

Széchenyi István University  
Audi Hungaria Faculty of Vehicle Engineering

# **THESIS**

**Kristóf Hege**  
**Vehicle Engineering BSc**

2022

[Spine:] Kristóf Hege, 2022



SZÉCHENYI ISTVÁN UNIVERSITY  
AUDI HUNGARIA FACULTY OF  
VEHICLE ENGINEERING

# **THESIS**

## **Ergonomics and Cockpit Design of a Formula Student Race Car**

**Kristóf Hege**

**Vehicle Engineering BSc  
Internal combustion engines**

**Supervisor:**

**Martin Kaszab**

**Department of Whole Vehicle Engineering**

**Győr, 2022**

# Task assignment form

## Student data:

Name: Kristóf Hege

Neptun-code: HRWPTP

Programme: Vehicle Engineering, BSc

Specialisation: Internal Combustion Engines

Type of programme: Full time

## Data of the Thesis

Start year and semester: 2021/22/1

Language: English

Type: Public

### ***Ergonomics and Cockpit Design of a Formula Student Race Car***

Several factors contribute to the results in motorsports, one of these factors is the performance of the driver. To achieve good results the driver needs to be on high alert as even small mistakes could cost several seconds. Therefore, we must do everything in our power to keep the drivers mind on the road without breaking concentration. In order to reach this, we must strive for the perfect ergonomic layout in the cockpit as if the driver could become one with the machine. There are vibrations in a race car that are harmful to the human body and can also negatively influence the race results therefore we have to look into this topic. The goal of the thesis is for the student to design and manufacture the seat of the ART\_08 race car taking the other components of the cockpit into consideration. Another issue for the student to be dealt with is finding solutions to further improve the ergonomics of the ART\_08 race car and/or other future cars mainly by decreasing the vibrations.

The goal of the thesis is to show the design of a Formula Student car's cockpit from ergonomics point of view. The main task of the student is to design the car seat, however as it coincides with other parts of the cockpit the student has to also include those parts as well. The designed and manufactured seats must be analysed. After testing the student has to draw conclusions and make suggestions for the future that could be helpful during the design procedure.

The detailed description of the tasks. The candidate should work out the following items during the period of the thesis project:

1. Literature Review, with specific focus on the following topics:
  - a. ergonomics of the vehicle
  - b. driver safety
  - c. cockpit components and requirements
2. Define the position of the seat keeping in mind the ergonomics, visibility, CoG.
3. Design and manufacturing process of the seat and the seat mold.
4. Draw main conclusions and outline the major directions for future work

A clear graphic representation of the results of the thesis project should be given by the candidate. The thesis should end with a summary and a critical evaluation of the results.

This thesis is an intellectual property of *[Kristóf Hege]*, any publication based on or containing parts of this thesis or the results of the thesis project can only be published with a written consent of *[Kristóf Hege]*. The contents of this thesis are to be treated confidentially until the date given in the non-disclosure agreement (part of the thesis).

Other structural and formal requirements regarding the thesis are given in the faculty regulations of the Audi Hungaria Faculty of Automotive Engineering and in the thesis guidelines of the Department of Internal Combustion Engines and Propulsion Technology, respectively.

#### Data of Supervisor

Name: Martin Kaszab

Department: Department of Whole Vehicle Engineering

Position: Research Engineer

Győr, 07.05.2022.

---

Martin Kaszab

*Supervisor*

---

*Dr.-Ing. Jan Rohde-Brandenburger*

*Head of Department  
Department of Internal Combustion Engines  
and Propulsion Technology*



## **Student's Declaration**

I, the undersigned Kristóf Hege, Vehicle Engineering, BSc, hereby declare that Ergonomics and Cockpit Design of a Formula Student Race Car is my own work where I only used the given references to the given extent in compliance with the rules of citation by accurately providing the references.

My results are based on my own work, calculations, research, real measurements and according to the best of my knowledge they are authentic.

---

date

---

Student's signature

## Kivonat

|                      |                                                               |
|----------------------|---------------------------------------------------------------|
| A hallgató neve:     | <b>Hege Kristóf</b>                                           |
| A diplomamunka címe: | Ergonómia és Cockpit Tervezése Formula Student Versenyautóhoz |
| Belső konzulens:     | Kaszab Martin, Kutatómérnök                                   |

A szakdolgozatom célja, hogy megértsük egy Formula Student versenyautó cockpit-jét, ergonómiai szempontból megvizsgálva, úgy tervezzük és gyártjuk az ülést, hogy közben figyelemmel tartjuk a többi pilótafülke alkatrészét és azok pozícióját. Ehhez meg kell érteni az ergonómia és a rezonanciák alapjait. Ezután meg kell vizsgálni a szövet és gyantatípusokat, hogy ki lehessen választani az erre az esetre legalkalmasabbat. Az ergonómiai elrendezés és a rögzítési pontok lehetőségei nagymértékben különböznek a térhálós- és a monocoque karosszériák esetében, mivel az utóbbinak rögzítésre alkalmas, teli oldallapjai vannak, amelyek több lehetőséget kínálnak a felfogatási pontoknak.

