# Structural Design Optimization of Monocoque Car Chassis

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***Abstract*: The desire of car manufacturers is to employ different less dense quality materials to meet the design objectives such as high strength, light weight and high rigidity. It is the fact that the efficiency and driving dynamics of motor sport vehicle are usually influenced by the weight and stiffness of chassis. Though many monocoque composite chassis have been designed, limited works are reported in open literature. The present work focusses design process of the commercial formula SAE monocoque race car chassis that requires a comprehensive analysis concerning all aspects of the chassis, starting from material selection, ply placement and layup sequence through to structural analysis and evaluate the chassis performance against the design requirements. In this work the weight, torsional stiffness and the torsional stiffness to weight ration are identified as key performance parameters. It is found that the chassis rigidity decreases with the increase of torsional stiffness. The results of the study concluded that the torsional stiffness of more than ~3 times the roll stiffness, easily adds more weight than handling performance. The choice of a carbon composite structure for the chassis over a steel space frame leads to great weight savings without compromising on performance. The superior material properties of the unidirectional woven carbon fiber which was considered along with the flexibility in composite layout and core design utilized to arrive an optimized monocoque composite design using ANSYS and achieve satisfactory torsional rigidity with minimal weight. Despite the disadvantages with a carbon composite chassis, namely high cost and difficulty in manufacturing, the conclusion is that the benefits outweigh the drawbacks**

***Index Terms*: Monocoque composite chassis, torsional stiffness, structural design optimization**

## I. INTRODUCTION

Chassis is the supporting member for all the components in the car. It supports the body, engine and other parts which make up the vehicle. Chassis lends the complete vehicle support and rigidity. The propose of automotive chassis is to take care of the form of the vehicle and to support the varied hundreds applied to that the protection of the chassis may be a major facet within the style, and may be thought of through all stages. Chassis may have different types of design including: ladder frames, space frame, monocoque and backbone style. The chassis is inherently important, as it is the frame, the internal structure that supports all the components and occupants of a race car, preferably in a well-balanced and effective manner. Rigidity in bending and torsion, efficient load absorption and low weight are key to strong chassis performance [1]. Space frame and monocoque are currently being preferred chassis types for Formula Student race cars. A space frame chassis involves the assembly of components onto a skeleton-like structure of steel rods. The body provides minimal structural support. Monocoque chassis, however, adapt a unibody approach, where the body is also the structure. In the present times weight and stiffness are possibly the most important chassis design concerns. In this context new materials are being experimented by many researchers and carbon fibre reinforced polymers are rapidly becoming a preferred option because of their inherently strong stiffness, tensile properties and low weight.

Composites are quite different from traditional materials in that composite parts comprise two distinctly different components - fibers and a matrix material (most often, a polymer resin) that, when combined, remain discrete but function interactively to make a new material, the properties of which cannot be predicted by simply summing the properties of its components. In fact, one of the major advantages of the fiber/resin combination is its complementary nature. Thin glass fibers, for example, exhibit relatively high tensile strength, but are susceptible to damage. By contrast, most polymer resins are weak in tensile strength but are extremely tough and malleable. When combined, however, the fiber and resin each counteract the other's weakness, producing a material far more useful than either of its individual components. Despite this, compared to legacy materials like steel, aluminum, iron and titanium, composites are still coming of age, and only just now are being better understood by design and manufacturing engineers. Further, composites are hindered by their non-isotropic nature, which makes them difficult to model and simulate. However, composites' physical properties combined with unbeatable light weight make them undeniably attractive. High-performance composites derive their structural properties from continuous, oriented, high-strength fiber reinforcement -most commonly carbon, aramid or glass - in a matrix that promotes processability and enhances mechanical properties, such as stiffness and chemical resistance. Carbon fiber by far the most widely used fiber in high-performance applications is produced from a variety of precursors, including polyacrylonitrile (PAN), rayon and pitch. The precursor fibers are chemically treated, heated and stretched, then carbonized, to create the high-strength fibers. Carbon fiber's properties are stimulating searches for alternative and less expensive precursor materials, such as lignin, which is derived from pulp and paper waste. While research efforts are gaining traction, such low-cost fiber materials still have far to go to become viable commercial reinforcement choices. Fiber orientation can be controlled, a factor that can improve performance in any application. In composite golf club shafts, for example, boron and carbon fibers oriented at different angles within the composite shaft enable it to take best advantage of their strength and stiffness properties and withstand torque loads and multiple flexural, compressive and tensile forces.A matrix may be polymeric, metal, or ceramic. The commonly used polymer matrices for most of the composites in high-performance aerospace applications and industrial are thermoset resins which are greatly insoluble infusible and when cured by thermal and/or catalyst or by other chemical agent. Curing of the resin generally occurs under conditions of high temperature and/or heat. The most commonly used polymers in composites are the thermosets. A thermoset cannot be restored to its uncured state after cure. While nearly all commercially used thermosets today are extracted from petroleum R&D, feedstocks, and commercialization is underway in the growing bio-resin sector. Bio-resins, produced mainly with a view to use green agricultural feedstocks, consist of ethanol and polyol and in differing proportions. Epoxy resins contribute strength, durability and chemical resistance to a composite. They offer high performance at elevated temperatures, with hot/wet service temperatures up to 121°C. Epoxies come in liquid, solid and semisolid forms and typically cure by reaction with amines or anhydrides. Epoxies are not cured with a catalyst, like polyester resins, but instead use a hardener (also called a curing agent). The hardener (part B) and the base resin (part A) co-react in an “addition reaction,” according to a fixed ratio. Thus, it is critical to use the correct mix ratio of resin to hardener in order to ensure a complete reaction. Otherwise, the resin will neither fully cure nor attain its full properties.

