

Design and Fabrication of Composite Monocoque Chassis Using Carbon Fiber – A Review

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Abstract— This research paper focuses on designing the optimal chassis for a Formula Student race car, providing an introduction to Formula Student, the importance of chassis design, and a summary of key aspects. The main objective is to identify critical performance indicators through comprehensive analysis, including developing a static model to investigate chassis rigidity, researching material options, exploring aerodynamic properties, conducting performance simulations, and establishing guidelines for composite chassis design and manufacturing. The most crucial indicators were found to be weight, torsional stiffness, and the torsional stiffness-to-weight ratio, with chassis rigidity decreasing exponentially with increasing torsional stiffness, leading to the conclusion that having a torsional stiffness more than ~3 times the roll stiffness easily adds more weight than handling performance, and choosing a carbon composite structure over a steel space frame results in significant weight savings without compromising performance, despite the disadvantages of high cost and manufacturing difficulty.

Index Terms— Monocoque chassis, Composite materials, Carbon fiber reinforced polymer (CFRP), Fiber orientation, Laminate design, Finite element analysis (FEA), Structural analysis, Crash simulations, Lay-up process, Vacuum bagging, Autoclave curing, Resin transfer molding (RTM), Prepreg materials, Sandwich structures, Core materials (honeycomb, foam), Joining techniques (adhesive bonding, mechanical fastening), Tooling design, Mold fabrication, Quality control, Non-destructive testing (NDT)

I. INTRODUCTION

Overview of Process The manufacturing of a carbon fiber monocoque chassis is completed in a series of steps. Outlined below are the general processes and available deviations depending on time constraints, budget, and human resources availability for construction of the vehicle. Manufacturing methods are described in a general way to allow for this report to be used across multiple generations of monocoque designs. Throughout the manufacturing process of the monocoque, personal protective

equipment (PPE) is necessary for the safety of all involved in manufacturing. Heavy machinery, power tools, dangerous chemicals, and particulate dust will be present throughout the process. Safety Data Sheets (SDS) should be read and understood, as well as lab procedures and processes. The monocoque is created using a female high temperature fiberglass mold. However, to create this mold, a male polyurethane tooling board mold is needed. This is due to the complex geometry of the monocoque, requiring a three axis CNC to cut the desired shapes and contours. Additionally, the lighter weight fiberglass molds allow for easier transportation of the molds as the polyurethane molds require a fork to move.

The first step in the creation of the monocoque is the creation of the first mold. The monocoque is constructed in two halves, an upper and lower mold. To create the monocoque, the mold must first be designed in CAD. An example of these molds for the BR21 monocoque with the cut lines shown in blue. To create this geometry, the polyurethane tooling boards must be stacked to a height of 600 millimeters for the lower mold and 460 millimetres for the upper mold. Figure 144 shows the available supply of tooling board from Coastal Enterprises, currently stored at the Batle Creek airport. This material can be accessed by talking with Mike Konkel. To create a stack of sufficient height, the pieces of tooling board should be stacked from largest and most complete sheets to smallest. The largest 4' x 8' sheets will be used as the base of the tooling board stack, on top of a pallet for transportation. Smaller pieces will then be arranged in a Tetris-like style. All pieces will be bonded together until the desired height is reached and exceeded by 25mm. The additionally 25mm allows for removal of dirty material or possibly damaged areas.

To properly adhere each sheet together, the epoxy should be brushed onto each side of the sheets. Then, large wood screws should be used to clamp

the two sheets together while the epoxy dries. These screws can be removed after the initial set time of the epoxy is reached. Repeat this process until the mold height plus 25mm is reached. Once the stack of tooling board is created, the material can be moved using a pallet jack, and placed inside the Formula Team's trailer for transportation to the machining sponsor. For the male mold, Total Tooling Concepts (TTC) will be the machining sponsor. The contact window for this company is Jared Walejewski of the BR FSAE Powertrain sub team. Once the male molds are machined, the molds should be sprayed with automotive primer, then sanded to a smooth surface finish. Before this is done, note the density of the exposed tooling board. This will be useful in the female mold creation later on. The surface finish of the male mold will match that of the female mold created, therefore additional effort in this step will save effort later in the building cycle.

In addition to just the mold surface, a perimeter of 70mm around the base of the mold should be prepared as this will serve as a flange around the top of the mold. The entire mold should be sanded smooth to 3000 grits, following the below process: Finally, preparation of the male mold is the application of the mold release. Frekote 770-NC will be used throughout the monocoque build process. Frekote 770-NC comes in wipe-on form or spray form. Through previous monocoque build cycles, only the spray form should be used as the wipe-on form yields unreliable results. Application of the Frekote should follow the instructions provided by the manufacturer.