Ezen felül a mi feladatunk, hogy baleset esetén megvédjük a pilótát, ez csak a megfelelő ütéselnyelő zóna, mozgást korlátozó eszközök és teljes pilótafelszerelés megléte mellett lehetséges.

A irodalomkutatás és az ide vonatkozó Formula Student szabályok megértése után megkezdődhetett a tervezés.

Bizonyos felületi minőséget és geometriai pontosságokat csak akkor érhetünk el, ha megfelelő szerszámkombinációt és csatolóanyagokat választunk hozzá. Ennek eléréséhez először is meg kell ismernünk a rendelkezésünkre álló anyagjainkat, ugyanis ezek nagyban befolyásolják a gyártási módszert. Ezt végül 3D szkennelési validálási folyamat során ellenőrizzük.

## **Abstract**

|                        |                                                             |
|------------------------|-------------------------------------------------------------|
| Candidate:             | <b>Kristóf Hege</b>                                         |
| Title of the thesis:   | Ergonomics and Cockpit Design of a Formula Student Race Car |
| Supervisor (internal): | Martin Kaszab, Research Engineer                            |

The aim of my thesis is to understand the cockpit of a Formula Student race car from an ergonomics point of view, then design and manufacture the car seat considering the position of other cockpit components. In order to be able to do so the basics of ergonomics and resonances must be understood. Then it is needed to investigate in the fiber and resin types so the appropriate one can be chosen. The ergonomic layout and opportunities for mounting points are highly distinct in case of a spaceframe and a monocoque chassis as the later has more defined panels that offer more options for pick-up points.

It is also our task to protect the driver in the event of an accident, this is only possible by the correct impact and restrain systems, next to the driver equipment.

After the literature review and understanding the relevant Formula Student rules, the design could be started.

A certain surface finish and geometrical accuracy can only be reached by choosing the correct tooling combination and consumables. In order to achieve this, first we must understand the materials available to us, as they greatly define the manufacturing techniques. Finally, this is checked during the 3D scanning validation process.

## Table of contents

|                                                                |    |
|----------------------------------------------------------------|----|
| 1. Introduction .....                                          | 1  |
| 2. What does ergonomics mean? .....                            | 2  |
| 3. Resonances .....                                            | 3  |
| 4. Cockpit components .....                                    | 4  |
| 4.1. Structural parts .....                                    | 4  |
| 4.2. Electrical parts .....                                    | 5  |
| 4.3. Comfort related parts .....                               | 5  |
| 5. Formula Student cockpit restrictions .....                  | 6  |
| 6. Types of composites used in Formula Student race cars ..... | 8  |
| 6.1. Fiber types .....                                         | 8  |
| 6.1.1. Dry fibers .....                                        | 8  |
| 6.1.2. Pre-impregnated fibers .....                            | 8  |
| 6.2. Resin types .....                                         | 10 |
| 6.3. Weave types .....                                         | 10 |
| 6.3.1. Non-woven fibers .....                                  | 10 |
| 6.3.2. Woven fibers .....                                      | 11 |
| 7. Types of Formula Student chassis .....                      | 12 |
| 7.1. Spaceframe chassis .....                                  | 12 |
| 7.1.1. General Chassis requirements .....                      | 12 |
| 7.1.2. Used materials in spaceframe chassis .....              | 13 |
| 7.1.3. Mounting points in spaceframe chassis .....             | 14 |
| 7.1.4. Spaceframe chassis bodywork .....                       | 15 |
| 7.2. Monocoque chassis .....                                   | 16 |
| 7.2.1. Specific requirements for composite structures .....    | 16 |
| 7.2.2. Used materials in monocoque chassis .....               | 18 |
| 7.2.3. Mounting points in monocoque chassis .....              | 19 |
| 7.2.4. Monocoque chassis bodywork .....                        | 19 |
| 7.2.5. Types of composite monocoques .....                     | 20 |
| 8. Driver safety .....                                         | 21 |
| 8.1. Driver equipment .....                                    | 21 |
| 8.2. Driver restraint system .....                             | 21 |