Earlier, race cars were constructed on massive lines, a design trait that reflected bridge- building more than performance engineering. Prior to World War II almost all car chassis were of the girder type, a construction of beams, usually I-shaped or Z-shaped. Mercedes-Benz introduced tubular beams in 1937. In such a chassis, the beams were parallel, from axle to axle and the construction was known as a twin-tube. It remained in vogue for racing cars until the early 1950s, when chassis with space frame principles started appearing with the Lotus Mark Six and Mercedes-Benz 300SL. Space frames continued to become widely used throughout the race car industry and were also implemented in some specialist road cars. The following are the commonly used chassis.

***Twin-tube or Ladder Frame Chassis***

The twin-tube or ladder frame consists of two bearing tubes that span in the driving direction of the car. Historically, these frames have been manufactured from steel tubes the Lister-Jaguar from 1958. In 2006 however, students from the Western Washington University built a twin-tube chassis out of carbon tubes. The mechanisms holding the two tubes together were milled aluminium bulkheads. The main advantages of a steel twin tube chassis include: simplicity, cheapness and general ease of construction. A twin-tube chassis is however not recommended for any serious, competitive motoring because it provides too low torsional stiffness. Building a lightweight twin-tube chassis is not easy, 6 because all the mounting points need extra sub-frames. These sub-frames rarely increase the torsional stiffness.

***Multi-Tubular Chassis***

The term multi-tubular refers to a chassis that is built up with more than two bearing beams, which could be used to describe all chassis types beside the twin tube described above. In practice, the term is perhaps best applied to those chassis, which utilizes four main side rails but cannot be classified in the true space frame category. Essentially, this chassis offers poor performance, but has proven to be a successful compromise between the twin-tube chassis and the space frame in terms of stiffness and production cost. Often, the frame member diameter, which is the outer diameter of the frame, has to be increased to attain a suitable torsional stiffness.

***Space Frame***

The general principle of a space frame is to only have beams loaded in tension or compression. This is achieved by welding the frame members together at the nodes. Ideally, the nodes absorb significant loads by having a supporting beam in all loaded directions. Because the frame members are only loaded in tension and compression, it is possible to avoid the bending of beams, which is what causes the greatest losses in torsional stiffness.

***Monocoque chassis***

A monocoque chassis is a one-piece structure, which defines the overall shape of the car. Monocoques were first widely used in aircraft in the 1930s. The 1960s race cars, which used monocoque chassis, had a cylindrically formed construction to improve the torsional rigidity.The monocoque chassis provides the main structural support, and thus absorbs all the loads affecting the car. In race cars today, the most common type of monocoque chassis are made of different types of composites, for example Carbon Fibre Reinforced Polymers (CFRP). The benefits of monocoque chassis (in particular, composite monocoque chassis) include high torsional stiffness and light weight. There are also some disadvantages, such as challenging design and high price. Other materials that can be used in monocoque constructions are for example glass fibre and aluminium. The hybrid monocoque space frame solution, as shown in figure 3.6, is a combination of a composite monocoque chassis and a rear space frame. The monocoque contributes with its low weight and high torsional stiffness, while the space frame offers an easy to construct rear, in most cases giving better access to the engine. However, some complications that might appear when using a hybrid chassis are to achieve a good enough integration between the two sections and the ability to predict the load paths between them.

