows a general model of monocoque chassis.

Figure 1. Standard Chassis rules (15).

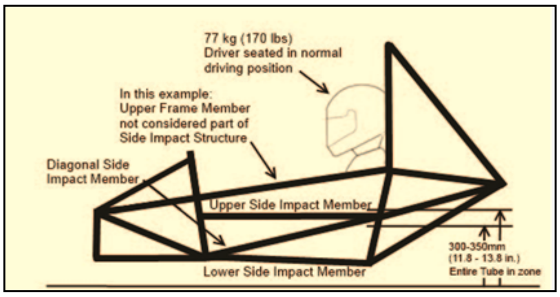


Figure 2. A Monocoque Chassis structure (7).

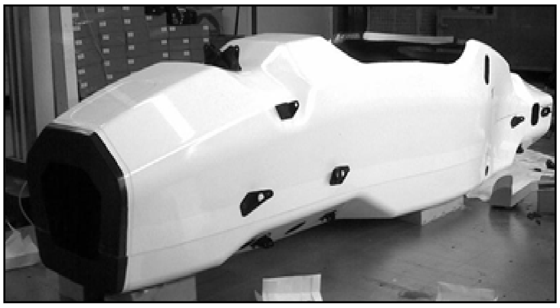


Figure 3. Hybrid Chassis design (3).

The monocoque chassis is mainly manufactured out of carbon fibre composites as due to its lightweight and high torsional stiffness towards the structure, along with this it adds limitations towards the design and high manufacturing cost. Other materials such as aluminium and glass fibre are also considered for chassis production. This chassis is a hybrid version of monocoque chassis with a rare end as a space frame. This chassis structure offers a lightweight and high torsional stiffness properties along with the accessible construct rear, providing better access to vehicle components such as an engine. An example of a hybrid monocoque chassis is shown in the figure below. Loading paths are meant to be predicted, and the integration among the two sections are necessary to be determined for avoiding complications during the use of hybrid chassis [7] shown in Figure 3.

Chassis Load Cases

Chassis plays a vital role like a skeletal edge in the automobile, which is attached to different mechanical parts for the example suspension system, braking and handling, power train, engine, the body as well as tires [16]. Weak chassis design and strength may lead to failure for other mechanical parts to function well to all car systems. The other function of a chassis relies on both static and dynamic load, which is applied to resist fewer failures like distortion and deflection.

Global load cases are defined as the loads acting on the whole chassis structure of the race car. These global loads are of four types described as:

- Torsional stiffness.
- Vertical bending.
- Lateral bending.
- Horizontal Lozenging.

As of this study solely focus on torsional stiffness and vertical bending of the monocoque chassis structure made of carbon fibre.

Torsional Stiffness

The main loads which are kept in consideration during the design and construction phase are the torsional loads. These loads attempt to create a moment or rotation on one or the other end of the chassis, hence adding a negative impact on the handling performance of the car. Various conditions are responsible for torsional loads; however, the most common case is shown in Figure 4 below, demonstrating a torsional loading on one-wheel bump model.

The figure shows the upward bump of one wheel causes a torque to act upon the chassis while the rest three wheels remain at their original vertical orientation. Several different methods are considered nowadays for estimating the torsional stiffness of a vehicle. However, the target for torsional rigidity varies from 2-10 times of anti-roll stiffness. The chassis can be designed to have a stiffness which can be x times the variance between the front and rear suspension stiffness or x times the total roll stiffness of the suspension where x varies from 2 to 5 times(12). According to Deakin and Crolla, a factor of 4 is enough to determine the stiffness; that is four times of anti-roll stiffness [5].

Based on the FSAE competition, the highest torsional stiffness was recorded to be of 300 KNm/rad for a chassis mass <20 kg. On the average scale, the torsional stiffness of 140 KNm/rad for a chassis mass of 25 kg. However, torsional stiffness concerning chassis mass is shown in the below.

Figure 4. One-wheel bump model(12).

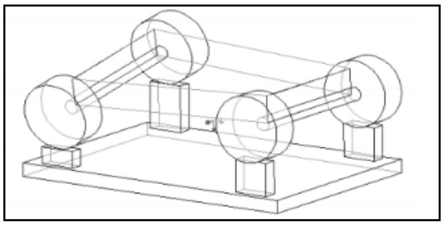


Figure 5. General model of chassis and suspension torsional stiffness(10).

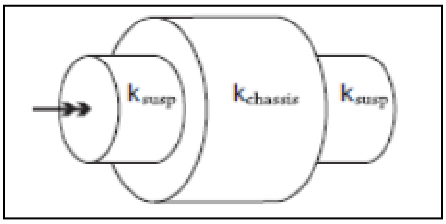


Table 1. FSAE competition performance data and project target(10).

FSAE Competition	Mass(kg)	Torsional stiffness (k)(KNm/rad)	Specific stiffness(KNm/rad/kg)
Low	30	50	1.7
Average	25	120	4.8
High	<20	200-300	>11
Project Target	<25	>200	>8

Typically, high torsional stiffness is attainable through measuring specific stiffness which is defined as stiffness per kilogram of cases. On the other hand, increasing the toughness of chassis is not exceptionally successful over a certain level. The following Figure 5 demonstrates the three torsion tubes in series. In the equation, k_{susp} stands for the suspension system of front and main tube in torsion and $k_{chassis}$ represents the stiffness of chassis. This stiffnessindicates the resistance of vehicle imperviousness to torsional bend given as k_{veh}. It is clearer that k_{veh} is then partitioned by the summative suspension stiffness to show the firmness for the torsional case.

$$\frac{1}{k_{veh}} = \frac{1}{k_{susp}} + \frac{1}{k_{chassis}} \quad \text{----- (1)}$$

$$k_{rel} = \frac{k_{veh}}{2 / k_{susp}} \quad \text{----- (2)}$$

Bending Stiffness

Bending stiffness of the chassis during torsion is a vital part to be focused. As a result of this bending stiffness depends on the elastic modulus of the material and moment of inertia of the structure (E and I), there are several ways of increasing the bending stiffness as listed below,

- Increasing El by considering a sandwich panel.
- Folding open edges in perpendicular to the plane.
- Using material with high E/ϱ, E^2/ϱ and E^3/ϱ.