|                                                                  |    |
|------------------------------------------------------------------|----|
| 8.3. Driver head and helmet protection .....                     | 22 |
| 8.4. Firewall .....                                              | 22 |
| 8.5. Impact system .....                                         | 22 |
| 9. Seating position .....                                        | 24 |
| 9.1. Seat .....                                                  | 25 |
| 9.2. Pedal box .....                                             | 25 |
| 9.3. Steering Wheel .....                                        | 25 |
| 9.4. Alignment of components .....                               | 26 |
| 9.5. Visibility .....                                            | 27 |
| 10. Seat Design .....                                            | 28 |
| 10.1. Seat mold design .....                                     | 28 |
| 10.1.1. Materials used in the seat mold .....                    | 28 |
| 10.1.2. Seat mold manufacturing .....                            | 30 |
| 10.2. Seat design .....                                          | 31 |
| 10.2.1. Seat geometry .....                                      | 31 |
| 10.2.2. Seat mounting .....                                      | 32 |
| 10.2.3. Materials used in the seat .....                         | 33 |
| 10.2.4. Manufacturing of the seat .....                          | 35 |
| 11. Resonance measurements .....                                 | 37 |
| 11.1. Drivers' feedbacks .....                                   | 38 |
| 12. Validation .....                                             | 39 |
| 12.1. 3D scanning .....                                          | 39 |
| 12.1.1. Seat .....                                               | 39 |
| 12.1.2. Steering wheel .....                                     | 40 |
| 12.1.3. Brake pedal .....                                        | 41 |
| 12.2. Failure Mode and Effects Analysis (hereafter "FMEA") ..... | 41 |
| 13. Conclusion .....                                             | 43 |
| 13.1. Seat .....                                                 | 43 |
| 13.2. Resonance measurement .....                                | 43 |
| 14. Future plans .....                                           | 44 |
| 14.1. Seat design .....                                          | 44 |
| 14.2. Sustainable composites .....                               | 44 |
| 14.3. New monocoque and cockpit geometry .....                   | 44 |
| 15. List of figures .....                                        | 45 |

|                                    |    |
|------------------------------------|----|
| 16. List of tables.....            | 47 |
| 17. Abbreviations and symbols..... | 48 |
| 18. Bibliography .....             | 49 |

# 1. Introduction

I have joined Arrabona Racing Team the Formula Student (hereafter “FS”) team working on Széchenyi István University in October, 2018. Formula Student is an international race for engineering students to challenge themselves to design, build and race with an open-wheel single seater racecar. Figure 1 First my task at the chassis department was to gather knowledge about ergonomics and design the sixth-generation race car’s seat. Since then I am designing the cockpit as well, which amongst others consists of defining the position of three major components, the seat, the steering wheel and the pedal box. In September, 2021, I got promoted to be the leader of the chassis department, which is an incredible honor yet an extremely challenging job. My task here is not only to design the cockpit, but also to coordinate the department members and to provide every necessary information, advice and material, so that they can concentrate on the actual work.

The design and manufacturing process I am going to go through is the eighth generation race car’s composite seat. During the years in FS I have gained lots of knowledge about composites, and their manufacturing techniques with professional tools in rapid speed. Furthermore, I got the chance to do 3D scanning analyses and master my turning skills. All things considered the world of Formula Student provides the best possibilities someone can have at this age, that is why I do not want to stay out of it.



*Figure 1 ART\_08 at Formula Student Austria 2021*

## 2. What does ergonomics mean?

When talking about ergonomics of a race car, we have to deal with the environment where the driver interacts with the vehicle in. An ergonomic cockpit means that every instrument is in an easily reachable position, they require as less work to operate as possible, while providing enough feedback to be fast and accurate. Driving a race car is an exhausting task, meaning all body parts must be in a position where from rested, they can be moved to the correct direction to with minimal effort. Vision, hearing and other senses must be taken into consideration as they are the main input sources of the human body. [1]

In order to achieve as less initial stress on the drivers' muscles and joints as possible we have to look into the human Neutral Body Posture. (hereafter "NBP") Figure 2 It is recommended not to differ to much from this, because it increases the load on the body parts. It is also worth mentioning that not all humans are the same and all the drivers have different needs and preferences.