The present work focused on the design of a composite monocoque chassis for a formula SAE type car. The techniques are presented based on the design of a formula SAE monocoque. While the particular design is not representative of all composite chassis, the techniques and results should be of interest in most composite chassis situations. Although carbon composite structures have great advantages in stiffness to weight ratio they are not easy to design and build. The main purposes of the monocoque are, first, to provide rigid, safe, and sufficiently strong supports and protection to the driver, engine, and all components on a car at minimum weight. Second, the monocoque should enable the suspension to exhibit excellent handling. There are two approaches to designing a chassis to help handling, one is to make the monocoque sufficiently strong but allow it to be somewhat soft, and design the whole chassis based on the predicted chassis deflections under various driving loads. This approach generally only works for cars with minimal or even no suspension systems, such as Go-Karts. However, the softer the chassis is, the bigger the deviations of the structural deflections get, and thus, the suspension design turns to be very difficult due to various combinations of tire camber, loading, and steer angle changes induced by varying local and overall chassis deflections. It is also very difficult to damp motions of a flexible chassis. The other approach is to design the chassis as rigid as needed to be able to design the suspension based on an essentially infinitely stiff monocoque. This is very effective for cars that rely on their suspension system for handling, and have a wide range of suspension setups. Since the suspension system has a crucial effect on the car's handling, it is usual to attempt to make the monocoque adequately stiff enough to be considered effectively infinitely stiff. [1] In this paper an attempt has been made to design a chassis that improves the overall dynamic performance of the racing car it is important to understand what parameters that affect the performance. Key load cases that the chassis will experience are to be determined and studied to understand how they impact chassis performance. A CAD-model will be created to simulate the most important load cases and to gain knowledge about analysis of composite materials. As carbon fibre offers a lightweight construction and since many of the top teams are using monocoque solutions, more focus will be put into the analysis of carbon fibre. In the next Section the relevant literature is reviewed concisely and the materials and methods employed are presented in Section III. Later results and discussions were made in Section IV. The Section V is devoted to mention final conclusions of the work.

## II. LITERATURE REVIEW

Depending on its shape and manufacture, a chassis exhibits a certain resistance to deformation, which is stiffness. The term chassis stiffness or rigidity generally indicates resistance to bending or flexing while torsional stiffness indicates resistance to twisting. Traditionally, optimizing a vehicle body starts with improving the fundamental torsion and bending frequencies. In generally, the main design objective for a racing car frame is increasing structural stiffness, in order to improve the general dynamic response, knowing that a highly deformable frame will induce uncontrolled and unacceptable movements. According to Costin et al [1] "it is difficult to imagine a chassis that has enough torsional stiffness without having ample rigidity in bending" so that "the criterion of chassis design, and in fact the primary function of a high-performance chassis, is torsional rigidity". Beyond controlling the structure's global stiffness, an adequate balance is needed between the front and the rear chassis areas to avoid dynamic weight transfer that would increase under-steer or over-steer behaviour. Although physical tests shown that better performance of the vehicles with higher stiffnesses but the exact factors that impacts the torsional stiffness has on performance is not entirely known [2]. A dynamic test on FSAE car chassis performed by Riley and George [3] using simulation and real proof where they used the simple mathematical model to develop chassis structural stiffness in which the results passed the target. Singh et al [4] analysed the structural performance using tested static shear, static overall bending, static torsional loading, acceleration analysis, and frequency analysis by simulated FSAE chassis design and the results the chassis performed well in static and dynamic condition as per the objective. Chandan Sn et al [5] designed the chassis for structural performance based on the 95% male that can fit inside the chassis cockpit. FEM was used for the analysis and design of the chassis experiments for high-speed conditions coupled with safety for which the stress and the maximum performance were to be minimal.