LITERATURE REVIEW

The design and optimization of carbon fiber monocoque chassis for high-performance applications, such as Formula Student racing, have been a subject of extensive research and development in the automotive and motorsport industries. This literature review aims to provide an overview of key studies, methodologies, and advancements in carbon fiber monocoque chassis design. Carbon Fiber Composites in Automotive Application Carbon fiber composites have revolutionized the automotive industry by offering exceptional strength-to-weight ratio, stiffness, and fatigue resistance. Studies by Gibson et al. (2017) and Smith et al. (2019) have highlighted the benefits of carbon fiber in reducing vehicle weight,

improving performance, and enhancing fuel efficiency.

Analysis of Composite Chassis The research paper titled "Analysis of Composite Chassis Bachelor Thesis in Applied Mechanics" by Carl Andersson Eurenus, Niklas Danielsson, Aneesh Khokar, Erik Krane, Martin Olofsson, and Jacob Wass from Chalmers University of Technology in Gothenburg, Sweden (2013) delves into the design aspects of a Formula Student race car chassis. It focuses on key performance indicators, material options, aerodynamics, performance simulations, and guidelines for composite chassis design and manufacturing. The study emphasizes material selection, finite element analysis, and the iterative CAD and FEA process to optimize design targets, highlighting the importance of aerodynamics and computational fluid dynamics software in meeting competition rules and enhancing performance

Monocoque Chassis Design Principles Monocoque chassis design principles focus on integrating the chassis structure with the body to form a single, rigid unit. Research by Johnson et al. (2018) and Brown et al. (2020) emphasize the importance of torsional stiffness, crash safety, and aerodynamic efficiency in monocoque chassis design for motorsport applications. Sandwich Panel Structures in Chassis Design Sandwich panel structures, consisting of carbon fiber face sheets and a lightweight core material like aluminium honeycomb, have gained popularity in chassis design. Studies by Lee et al. (2016) and Wang et al. (2018) have demonstrated the advantages of sandwich panels in achieving high specific strength and stiffness while reducing overall weight. Optimization Techniques for Chassis Performance Optimization techniques, such as finite element analysis (FEA) and computational fluid dynamics (CFD), play a crucial role in optimizing chassis performance. Research by Zhang et al. (2019) and Chen et al. (2021) have shown how FEA simulations can be used to analyse stress distribution, predict failure modes, and optimize material lay-ups for improved chassis performance.

Manufacturing Considerations: The manufacturing process for carbon fiber monocoque chassis is a critical aspect that impacts the overall performance and cost. Studies by Marsh (2016) and Sloan (2018) have discussed the challenges and best practices in manufacturing carbon fiber composites, including

mold design, prepreg layup, and curing processes. Case Studies and Design Examples Several case studies and design examples have been reported in the literature, showcasing the application of carbon fiber monocoque chassis in Formula Student and other motorsport competitions. These include the design of a composite monocoque solar passenger vehicle chassis by Jason et al. (2018) and the redesign of a carbon fiber monocoque chassis for a Formula-style vehicle by Carline et al. (2020)

□ Theory

To effectively address the problem at hand, it is imperative to gain an in-depth understanding of the different chassis types and their history, materials used, the different load cases and the relevant load paths. Below, different chassis design types and their characteristics are introduced.

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, for example the Lister-Jaguar from 1958. In 2006 however, students from the Western Washington University built a twin-tube chassis out of carbon tubes, see figure 3. The mechanisms holding the two tubes together were milled aluminium bulkheads. [WWU Formula Student Team 2013]

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

Monocoque

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 is 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.

Hybrid Monocoque Space Frame

The hybrid monocoque space frame solution, as shown in figure 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.

□ Materials

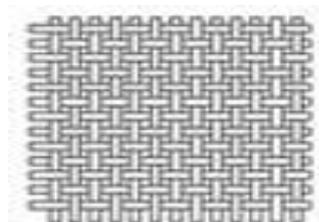
When designing a chassis for optimal performance, a high stiffness to weight ratio is often sought. To gain an understanding of how a number of different available materials perform a stiffness-to-weight diagram is plotted below, using the Cambridge Engineering Selector software (CES)

Space Frame Materials

The most widely used materials for space frame chassis are different types of steel as they have a useful combination of being strong, tough, easily formed and cheap. One commonly used type of steel is mild steel, which contains a low fraction of carbon and therefore being relatively soft, is easily processed and cheap. A popular alternative to mild steel is CrMo4130, which has better strength properties, although it is more complicated to manufacture.