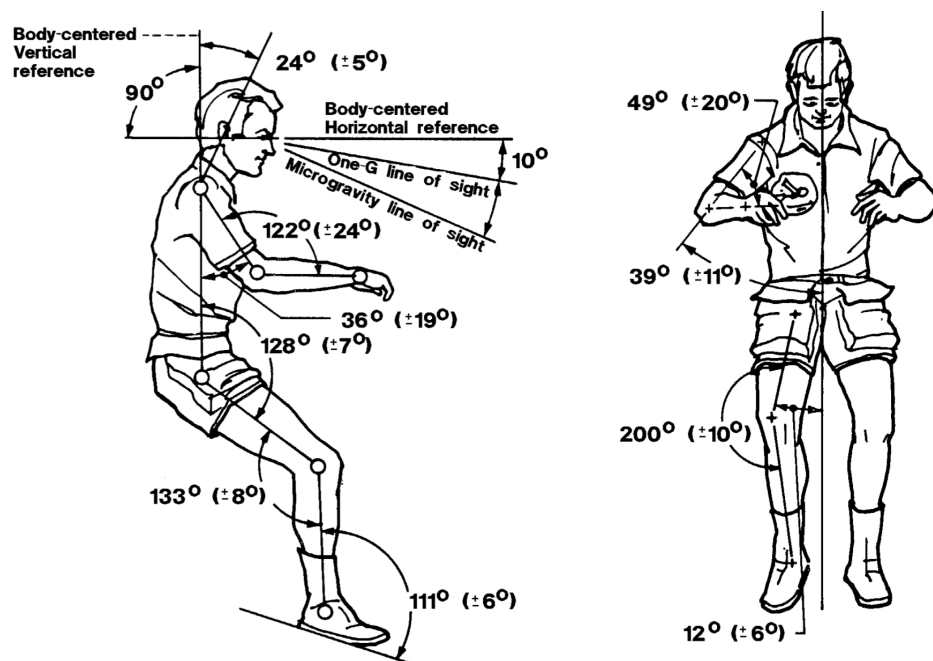


Figure 2 Human neutral body posture [2]



### 3. Resonances

Resonance happens when a body gets vibrated on its natural frequency (also known as eigenfrequency), from that point, if we leave the system alone, without any energy input, it can still continue to vibrate. Where a force applied at a frequency close to the eigenfrequency results in the greatest amplitude motion, it is called resonant frequency. Vibration at natural frequency is dangerous, because it puts a resonant stress on the parts which can lead in a failure of the material. [3] [4]

An object's natural frequency highly depends on its mass which means, that the race car has different eigenfrequencies with each driver. Unfortunately changing the natural frequency by adding mass to a race car is not an option so the connection between the resonant parts should be taken into consideration.

We also have to deal with the eigenfrequency of different body parts Figure 3 and make sure there are no frequencies on the car that has the same natural frequency as human organs. If it is not possible to eliminate the frequency peaks, then our task is to minimize them to prevent any damage in the human systems.