Another problem which is a need to be prevented is delamination which may result due to open ply ends. With increasing *I*, the open-end ply can be prevented, as shown in Figure 6 below.

Vertical Bending

This bending is due to the vertical loading of the driver, combustion engine and other components of the vehicle causing the chassis to squats or dives during the acceleration or deceleration period. Vertical bending is shown in Figure 7usually come into focus because of the longitudinal load transfer initiated by the variation in speed. The squat behaviour can be control through introducing suspension linkages with the anti-squatsystem to decrease the reaction force. The other response to the vertical loading is the divingbehaviour caused by the braking, which can be reduced through optimized suspension linkage [18].

According toMilliken and Milliken, the vertical bending is not considered as an essential factor during the designing process of the chassis as it does not affect the wheel loads. As from the source, it can be found that a chassis which provides an excellent resistancetowards torsional rigidity has a sufficient bending stiffness for the performance shown in Figure 7 [12].

In the static position, the chassis must be available to support the weight of all vehicle components which sums up to 250 kg. As in our case, uniform distribution of pressure is applied on the lower surface of chassis with its rare and front end fixed to demonstrate the maximum weight it can withstand.

Figure 6. Preventing open ply edges (left), Increasing edge bending stiffness(centre), a combination of both (right) (10).

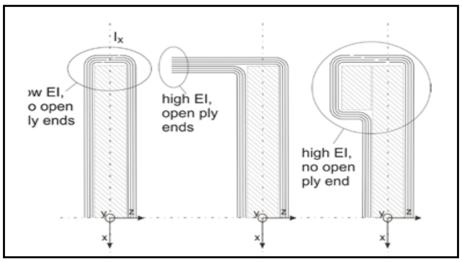


Figure 7. Vertical bending caused by the squatting (12).

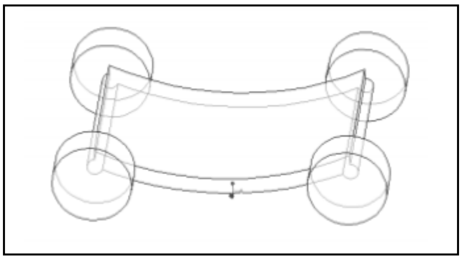
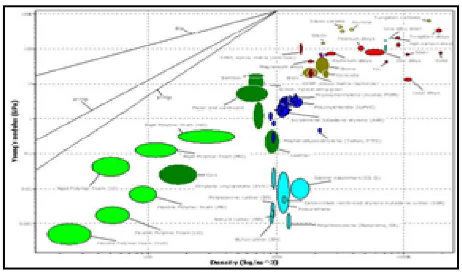


Figure 8. The list of materials based on young modulus and density (7).



Material Selection

Material properties play an essential role in defining the performance of the chassis structure. The chassis performance limits (i.e. strength to weight ratio) can be kept in focus during the designing stage for optimizing the geometry of the structure by material properties. Eurenius and his team with the help of CES (Cambridge Engineering Selector software) have done analysis is performed in the form of thebubble diagram Figure 8, presenting a list of materials based on strength to weight ratio [7].

From the above chart, carbon fibre composites show a high-performance figure based on strength to weight ratio, the reason they are trendy in the industrial market of theautomotive industry. Some alloys of steel, aluminium and in some cases wood also show required properties for monocoque chassis structure. Based onthe above chart, Carbon fibre composite is the optimal solution for the chassis design.As discussed before, the material properties itself does not reveal the chassis performance; however, the geometry and the design aspects are also crucial, for instance, steel is much more suited for space frame and Carbon fibre, due to its flexibility is more prominent for monocoque chassis.

Space Frame Materials

Different types of steel alloys are mostly considered for space frame structure as they exhibit properties of being tough, durable, easily formed and cheap. Mild steel is widely considered because of its low fraction of carbon makes it adhere properties of being soft, easy to shape and relatively cheaper manufacturing cost. Other than mild steel, CrMo-4130 also reflects high strength properties, but it is more complex to manufacture.

As from the previous research and experimental results it can be noticed that the materials with high strength to weight ratio other than steel can successfully help in improving chassis performance such as CFRP (Carbon Fibre Reinforced Polymers) shows highly suitable properties but are very difficult and complex to manufacture as compared to steel. [13].

Monocoque Chassis Materials

The requirements of material properties and load cases changeentirely for the monocoque type of chassis, CFRP is the most widely used material in today's industry for the monocoque structures. CFRP (Carbon Fibre Reinforced Polymers) as from name it explains itself that, a set of carbon fibre are woven together and reinforced by a polymer matrix material (epoxy). In the CFRP, the matrix material helps in transmitting loads to the fibre where the mechanical loads are carried by the fibres hence providing the required toughness and ductility along with protecting it from being damaged from the surroundings [7]. An example of the woven fibre matrix is shown in Figure 9.

For the monocoque chassis, the carbon fibre matrix is sandwiched with other material with core properties to form a sandwich structure. Figure 10 shows a general layout of thesandwich structure where the sandwich structure is generally compromising of two face skins on either side sandwiching a core of other material. Combination of face skin with core gives the required resistance towards bulking and bending loads, as this sandwiching results in an increase of moment of inertia.