Apart from the research on torsional rigidity, a few researchers focused on the topology optimization as it forms one of the structural optimization especially used for structural material layout [6] and in a few cases a portion of the elements can be modified or removed to minimize the weight while keeping the rest of parts are reliable and safe during the load transfer [7]. Rajak Ab et al [8] achieved the ergonomics and performance of electric vehicle racing car by designing the chassis using topology optimization method. Furthermore, to provide sufficient strength, rigidity and durability and in order to meet the evaluation requirements of the Formula racing guide lines [9]. Studies on the lightweight design of components of formula racing cars have been carried out in the recent past by using topology optimization techniques. Yuan Shouli [10] performed the weight minimization of the racing frame using the SIMP topology optimization method to lightweight. Li Renren [11] used a topology optimization method to ensure light weight of the racing car bracket. To design a light racing frame, Li Fang [12] Variable density topology optimization technique used. Hou Zhanfeng [13] established the topology optimization model for the light racing rocker arm. Recent work by Jixiong Li [14] on topology optimization of the upfront upright structure with the objective of minimization of weight resulted in improvement of the fuel saving performance of the car. Chassis stiffness has the most important influence over the vehicle's handling behaviour, so it is essential to reach an adequate compromise between stiffness and weight, it not being acceptable an excessive weight loss to improve straight-line performance through excessive weight loss at the expense of a sacrifice in suspension efficiency, which reduces cornering capability [15].The overall weight must remain small in order to be as close as possible to the required mandatory weight. The distribution of body weight must therefore ensure that the center of gravity is small enough to reduce friction at the corner and that the position of the center of gravity is oriented both lengthwise and transversely [16]. The aim is to build a chassis that is rigid enough to allow adjustments in the setup of the suspension that makes a noticeable improvement in the car's handling characteristics while maintaining the weight as low as possible [17]. One of ways to tackle this problem is to determine the suitable method of transferring the loads from the suspension through the structure and the deformation mode associated with those loads [18]. By connecting the deformation to the change in handling characteristics of the vehicle, a stiffness target can be defined for each deformation mode. Heisler [19] proposed longitudinal torsion, lateral bending, vertical bending and the horizontal lozenging as the main deformation modes for an automotive chassis.

In today's competitive world, the need to develop a vehicle in the most efficient manner is of utmost importance. The role of computer-aided engineering (CAE) in the automotive industry is rapidly increasing. Functional performance are fine-tuned more and more on the basis of numerical predictions, so that the expensive physical prototyping phase can be shortened considerably. Traditionally, optimizing a vehicle body starts with improving the fundamental torsion and bending frequencies. Three-

Dimensional (3D) Computer Aided Design (CAD) modeling and Finite Element Analysis (FEA) test is the solution to get durable, cheap, and ergonomic but still, fulfill the regulation and secure the driver without wasting time and money making a real 3D model. In CAD, the designer just has to go a reliable model that represents the actual chassis. Moreover, the vertical bending strength, torsional rigidity, and Von Mises Stress were performed to test the capability of the frame. Finite Element Analysis was done using simulation software. In FEA test, the designer has to make a boundary condition that represents the real situation in competition. 3D CAD modeling software used Autodesk Fusion 360, while the structural analysis employed ANSYS. The team chooses Autodesk Fusion 360 and ANSYS to make and analyze their chassis because Autodesk Fusion 360 is one of the best software to create solid modeling and ANSYS is no doubt the best simulation software.From the past few decades, the Composite materials play a significant role in the manufacturing industry and increased its share starting from packaging to aerospace industry. and recently its usage has been increased in automobile industry due to the requirement of high strength to weight ratio. Specially the synthetic fibers like glass, kelvar and carbon fibers occupied a major share. Although carbon composite structures have great advantages in stiffness to weight they are not easy to design and build [20]. The research by Naoyuki Takahashi [21] succeeded in greatly minimizing the voids by using a prepreg structure coupled with extraction of air from the passageways in the knitted fabric the layers at low pressure rather than by high-pressure squeezing under vacuum molding conditions. Jingsi Wu et al[22] initially used the isotropic modelling to set the primary design targets and moved ahead with anisotropic composite analysis by using the carbon reinforced composites for the design of monocoque chasis to obtain the optimized monocoque composite design and layup which produced the satisfactory hardpoint, bending stiffness and torsional results with minimal weight. Tatthep Kanketr et al [23] worked on design of CFRP monocoque chassis with the sandwich structure and the optimization done with regarding to tacking sequences and the thickness of composite plies using the FEM simulation to achieve the design objective of maximization of torsional stiffness.