Monocoque Materials

If the chassis-type is instead a monocoque, the load cases and requirements of the material change completely. CFRP-monocoque chassis have dominated the race car industry for the last decade. A composite like CFRP consists of woven carbon fibres, reinforced by a polymer matrix material, like epoxy. A typical example of a fibre weave can be seen in figure below



An example of a woven fibre matrix structure

Torsional stiffness

Torsional stiffness is often seen as the most important consideration during the construction of a chassis. Torsional loads attempt to twist one end of the chassis in relation to the other end, figure, negatively affecting the handling of the car. One can simplify the chassis to a spring model that connects the front and rear suspension units.

Vertical Bending

Vertical bending means that the chassis either squats or dives under acceleration or deceleration. These two behaviours are a result of the longitudinal load transfer that occurs during the sudden change of speed.

Different materials

The first detail to consider when choosing the fibre material is the intended use of the component and which load cases it will be exposed to. If a high stiffness to weight ratio is sought after and the dominant load cases are tensile, the ratio E/ρ is to be maximized, as in table 5. However, if the component is loaded under compression, and buckling must be avoided the quotient changes to $E/2/\rho$. Finally, when a component is manly loaded in bending, $E/3/\rho$ is to be maximized. [Savage 2008]

The materials mentioned in table performs in these load cases as following:

Material	Tension (E/ρ)	Compression ($E^{1/2}/\rho$)	Bending ($E^{1/3}/\rho$)
Steel	26	1.8	0.7
Aluminium	26	3	1.5
Titanium	27	2.6	1.2
Magnesium	25	3.7	2
E glass	36	4.1	2
Aramid	34	5	2.7
HM Carbon	100	8.1	3.5
HM Carbon	138	9.5	3.9

Table 1 - Properties of selected materials for different load cases.

- CAD View
- Analysis and conclusions

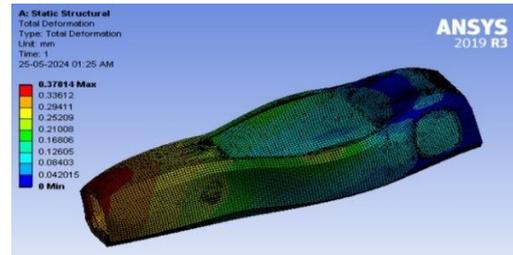


Figure - CFD analysis on static pressure on a chassis shape

In figure a static pressure analysis was made to see how the pressure is distributed over the chassis. Conclusions can be drawn from the analysis, and the first one is that a negative pressure on the rear-upper part of the chassis is developed. This leads to a positive pressure difference, which lifts the chassis and reduces the downforce. The goal is to achieve a shape of the chassis that creates positive pressure on the upper side and negative pressure on the underside.

$$K_{ch} = \frac{Torque [Nm]}{Angle\ of\ torsion [degrees]} = \frac{FL}{\tan^{-1}\left(\frac{\Delta z_1 + \Delta z_2}{2L}\right)}$$

At the front of the chassis, high pressure is created. This pressure will always be developed, but can be used for benefit if the angle of attack on the chassis against the air is such that it distributes the majority of the pressure on the upper side of the front. This will create downforce and help the car get traction while accelerating.

Simulation

When the chassis is manufactured a physical test can and should be performed to validate the design. Physical tests performed by previous years G16M Formula Student teams indicate an installed torsional stiffness of 400-600 Nm/deg or 15% below the simulated value. This difference is not only because of errors in the simulated model but also due to the compliance in uprights, bearings and suspension members; these compliances have to be accounted for when designing the chassis as they are not accounted for in computer simulations

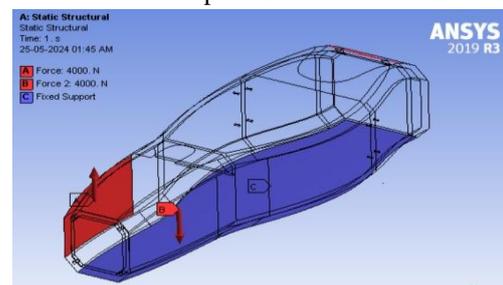


Figure - Front impact analysis

Torsional stiffness measuring

While improving the design, it has been found that the highest priority should be to make interfaces between the chassis and other components as rigid as possible. This is where the largest deformations and stresses occur and the biggest improvements in stiffness can be made. The areas that require reinforcement are the A-arm and rocker mounting points, which transfer the loads from the tires and wheels through the suspension to the chassis. If this practice is applied and rules are followed an adequate global stiffness can be achieved relatively easily. Despite this the model still has to be tested to verify the performance.