Selection of right material for the core and its combination with face skins decides the structural strength and the bending stiffness of the monocoque chassis [2] shown in Figure 10. The structure of the core material is also a factor towards the performance of the chassis. Several different ways are considered nowadays in the industry for manufacturing the core structure. Mostly metal foams are considered fo core material choice. However, another structural shapes honeycomb is highly recommended due to its low density along with high compression and shear properties. The core can also be substantial such as wood [4]. As most of the load acts on the face of the sandwich panel, the core material must be stiff and keen to provide the required resistance towards the acting load. As sandwich panel large volume is being covered by the core, it should possess properties of being light, strong and stiff, necessarily enough to show resistance against the shear stresses cause due to acting loads on the structure panel [2].

According to Savage, the performance of the sandwich structure

Figure 9. CFRP in woven fibre matrix(7).

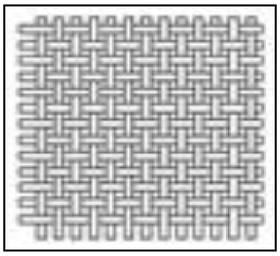
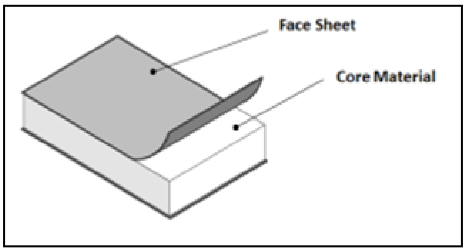


Figure 10. Layout of a general Sandwichstructure panel.



mainly depends on the core type. On the industrial basis, two commonly used cores are Foam and Honeycomb [17].

The combination of Carbon fibre woven matrix as face skin with Nomex honeycomb core gives the required stiffness to weight ratio for fulfilling performance limits; however, the downside for CFRP is the complicated manufacturing procedure of woven fibre matrix and cost. Aluminium can be considered as the core material for low cost but provides low stiffness to weight ratio when to compare to CFRP [6].

Core thickness

Core thickness has a direct relation with the strength, stiffness and weight of the sandwich structure. Hence in order to compromise with the design limitations, below Table 2 demonstrates a solution over core thickness compared to improved weight, strength and stiffness of the sandwich panel [17].

Table 2: Relation between core thickness and sandwich structure-mechanical properties.

It is to be noted that increasing the core thickness does not relatively provide the best solution as it complicates and limits the particular type of shapes and requires more space.

The failure modes associated with the core thickness gives an ideal limit for the core thickness selection. As demonstrated in the below Figure 11, some of the most common failure modes due to core thickness are core failure, face bucking, face indentation and face yield.

Core failure is mainly caused by the hinges in the face and the core itself under the load. Face buckling failure mode is mainly due to thin face skins and limited support of core structure. Face indentation depends on the impact area, and face yield occurs when one of thesurfaces are under high stress due to acting pressure [7].

Chassis Design and Methodology

Design Targeted Weight

According to Lamer, physically reduction in mass from the structure can affect the vehicle handling five times more than mass reduced numerically. The sensitivity of the lateral grip has been investigated by him in g is for both mass and height of CoG (centre of gravity) in cms [11] shown in Table 3 with sensitivity.

By looking at all the possible solutions, the weight of the vehicle can be reduced through using the material which adds properties like low density, flexibility and high strength for giving design freedom for high performance. However, additional use of material for the driver compartment for adding stiffness and strength can be considered in the design process. As from the competition, the weight of the monocoque chassis is set to be < 25 kgs. The centre of gravity of the vehicle can further be lowered by adjusting the driver seat in the right position and also by changing the drivers back angle, which may allow lowering the main roll hoop.

Selected material Properties

For the FEA techniques, two different thickness (5mm, 10mm) of Nomex honeycomb core were used for different chassis design for a variation in analysis results.Below Table 4 refers to the material properties to be used for the monocoque chassis.

As from the FSAE competition rules and regulations [15], steel is the only allowed material for the roll hoops. The mild steel of young modulus of 200 GPa and the Poisson ratio of 0.3 is being used of the main and front roll hoops as because of its low frac-

Table 2. Relation between core thickness and sandwich structure-mechanical properties.

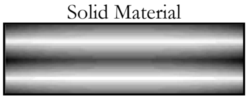
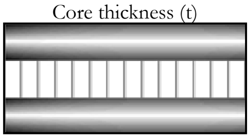
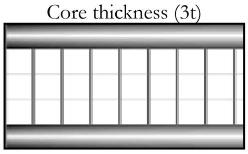
Solid Material 	Stiffness - 1 Weight - 1 Flexural strength -1
Core thickness (t) 	Stiffness - 7 Weight – 1.03 Flexural strength – 3.5
Core thickness (3t) 	Stiffness - 37 Weight – 1.06 Flexural strength – 9.2

Figure 11. Failure modes associated with core thickness (7).

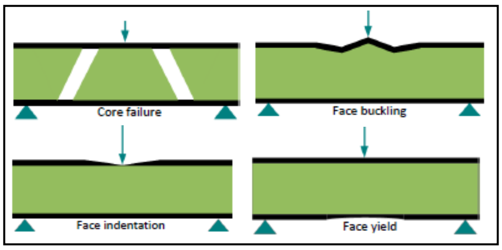


Table 3. Convenient numbers for defining sensitivities

Lateral g is to mass	Lateral g is to COG height
2.49* g/kg	11.75* g/cm

Table 4. Material properties for monocoque chassis(1)(9).

Material	E_{11} (MPa)	E_{22} (MPa)	v_{12}	G_{12} (MPa)	G_{13} (MPa)	G_{23} (MPa)
Plain-weave fabric	62052.81	62052.81	0.05	5515.805	5515.805	5515.805
Nomex honeycomb core	0.00689	0.007	0.5	0.00689	13.789	13.789

Figure 12. Driver clearance requirements (SAE International, 2016).