## III. MATERIALS AND METHODS

The present work is carried through design process from material choice, ply placement and layup sequence through to structural analysis to verify the chassis meets the design requirements. The steps involved in the design process to achieve the stated objectives are summarized below.

- Establish the key performance indicators or Define the design requirements/
- Selection of the composite materials
- Geometric modelling of monocoque chassis.
- Name the selected reinforce structure using Named Selections.
- Meshing of Monoquoq chassi
- Create the composite layup in ANSYS ACP(Pre)
- Extract the chassis properties using sensor
- Transfer parts to ANSYS Mechanical.
- Apply boundary conditions and loads to replicate rigidity and strength test.
- Extract chassis strength from ANSYS ACP(Post)
- Evaluate chassis performance against design requirements

### Key performance indicators

In the case of a Formula car chassis there are some key performance indicators (KPIs) of greater importance than others, and to identify these is important to be able to measure performance during the design process. When certain KPIs are established, analysis and modelling will use them as performance measurement to decide key aspects of the design. The following KPIs are considered in the present work to measure the chassis performance.

***Chassis Stiffness***

A key indicator to the performance of a race car chassis is longitudinal torsional stiffness. The rigidity of the chassis between the front and rear suspension points is paramount in load transfer and lateral grip in turning. The measure of chassis rigidity used for this workshop is specific rotational stiffness which accounts for chassis weight also, driving the design to be light weight and high stiffness. From the historical data below are the 3 divisions of specific torsional rigidity have been identified.

Low performance - 2 KN-m/rad/kg
Average Performance - 5 KN-m/rad/kg
High Performance - 15 KN-m/rad/kg

The chassis for the present study must have a specific stiffness of at least 8 kNm/rad/kg to place it in an above average stiffness category.

***Chassis Strength***

To ensure a safe design, the chassis must have a generous reserve factor under operational conditions to account for any damage, manufacturing imperfections or unexpected loads the car may encounter.The chassis for the study must have a minimum reserve factor of 0.5 under a maximum torsional load encounter under full braking and an impact with a track bump. This load is calculated to be 2500N-m

***Chassis Weight***

A light weight chassis will improve the cars performance in acceleration, braking and cornering, three divisions of chassis weight have been identified as given below

Low performance - 30 kg

Average Performance - 25 kg
High Performance - 20 kg
The chassis for this workshop must have a weight of no greater than 25kg to qualify it in a high-performance weight category

**Materials**
To reach certain chassis performance limits, the designer can choose to optimize the geometry of the chassis or the material it is made of. The ideal solution is obviously to optimize both and hence the material choice is of great importance. When designing a chassis for optimal performance, a high stiffness to weight ratio is often sought. To allow easy layup of the chassis over the mould, a woven carbon fiber material will be chosen for the majority of the structure. For selected reinforcements, a uni-directional prepreg material will also need to be used allowing weight efficient reinforcement and precise fiber orientation.

**Modelling of Chassis**
The chassis for this workshop must have a weight of no greater than 25kg to qualify it in a high-performance weight category. The exploded view of chassis is shown in Fig.1. The model has been set up as a shell model divided along major edges. Expand each branch in the project tree to familiarize yourself with the model, summary of the key features will follow.