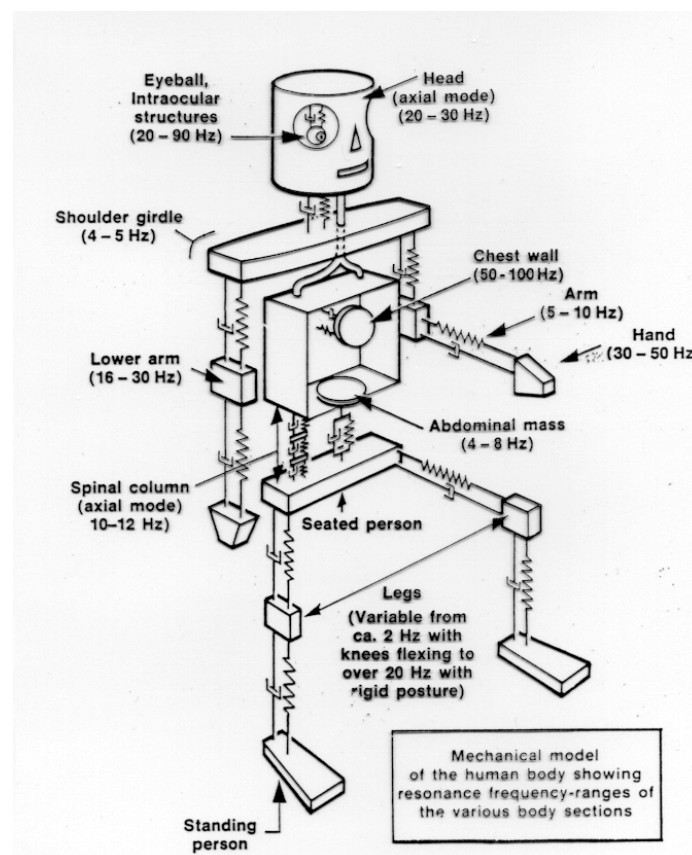
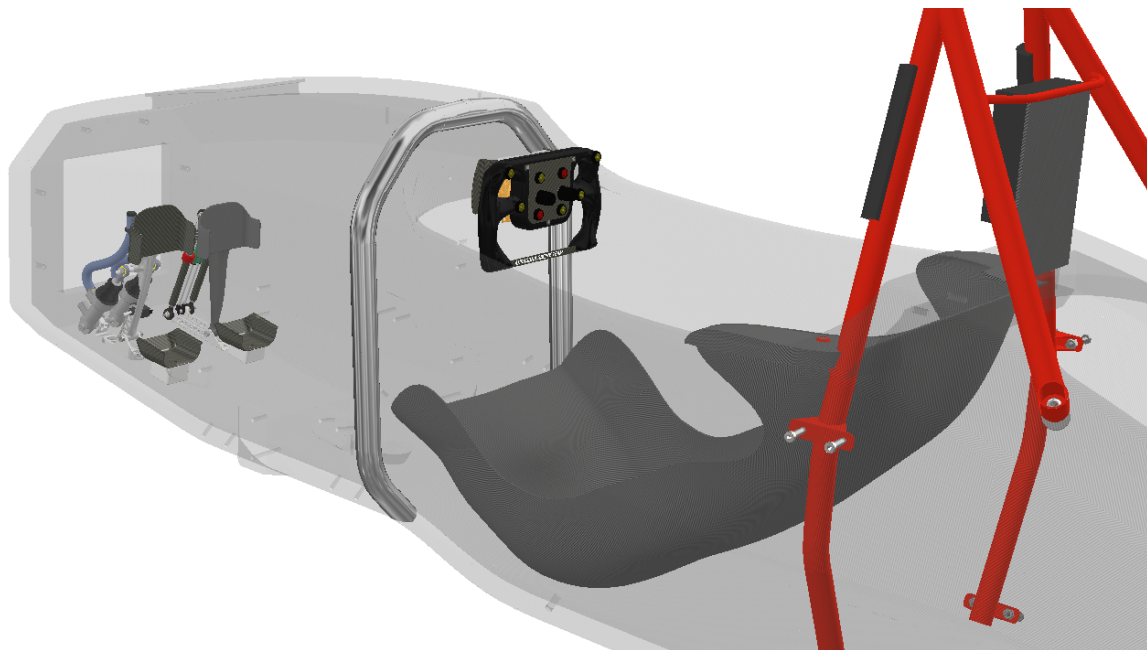


Figure 3 Eigenfrequency of human body parts [5]

## 4. Cockpit components

The cockpit is the part of the vehicle where the driver interacts with the car, because of this it is needed to have the most sophisticated solutions in every component of it. The three main elements are the seat, the steering wheel (hereafter “SW”) and the pedal box (hereafter “PB”), the latter includes both the accelerator and brake pedals. Figure 4 These ensure that the driver sits comfortably in the race car and have a perfect control of it at any time. Other cockpit components serve mostly for the safety, but also for the comfort of the driver.



*Figure 4 Arrabona Racing Team's eighth generation race car's cockpit*

### 4.1. Structural parts

The restraint system, secures the driver to the car and provides the best possible safety case in an event of an accident. With the help of it, the person does not move freely inside the cockpit preventing any other major injury and the possibility to fall out of the car. The head restraint is present to limit the rearward movement of the operator's head. Roll bar paddings must be included in the vehicle so the driver's helmet does not get in contact with any rigid parts. There are several ways, how the driver's leg and fire-resistant suit must be protected from any sharp edges, moving suspension and steering components. This can be achieved by using rubber edge protectors, bolt caps and shields. One main member which serves for safety inside the cockpit is the firewall that separates the driver from all components of the fuel system,

hydraulic fluids, flammable liquids and the low voltage battery. [6]

## **4.2. Electrical parts**

For the safety of the driver, an inertia switch has to be a part of the electrical system and be fitted inside the cockpit. In case of a collision this device opens the shutdown circuit which results in cutting the electrical supply of the race car. Next to this a shutdown button must be rigidly mounted on the dashboard alongside the steering wheel. In the pedal box a 'Brake Over-Travel Switch' and a 'Brake System Plausibility Device' should be placed. The BOTS ensures that in case of an accelerator pedal failure, the driver is still able to stop the car, while the BSPD gets activated when both the accelerator and brake pedals are pressed at the same time for more than 500 [ms]. When any of the above-mentioned devices are actuated, they open the shutdown circuit and shuts the engine so the risk of any further damage is significantly decreased. [6]

## **4.3. Comfort related parts**

It is worth mentioning that comfort related components are also important functional parts, because if the driver sits comfortably in the race car, there are no disturbing factors so he/she can concentrate more on the driving.