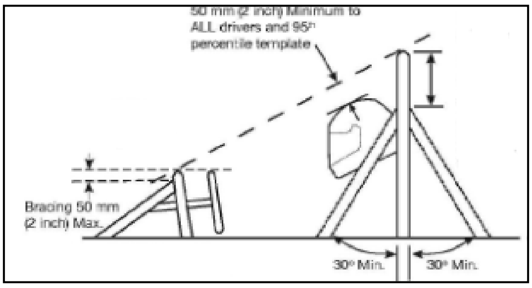
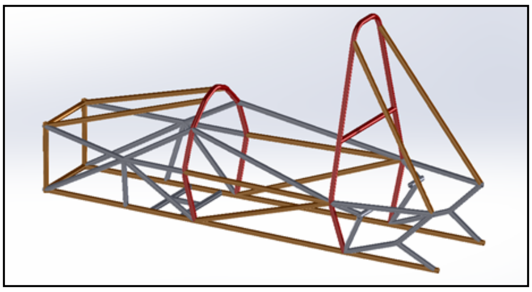


Figure 13. Coventry University FS-CAR space frame.



tion of carbon makes it adhere properties of being soft, comfortable to shape and relatively cheaper manufacturing cost as well provides the required strength and stiffness.

Design Shape Development

Some set of data and limitations to be considered during the design aspects of the structure. Following approach were taken into account for high-quality design,

• Possible limitations, due to provided material affecting the structure performance were investigated.
• Specifications based on Formula SAE rules were considered shown in Figure 12.
• Structural loading path on the chassis wasanalyzed.
• Ergonomics and safety factors were estimated.
• Combining all the aspects as mentioned above in the final Design for FEA analysis.

Four different geometrical hybrid monocoque chassis was designed by the provided SOLIDWORKS model of (2016) Coventry University FS car space frame. (as shown in Figure 13).

All the designs of hybrid monocoque chassis were following FSAE rules and regulations as well as other contributing factors such as aerodynamics, ergonomics and manufacturability ease was also considered, following Figure 14, Figure 15, Figure 16 and Figure 17 show all the assembled monocoque chassis with front and the main roll hoops, the surface modelling was performed in the Catia V5 software.

The surface modelling was performed by using the geometrical dimensions of the Coventry University (2016) FS car space frame and implementing these figures in the Catia v5 software by careful placement of the planes. Sketching was performed on different planes based on the diameter of the chassis surface and shape. Ones all the outer boundaries of the chassis were defined, with the help of multi-section surface option, a surface model was made and later assembled with the front and main roll hoop. The minimum dimensions of the main and roll hoops which must be maintained were defined in FSAE rules, shown in (15).

Some variations were made on the chassis designs based on dimensions and geometrical constraint without affecting the FSAE rules and regulations, hence considering thelowcentre of gravity point, strength and other relevant performance factors.

Manufacturability

The study has been performed on the numerical study, but no component was manufactured for any physical analysis. However,

Figure 14. Surface modelling of design 1.

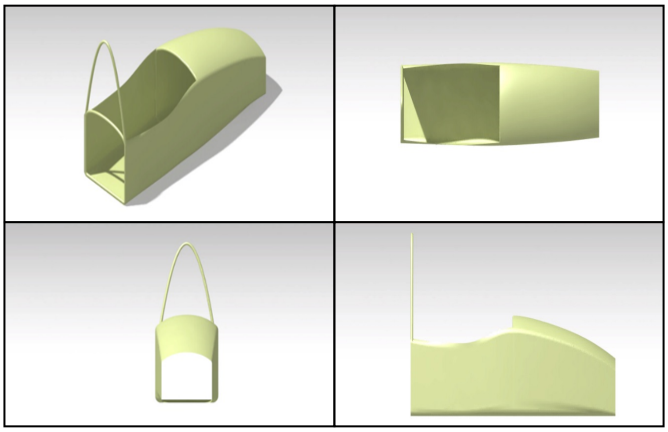


Figure 15. Surface modelling of design 2.

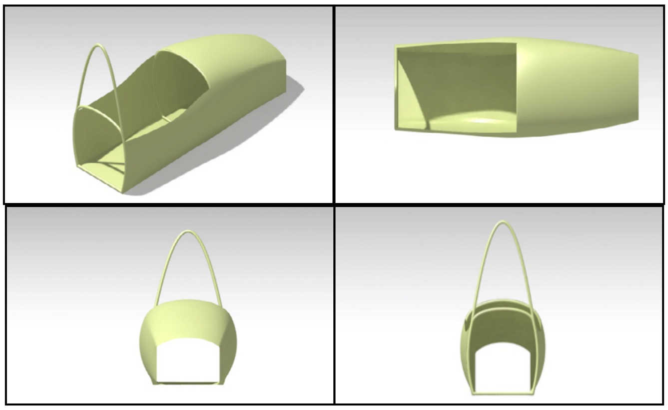


Figure 16. Surface modelling of design 3.

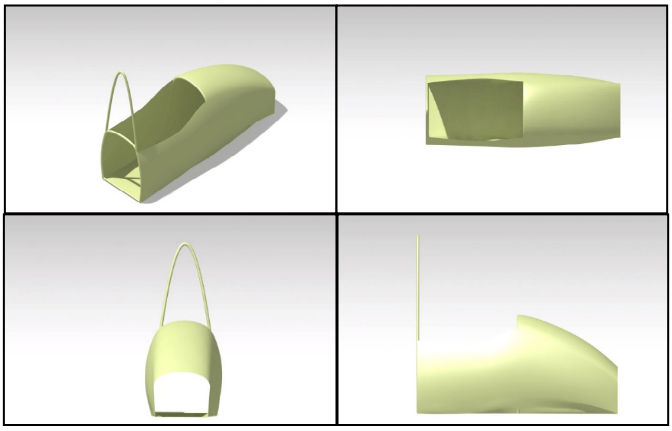
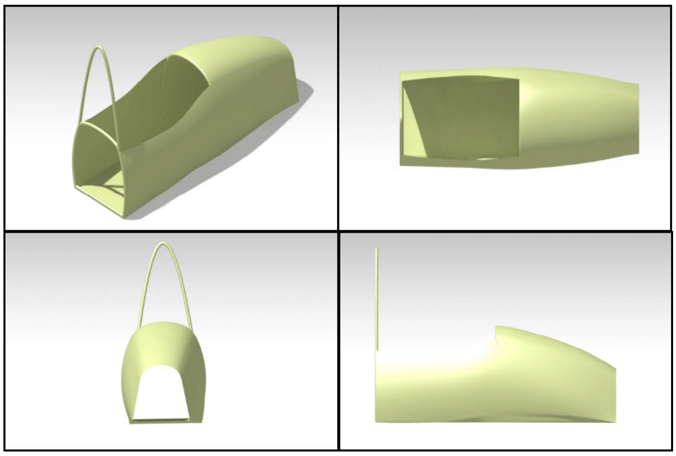