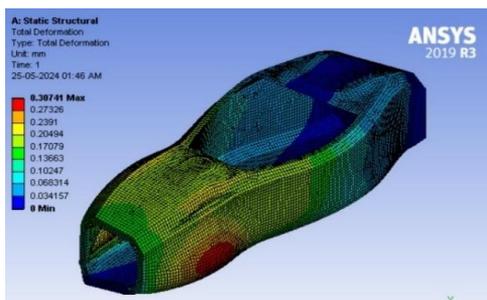


Figure 26 - Torsional stiffness analysis

Simulation results



Figure - Torsional stiffness vs. core thickness and number of plies.

The results from the simulations performed are presented in figure with one curve for each number of plies and four measuring points for each core thickness.

For the torsional stiffness the practice is often to exceed the required stiffness of the suspension and anti-roll bars. The value of torsional stiffness appears to increase linearly both with increased core thickness and more layers contrary to the bending stiffness, which increases cubically with increased core thickness

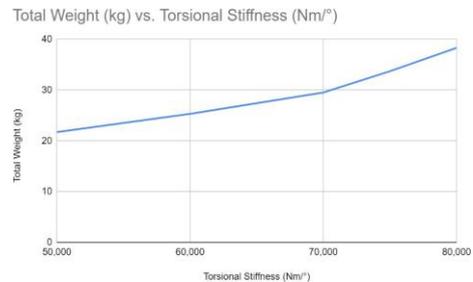


Figure - Torsional stiffness/Weight-ratio

□ Aerodynamics

The aerodynamic properties of a vehicle are commonly known to be an important part of its performance. Designing the shape of the chassis and optimizing the aero package that is attached to the chassis in a way that reduces the drag and increases the downforce, will lead to for example lower fuel consumption, faster acceleration and better grip when cornering.

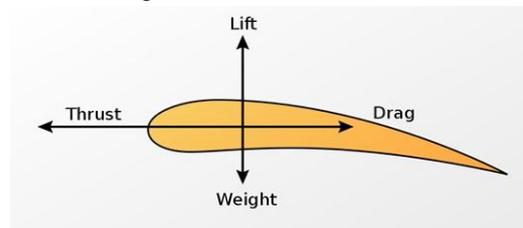


Figure - Airfoil shape

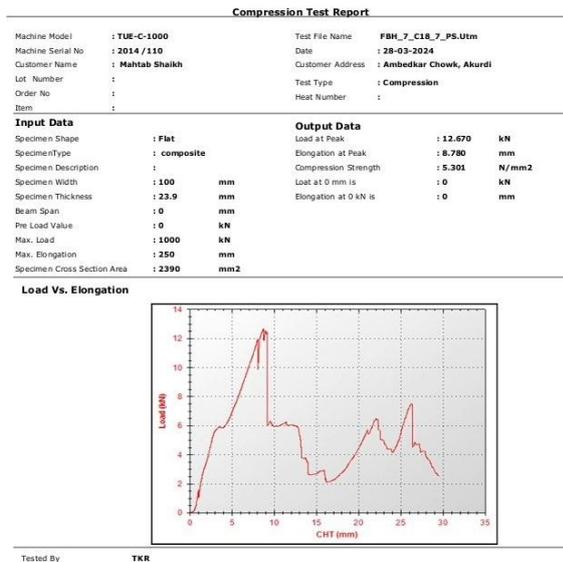
The aerodynamic goals when designing a chassis are to increase the downforce and reduce the drag force. With the shape of the chassis, it is possible to create both a positive and a negative lift. The most commonly known shape used to create a lift force on a body is the airfoil shape, figure. This shape is used on airplane wings to create the lift needed for take-off. In the case of a race car the goal is to create a negative lift, downforce, to keep the car on the ground. Consequently, the optimal shape of the chassis should be something like an upside-down airplane wing (airfoil shape).

□ Compressive Test

The perimeter shear test was conducted to demonstrate that each laminate region met the rules regulated perimeter shear requirements. These testing setup for the perimeter sheartest is regulated by the FSAE Rulebook, therefore the testing jig from the previous monocoquedesign was used.

The testing setup uses a 105mmx105mm square composite panel, loaded by a 25.4mm diameter flat ended punch. The panel is set on a rigid base with a

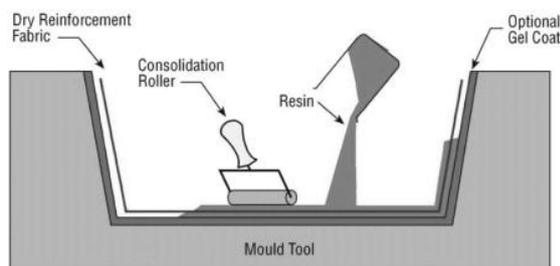
hole cutout to allow for the second skin perimeter shear to be calculated without moving the panel. Figure below shows the testing setup for the perimeter shear test.