The knee padding while it's not a Formula Student rule restriction it is important to use it in the cockpit because it limits the transverse movement of the driver's knee. With this the seat geometry could be substantially simplified at the thigh area and there is a lower risk of leg injuries at high speed corners. Also, the fire-resistant race suit is protected in that specific area, where it would rub to the inside surface of the chassis.

## 5. Formula Student cockpit restrictions

When designing the cockpit, there are several rules, we have to take into consideration, the three most important is the Cockpit Opening - (hereafter “COT”) and Cockpit Internal Cross Section templates (hereafter “CICST”) Figure 5 next to a 95<sup>th</sup> percentile male representative figure. (hereafter “Percy”) All three must fit into the cockpit of every FS car therefore restricting the minimum dimensions of it. In case of a monocoque chassis, the COT held horizontally must pass until its 320 [mm] above of the lowest inside chassis point and the CICST held vertically must fit between the cockpit opening and a plane 100 [mm] rearwards of the face of the rearmost pedal. The steering wheel, seat and any padding may be removed without the need of any tools in order for the cockpit templates to fit. [6]

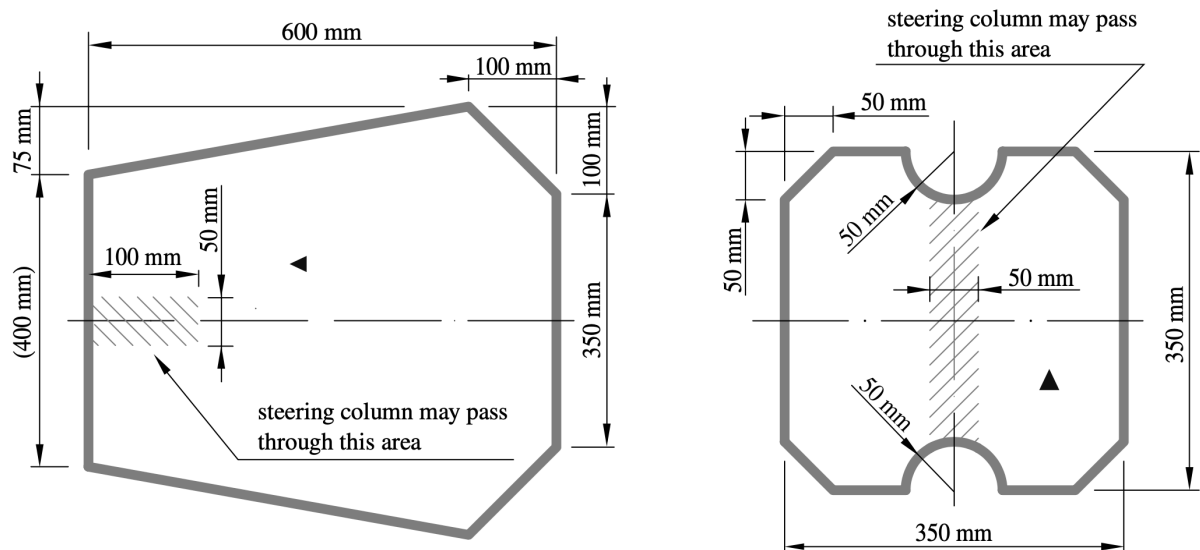


Figure 5 Cockpit Opening Template (left); Cockpit Internal Cross Section Template (right) [6]

Diagram illustrating the dimensions and components of a vehicle seat and restraint system:

- Head Restraint:** Indicated by a vertical line on the left.
- Seat Back:** Indicated by a diagonal line on the left.
- Seat Bottom:** Indicated by a horizontal line at the bottom.
- Dimensions:**
  - 25 mm (Horizontal distance from Head Restraint to the top of the seat back).
  - 300 mm (Radius of the upper circular component).
  - 280 mm (Vertical distance between the centers of the two circular components).
  - $\phi 200$  mm (Diameter of the upper circular component).
  - 490 mm (Distance from the center of the upper circular component to the center of the lower circular component).
  - $\phi 200$  mm (Diameter of the lower circular component).
  - R915 mm min. (Radius of curvature for the lower circular component).
  - rearmost Pedal Face (Indicated by a vertical line on the right).