Figure 17. Surface modelling of design 4.



the most effective and cheap procedure for constructing monocoque chassis can be vacuum injection moulding process.

The method requires the use of dry pre-woven plies along with the resin. The resins are inserted from one end of the mould while vacuum pressure is applied on the other end. This vacuum suction allows a smooth transfer of resins throughout the surface hence giving a smooth finishing touch at the mould side. However, the manufacturing process is cheap but required great operating skills for needed properties, and the mould should not be resistant to pressure and temperature during the process.

Analysis and Results

Finite element analysis of the hybrid monocoque chassis was performed in the ABAQUS software. As of the Project for defining the strength properties, two main analyses were performed for determining the following:

- Torsional Stiffness.
- Uniform Vertical Bending.

As of the shell model setup for analyses, the following Table 6configurations were used for all the chassis design for determining the load factors.

Assembly of the monocoque chassis with the front and main roll hoops were performed, and material properties were defined in the Abaqus during the analysis procedure. Mesh size of 10 was set for the complete model for performing an accurate analysis. Ones all the boundary conditions were defined; loads were setup for performing the tests. The job was created, and the analysis was performed. The figure below shows a general model setup of design (1).

Torsional stiffness

A 3D shell model of monocoque chassis was assembled with the front and main roll hoop. The wall thickness of the front and main roll hoops was set to be of 2.5 mm, hence complying with FSAE competition rules [15]. With the help of composite layout function, the material properties of the monocoque chassis were defined. The chassis structure was sandwiched with a Nomex honeycomb core and multiple plies of 0° and 90° woven fabric depending on the configuration. Boundary conditions were applied on the rear end of the chassis, hence fixing the end of chassis (long with main roll hoop). A load of 10KN (safety factor) was applied vertically on both front-wheel placements, acting in opposite directions for creating a torque to define torsional stiffnessshows in Figure 19 the procedure for applying torsional load.

For calculating the torsional stiffness in KNm/rad of the chassis structure, the following relation can be applied:

$$k = \frac{M}{\beta} \text{ -----(3)}$$

$$\therefore M = 2Fl \text{ ----- (4)}$$

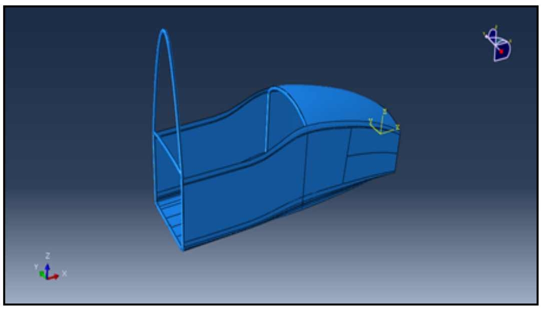
Table 5. Design specification for roll hoops(15).

Component	Roll hoops shoulder harness mounting bar of Main and front
Outer diameter Xwalls thickness	25.0 X 2.50 mm or 25.4 X 2.40 mm

Table 6. Monocoque chassis design configurations for analysis.

Configuration	Material		Thickness		No. of Layers	
	Face skin	Core	Face skin (mm)	Core (mm)	Face skin on each side	Core
Configuration (1)	CF weaved fabric	Nomex honeycomb	0.25	5	8	1
Configuration (2)	CF weaved fabric	Nomex honeycomb	0.25	10	4	1

Figure 18. Shell model setup in Abaqus.



$$\therefore \beta = \tan^{-1}\frac{\Delta z}{l} \text{ ------ (5)}$$

$$k = \frac{2Fl}{\tan^{-1}(\frac{\Delta z}{l})} \text{ ------ (6)}$$

Where,

k, torsional stiffness, Δz, vertical displacement, M is the torsional moment, β is the angular deflection caused by the load, and l is the length between the centre and acting load point.

Below Figure 20, Figure 21, Figure 22 and Figure 23 are the maximum vertical displacement results for all the chassis designs with different configurations which tabulated in Table 6used for calculating torsional stiffness, produced from the Abaqus.

With the help of torsional stiffness, (k) calculations are performed, and the results are presented in the below Table 7.

The total mass of the chassis was determined in the Abaqus software itself by defining the density properties of the material. Based on the FSAE competition, the highest torsional stiffness was recorded to be of 300 KNm/radfor a chassis mass <20 kg. On the average scale, the torsional stiffness of 140 KNm/radfor a chassis mass of 25 kg.

However, torsional stiffness for chassis mass is shown in Table 1, and through comprising torsional stiffness results of all the chassis design with data from Table 1, it can be found that torsional stiffness of all chassis design with configuration (1) and (2) are above average requirement of the FSAE competition.

However, design (1) and design (3) with configuration (2), gives the highest torsional stiffness and specific stiffness under the action of 10KN load (safety factor). Configuration (2), defines the chassis structure as a sandwich panel comprises of a 10mm thick-

Figure 19. Method for applying torsional load (7).