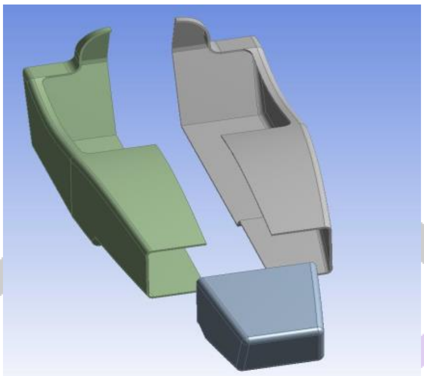

Fig.1 Exploded view of chassis showing key structural components

In addition to the global coordinate system, three extra systems have been setup to help with loading the model.
*Right/Left Front Wheel*: a coordinate system at the approximate position of each of the two front wheels, their separation in X represents a track width of 1225mm.
*Rear Bulkhead*: a coordinate system at the approximate position of the rear suspension mounting points and the center of roll for the car. The Z-coordinate of the rear bulkhead represents a 2000mm wheel base. In addition to the main structural divisions, other smaller divisions were made to break the model down into key areas, this process allows the designer to customize ply placement by creating complex ply shapes consisting of several model surfaces. The divisions have been made in to Named Selections to allow fast selection of the key structural groups. A summary of the Named selections will follow
*Right Body Full*: Right hand side of chassis in a single group, will be used as first ply over hypothetical mold.
*Left Body Full:* Identical to Right Body full but consist of lefthand side of mold.
*Floor*: Group on the bottom of the mould running from back of chassis to the nose, will reinforce joint between left and right sided moulds and support drivers weight.
*Bonnet*: Group on top off mould running from the front of the chassis opening to the nose, will reinforce joint between Left & Right sided moulds.
*Headrest Full:* Group consisting of all surfaces in the headrest, will be used to form the shape on the mould.
*Headrest Reinforcement:* Group consisting of the overhead loop of the headrest, will reinforce joint between left and right sided moulds and give the headrest its strength.
*Left Nose Full*:Left hand side of nose in a single group, will be used as first ply over hypothetical male mould for the nose section.
*Right Nose Full*: Identical to Left_Nose_Full but consist of right hand side of mould.
*Nose Vertical Wrap*: Group running along the top, front and bottom surface of the nose section, will reinforce joint between Left & Right sided moulds.
*Cockpit*: Group consisting of chassis opening edges, bonnet section and chassis side walls, will reinforce opening to improve stiffness and strength.
*Rear Bulk head*: Group at rear of chassis, will reinforce joint between left & right sided moulds and support loads from rear space frame.
*Right Side Panel*: Group consisting of all right hand side panels running from the rear of the chassis to the nose. Will reinforce chassis to improve stiffness and strength.
*Left Side Panel*: Identical to Right Side Panel but consist of left hand panel.
Reverse Bonnet: Group consisting of bottom and side walls around indented section of chassis, will reinforce joint between Left & Right sided moulds.
*Bulkhead Wrap*: Group at rear of chassis including headrest and section of chassis side. Will be used to reinforce rear bulkhead.
*Nose Horizontal Wrap*: Group running along the left-hand, front and right-hand surface of the nose section, will reinforce joint between Left and Right sided moulds.

*Suspension Reinforcement*: Group consisting of bottom wall at chassis indent, will be used to reinforce area and carry loads from front suspension
*Cockpit Reinforcement*: Second selection for chassis opening reinforcement, neglects side panels
*Headrest Edge*: Edge set required for accurate ply draping around headrest. Does not offer structural selection.