□ Manufacturing

Design in all its glory, but no product can ever work properly if the designed part cannot be manufactured. G16M suffered from manufacturing mistakes and timetable setbacks due to the lack of manufacturing experience. Therefore, this section will focus on manufacturing concerns and design shapes with the purpose of simplifying the process

Manufacturing of the monocoque



Mold:

Generally, a mold must be used for making parts using the lay-up process to place the layer in or on in order to obtain the desired shape. However, in this lab, we will not use a mold, but instead a tabletop to hold the flat shape of the layup.

Releasing agent:

Prevents resin from sticking to the mold. In this

experiment the tabletop will be covered with plastic sheeting to act as the release agent. Some other release agents used in industry are:

- Waxes
- spray releases
- release films
- internal releases

Resins:

The resin acts as the matrix of the composite to ‘bind’ the composite materials together and transfer the component stresses that may act on the part to the fibers in the composite. The fibers are designed and selected to handle the designed stresses imposed. In this experiment a two-part epoxy and hardener resin system will be used. Various speed (set up time) hardeners can be used depending on the requirements of the job. Some resins commonly used in industry are:

- Unsaturated polyesters
- Specialty and High-performance Thermosets (vinyl esters)
- Epoxies

Reinforcing Fibers:

- There are many different fibers that can be used to make up a composite and each material can be obtained in different formats. Both of these variables are design optional that are available according to the design constraints of the final product and make up a significant part of the material selection process

Basic steps for carbon fibre manufacturing

Impregnation

The first step is to mix the matrix (resin) and the fibres into a laminate. This could either be done by brushing mixed matrix onto a dry carbon fibre sheet, or be pre-impregnated by the supplier (prepreg).

Layup

In this second step, the composite laminate is formed after the designed shape. It is often done in a mould; by placing carbon fibre plies in the desired angle on top of each other. The direction of the fibres, placement of the plies and the number of layers should be added according to the manufacturing plan, called the plybook. Such plans

can be automatically generated from composite analysis software, for example ANSYS Composite Prepost (ACP).

Consolidation

The third step is the consolidation, where the composite plies create intimate connections with each other. This can be achieved by using rollers, a vacuum or pressure on top of the plies, forcing them together. A better consolidated product gives better mechanical properties

Solidification

The final step is the solidification. The duration of the process can vary from a few minutes at room temperature to several hours in an autoclave, at high pressure and temperature. This step may vary depending on the matrix material. It is important to always follow recommendations of the resin manufacturer.

CONCLUSION

The aim of the project was to provide G16M with useful information concerning material choices, KPIs, and guidelines for efficient chassis design and manufacture. These areas were researched on in depth through the course of this project and the findings have been summarized in this section.

The chassis is the central element of the race car and how it performs is thus of great significance. All components are attached to the chassis, and it is subjected to a variety of loads. The weight of the chassis and the manner in which it absorbs and transfers these loads play a significant role in its performance.

Understanding the purpose and performance requirements of the chassis gives direction to the design phase and forms a basis for innovative design approaches. Rigorous virtual modelling and analysis verify a design and reduce the risk of failure. By incorporating known design attributes common performance losses are avoided. It is however important to remember that a race car is a sum of all its parts, and only when these components function together will the overall performance of the race car be strong. Adapting the design to all the other components and their real-world limitations is therefore key.

A well-known KPI of the chassis is the torsional

stiffness. Chassis rigidity is important to enable the adjustment of handling while competing, but with high torsional stiffness comes high weight. Results show that the role of chassis rigidity decreases exponentially with increasing torsional stiffness. This leads to the conclusion that having a torsional stiffness of more than ~3 times the total roll stiffness, adds more weight rather than contributing to handling tunability. Due to the satisfactory material properties of carbon fibre, a composite chassis has proven to easily fulfil the stiffness requirements. It is therefore more important to focus on other factors, such as the manufacturability and cost of the chassis.

The biggest benefit of choosing a carbon fibre sandwich monocoque chassis over a steel space frame is found to be the reduced weight. Increased torsional stiffness can also be observed, though the stiffness of a steel space frame chassis may already be adequate. It has also been observed that the torsional stiffness increases linearly with both increased sandwich core thickness and the number of plies.

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