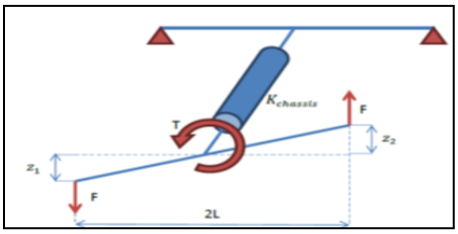


Figure 20. Vertical displacement in the z-direction for configuration (1) [left] and configuration (2) [right].

Design (1)

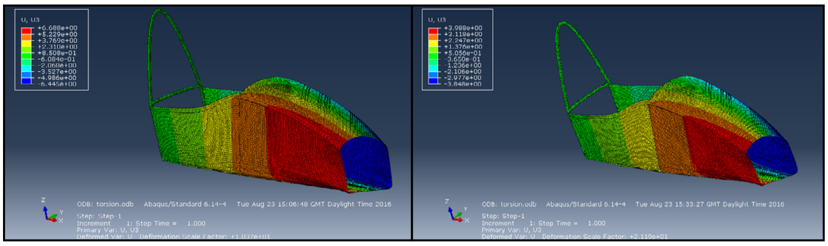


Figure 21. Vertical displacement in the z-direction for configuration (1) [left] and configuration (2) [right].

Design (2)

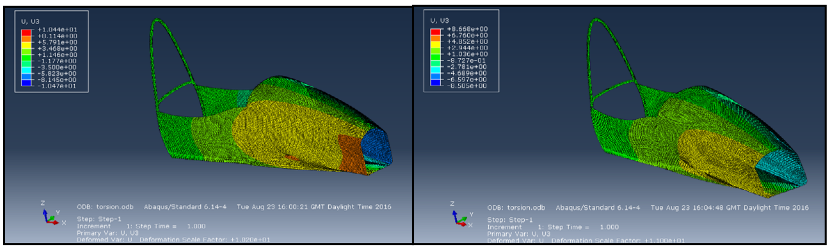


Figure 22. Vertical displacement in the z-direction for configuration (1) [left] and configuration (2) [right].

Design (3)

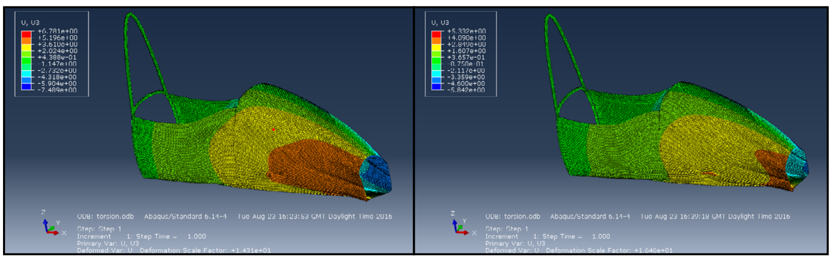


Figure 23. Vertical displacement in the z-direction for configuration (1) [left] and configuration (2) [right].

Design (4)

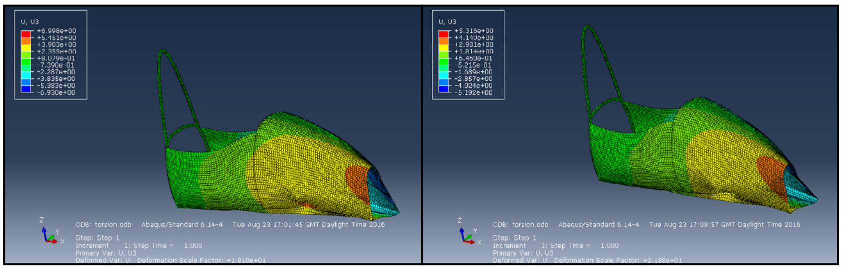


Table 7. Torsional stiffness and weight for all the chassis designs.

Design and Configuration		Force F, (KN)	Length l, (mm)	Vertical Displacement, Δz (mm)	Torsional Stiffness k, (KNm/rad)	Total mass m, (kg)	Specific stiffness (KNm/rad/kg)
Design 1	Config. 1	10	235.504	6.688	165.54	24.5	6.757
	Config.2			3.988	277.576	16.2	17.134
Design 2	Config. 1	10	252.007	10.44	121.728	24.3	5.009
	Config. 2			8.668	146.587	16.2	9.049
Design 3	Config.1	10	228.884	6.781	154.525	23.5	6.575
	Config. 2			5.332	196.553	15.6	12.599
Design 4	Config.1	10	214.607	6.998	131.672	23.4	5.627
	Config. 2			5.316	173.308	15.5	11.181

ness of Nomex honeycomb core with four plies of carbon fibre woven matrix (0.25 mm thickness) faced on each side of it.

As on design failure, Design (4) shown in Figure 23 is undergoing a face buckling which may result due to the use of thin plies or due to exceeding design limitations for the required performance of chassis.

Considering specific stiffness according to FSAE competition, it can be seen that Design (1) and Design (3) with configuration (2) yields higher stiffness than that of high scale on FSAE competition.

Uniform Vertical Bending

Model for performing uniform vertical bending was also setup as same as of torsional stiffness analysis. However, instead of torsional load, a uniform pressure was applied on the lower surface area of the chassis structure, and boundary conditions were applied on the front and rear end of the lower surface area of chassis. As the chassis body has to be strong enough to carry the combined weight for the driver, engine, suspension system, brakes and other vehicle components; pressure equal to 2.4 KN (250 kg) was applied on the lower surface area of the chassis to analyze the displacement and stress over applied load.

Same configuration procedure was used for all the designs as in torsional analysis, and following results were gained from Abaqus in Figure 24, Figure 25, Figure 26, Figure 27, Figure 28, Figure 29, Figure 30 and Figure 31.

The results are presented in the following Table 8.

According to Milliken and Milliken, the vertical bending is not considered as an important factor during the designing process of the chassis as it does not affect the wheel loads(12). As from the source, it can be found that a chassis which shows a good resistancetowards torsional rigidity has a sufficient bending stiffness for performance.