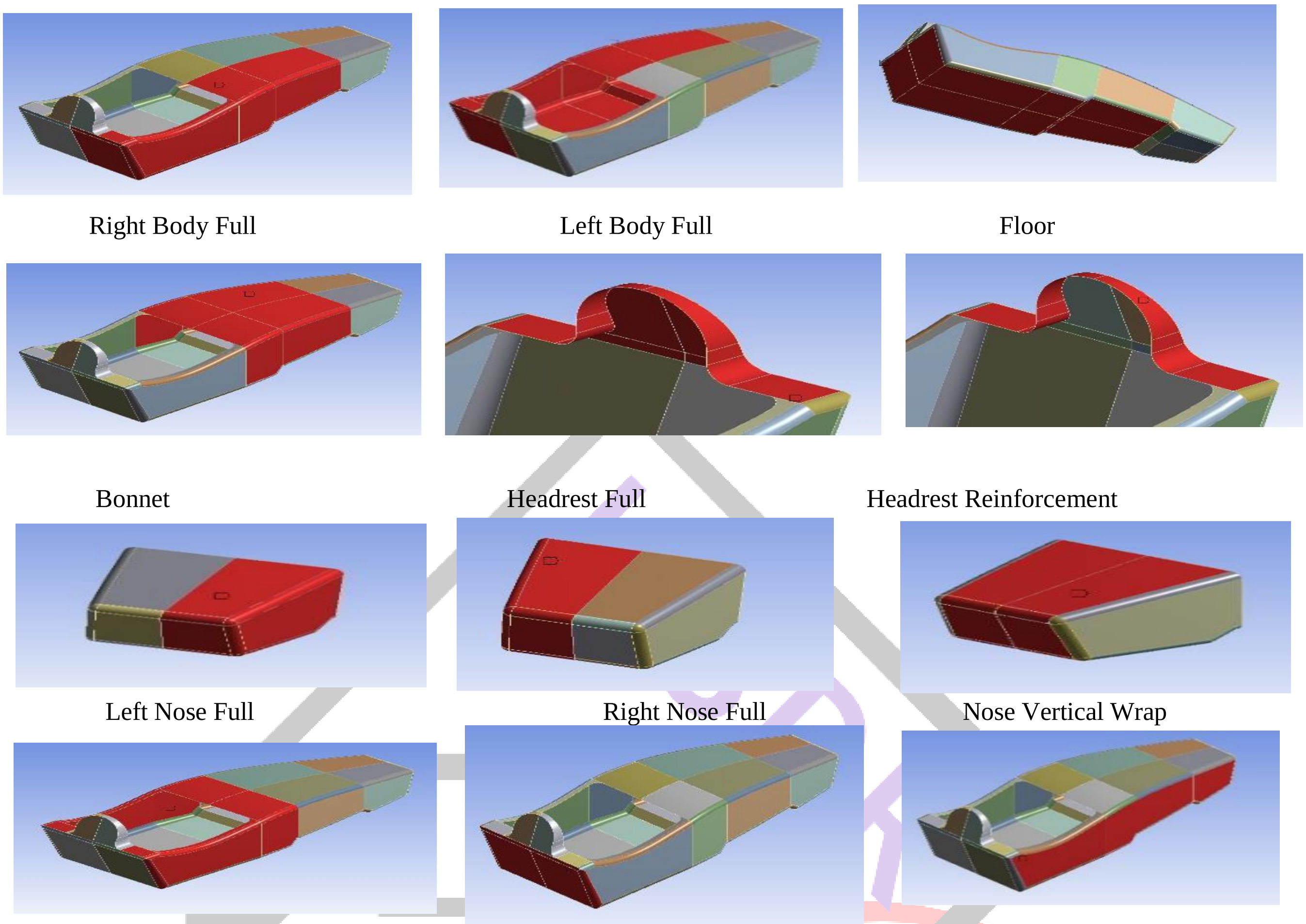


Fig. 2 Summary of selections

## IV. RESULTS AND DISCUSSION

The results obtained from the simulation are presented in the Table 1 and compared against their corresponding design targets. The chassis weight obtained as 25 kg which is and it is equivalent to average performance design target. The torsional stiffness is observed to be 9.44 KN-m/rad/kg which is in good agreement of the minimum limit of of 8 KN-m/rad/kg. Similarly, the IRF representing the torsional stiffness is noted as 0.340 which is below the acceptable limit. Overall, the design proved to be safe to use as a raw material for manufacture of monocoque chassis in order to reduce the weight of the monocoque chassis considered as safe and the composite material made of carbon fiber prepeg in epoxy produced satisfactory results and achieved the design targets.

Table 1: Key Performance indicators obtained from simulation

| S.No. | KPI | Result obtained | Design Target |
|---|---|---|---|
| 1 | Weight | 25.0 Kg | 25 Kg |
| 2 | Torsional Stiffness | 9.44 KN-m/rad/kg | 8 KN-m/rad/kg |
| 3 | IRF(Strength) | 0.340 | 0.5 |

## V. CONCLUSIONS

It is vital to have a chassis that provides enough torsional stiffness to the suspension. Here the unidirectional prepeg carbon fibre reinforced epoxy composite successfully proved to be a viable material for the monocoque chassis. The values of weight and the torsional stiffness are obtained as 25.08 kg as 9.44 KNm/rad/kg respectively which are acceptable as per the design targets. In addition, the IRF representing the strength is found to be 0.340 which is in safe zone. The value of the key performance indicators shows that the material selected and the design produced the satisfactory results and achieved the design targets. A further extension of this work possible can be possible to achieve the improved performance by changing the layup for different composite configurations like hybrid composites and honeycomb structure etc.

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