Two 25 [mm] diameter venting holes must be drilled through every enclosed chassis at their lowest point to prevent accumulation of any liquids inside the race car.

The visibility of the driver should be realized in a way that in normal seating position the driver has an angle of view (hereafter “AOV”) of at least 100° to both left and right directions. If it is not possible to provide, mirrors must be applied onto the car. [6]

## **6. Types of composites used in Formula Student race cars**

In order to design the cockpit and its components, we must understand the materials that are suitable for race car applications. There are various types of composite materials used in the world of FS but the most commonly used is epoxy resin reinforced with carbon fiber, as it provides the best structural rigidity - weight ratio for a price that is available for most Formula Student teams.

### **6.1. Fiber types**

The two main category of fibers are dry fibers and pre-impregnated (hereafter “prepreg”) fibers, other differentiation factors are grade, density, fiber count and weave types. In formula student race cars, usually normal and intermediate performance grade carbon fibers are used with a density of around  $200 \text{ g/m}^2$  in a 3k 2/2 twill weave.

#### **6.1.1. Dry fibers**

Dry fibers are not impregnated with resin therefore have the advantage that they could be used with any kind of matrix. This is useful if we want to make a laminate for a specific case like fire retardant composite or use bio resin for sustainable laminates. Dry fibers could be impregnated with resin in several ways, namely hand layup, resin infusion or resin transfer molding (hereafter “RTM”) which could be low or high pressure. The other benefit is that curing dry fiber composites can be performed at room temperature without the need of any expensive tools. [7]

The drawback of hand lamination is that it is hard to control the resin content of the laminate, because you apply it via hand. Using resin infusion or RTM the matrix content can be controlled in a way, that only fills the accessible space when injected and the excess material is sucked out of the laminate.

#### **6.1.2. Pre-impregnated fibers**

Prepregs as the name says are pre-impregnated with the matrix. The resin is pre-mixed with its catalyst thus it has a specific lifetime. At room temperature, most prepregs have a shelf life of 30 days, after that they lose their mechanical properties determined by the manufacturer. To prevent this, it is needed to store the material in a cold environment at around  $-20^{\circ}\text{C}$ , this way the lifetime can be extended to 12-16 months depending on the matrix system. [8]

The advantage of prepreg is that it is evenly impregnated with a specific amount of resin, which is noted by the manufacturer, hence you can buy the proper material for the desired application. Using prepregs is beneficial if you would like to make FE simulations on the part, because the resin content is consistent, meaning you could make nearly identical specimens at any time with which you can create a material card.

However, the major drawback of using prepreg is that it needs to be cured at a higher temperature dependent on the resin. The minimum cure temperature of epoxy resin is generally 80°C hence the mold of the composite needs to be heat resistant to at least that temperature. Curing can be made in an oven or in an autoclave as well, in case of autoclave curing we have the option to apply over-pressure on the laminate. Over-pressure gives us the opportunity to make stronger structures because there is a force acting on the layers meaning there is less air trapped between them, resulting in a more homogeneous component which is less prone to delaminate.

On Figure 7 a typical prepreg curing cycle can be seen. The process should be done in a way, that when the first heat-up segment reaches the desired temperature, the required over-pressure in the autoclave is reached as well. Then in the second step a soak segment is implemented, at this temperature the viscosity of the resin in the prepreg gets so low that it flows and fills the available space. After soaking, the laminate is heated to the curing temperature, where a longer soak segment is used to fully cure the epoxy resin. The volume of the autoclave is constant and it is known because of Gay-Lussac's Law that during the second heat-up as the temperature increases, the over-pressure in the clave increases as well. This must be compensated by releasing the over-pressure surplus to a constant value.

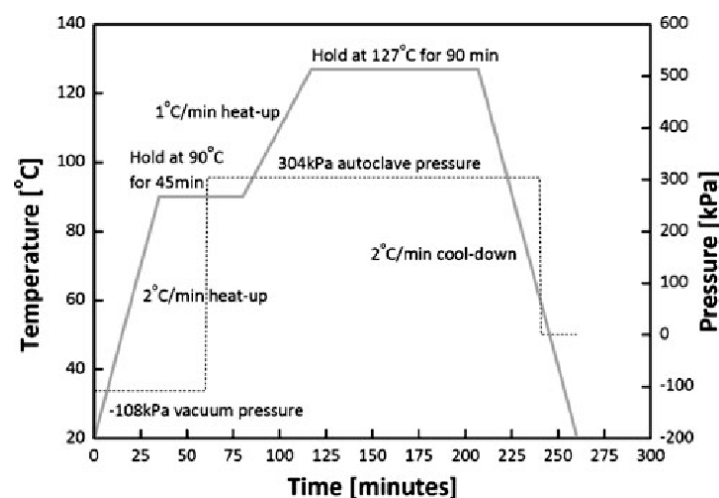


Figure 7 Typical autoclave curing cycle for prepreg [9]