All the designs show good resistance against vertical bending. As mentioned before, design (1) and (3) with configuration (2) shows the best torsional stiffness, however, from Table 8 it can be found that design (1) and (3) with configuration (2) also shows a good resistance towards vertical bending. Below Table 9 shows the chassis designs which complies best with FSAE competition requirements for high performance.

Design (1) and (3) with configuration (2) are the recommended designs to be considered for future construction of chassis of FS race car due to their high torsional stiffness and good resistance to vertical bending (as from Table 8), hence lying within the competition rules and regulations.

Conclusion

Results from the Abaqus analysis were compared with the current up to date torsional stiffness and specific stiffness performance parameters of the competition. Positive outcomes were observed based on all designs with different configurations. Design (1) and (3) with configuration (2) shows the best suitable performance parameters based on torsional and specific stiffness. The Project is completed by considering all the FSAE International Rules, hence successfully tackling the design limitations for the monocoque chassis structure and controlling the torsional stiffness and static loading by using multiple-ply layups of carbon fibre sheets and aerospace grated Nomex honeycomb core of different thickness for the weight purposes.

On the recommendation basis, configuration (2) are the ideal

Figure 24. Displacement (top) and stress (bottom) along the whole lower surface of the chassis with analysisDesign (1) configuration (1).

Design (1), Configuration (1) and Configuration (2)

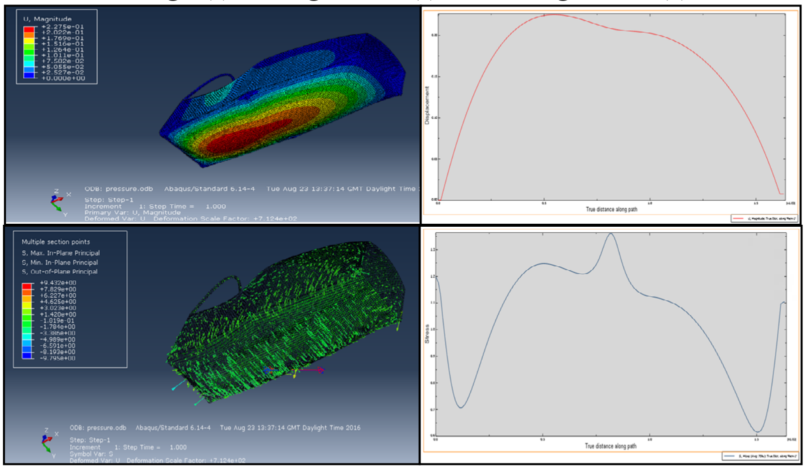


Figure 25. Displacement (top) and stress (bottom) along the whole lower surface of the chassis with analysis Design (1) configuration (2).

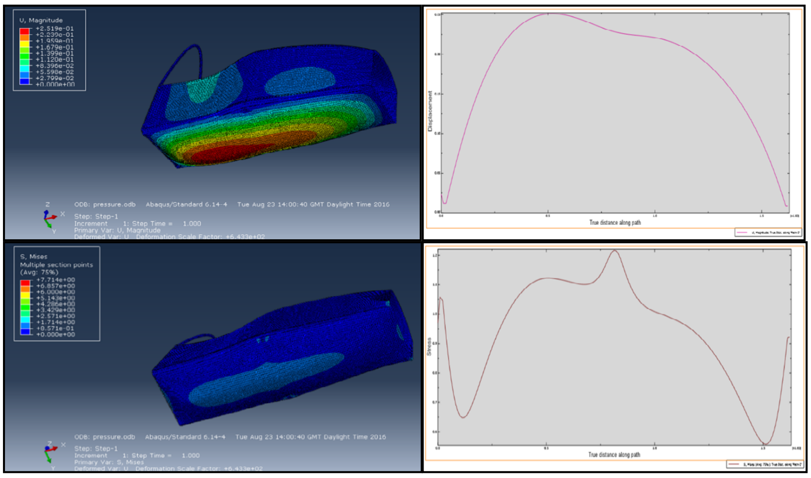
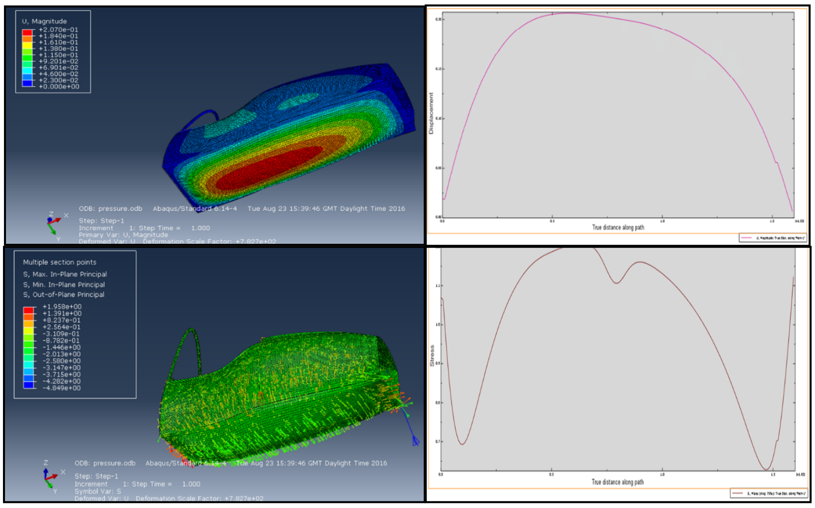


Figure 26. Displacement (top) and stress (bottom) along the whole lower surface of the chassis with analysis Design (2) configuration (1).

Design (2), Configuration (1) and Configuration (2)



choice of parameters for all chassis designs as it offers good torsional and specific stiffness for all the chassis designs along with low weight factor.

Design (1) and (3) can further be studied in details by considering aerodynamics and using other loading analysis such as hardpoint load and side-impact testing along with different plies orientation such as the use of multiple layers of Unidirectional CFRP in 0°, 90° and 45° orientations.

Further, these analyses can be performed by considering engine bracket and rim stiffeners assembly with chassis during the FEA, this may increase weight factor slightly but can result in a further increase in torsional stiffness and resistance to static vertical bending.

Figure 27. Displacement (top) and stress (bottom) along the whole lower surface of the chassis with analysis Design (2) configuration (2).

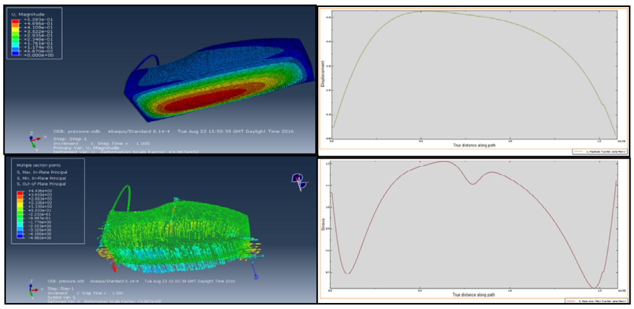


Figure 28. Displacement (top) and stress (bottom) along the whole lower surface of the chassis with analysis Design (3) configuration (1).

Design (3), Configuration (1) and Configuration (2)

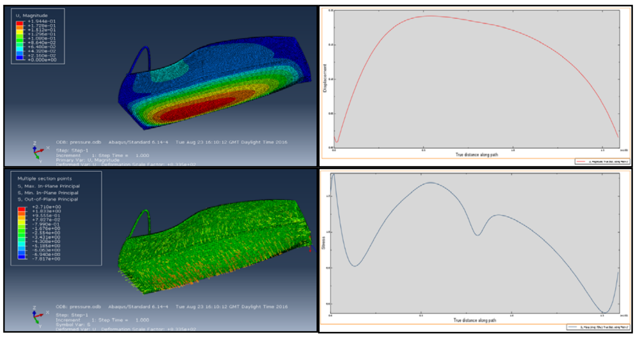


Figure 29. Displacement (top) and stress (bottom) along the whole lower surface of the chassis with analysis Design (3) configuration (2).

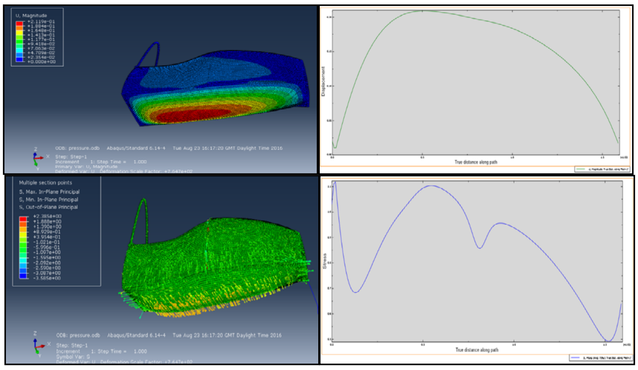


Figure 30. Displacement (top) and stress (bottom) along the whole lower surface of the chassis with analysis Design (4) configuration (1).

Design (4), Configuration (1) and Configuration (2)

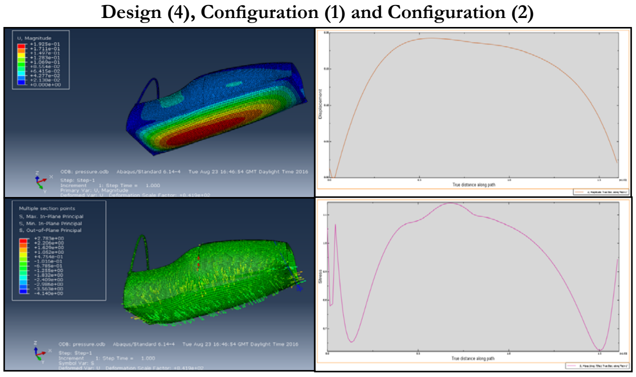


Figure 31. Displacement (top) and stress (bottom) along the whole lower surface of the chassis with analysis Design (4) configuration (2).

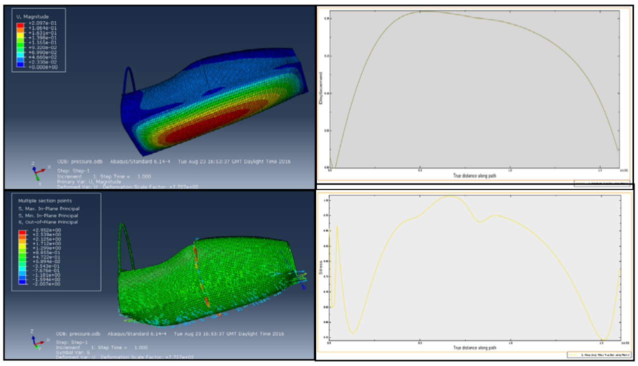


Table 8. Results of the uniform vertical bending analysis.

		Maximum Displacement, U (mm)	Maximum Stress, σ (MPa)
Design 1	Config. 1	0.2275	9.432
	Config. 2	0.2519	7.714
Design 2	Config. 1	0.2070	1.958
	Config. 2	0.5283	4.432
Design 3	Config. 1	0.1944	2.710
	Config. 2	0.2119	2.385
Design 4	Config. 1	0.1925	2.873
	Config. 2	0.2097	2.952

Table 9. High-performance parameters compared with the FSAE competition.

	Competition high-performance parameters	Design (1), configuration (2)	Design (3), Configuration (2)
Torsional Stiffness	200-300 KNm/rad	277.576 KNm/rad	196.553 KNm/rad
Mass	<20 kg	16.2 kg	15.6 kg
Specific stiffness	>11 KNm/rad/kg	17.134 KNm/rad/kg	12.599 KNm/rad/kg

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