## 6.2. Resin types

Most resins used with glass fiber (hereafter “GF”) or carbon fiber (hereafter “CF”) are thermosets namely polyester, vinyl ester, polyamide and epoxy, while the most common thermoplastic resin is polyethylene. Nearly all FS teams use epoxy resin because of its favorable physical and mechanical properties. By using special hardeners, the matrix could be modified to have high strength, great flexibility, hardness, heat and/or chemical resistance. There is a huge investigation in green and bio-based resins as bisphenol A (hereafter “BPA”) which is the main component used in epoxy manufacturing has a negative effect on the human body, including immune and reproductive systems. [10]

## 6.3. Weave types

Reinforcement fibers have multiple weave types that allows to use the exact material for the required application whether it is a FE optimized part or a mold.

### 6.3.1. Non-woven fibers

Nonwovens can be either oriented or non-oriented fibers. Oriented nonwovens have the great advantage that they can be applied in the direction of the load. With using unidirectional (hereafter “UD”) or non-crimp biaxial fibers Figure 8, the mass of the laminate can be minimized which is crucial in motorsport. Biaxial fibers consist of multiple UD plies layered on top of each other, this material can be a cost-effective solution if the direction of the unidirectional fibers is in that specific orientation, what the structural part needs based on the loads acting on it. [11] [12]

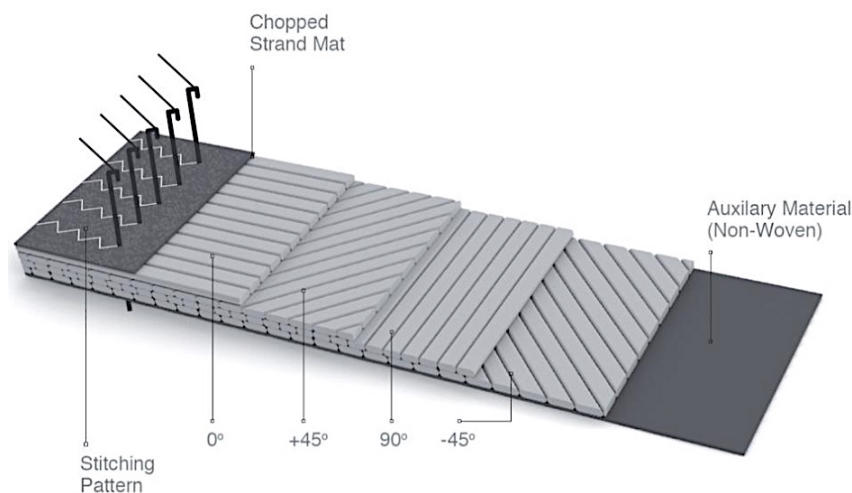


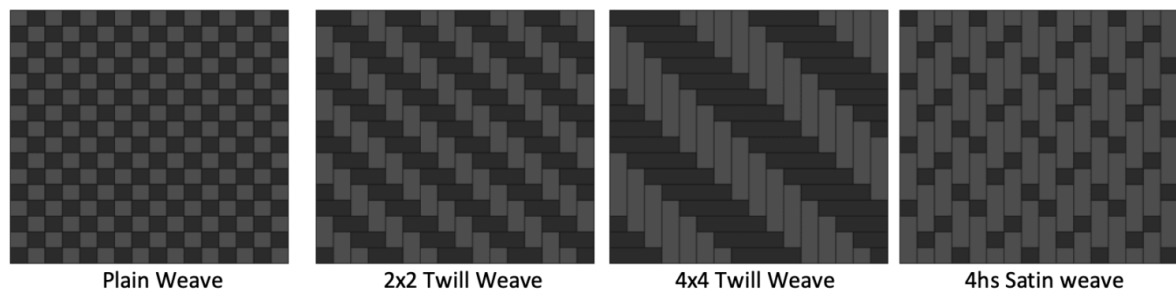
Figure 8 Non-crimp biaxial fiber [13]



Non-oriented nonwovens are either mats or chopped/forged fibers. This is a great way to give the fiber a second life as they could be manufactured from leftovers. Recycled carbon fiber (hereafter “rCF”) is more and more used in motorsport as well because of its sustainability, however non-oriented fibers do not have great mechanical properties mainly because of their relatively short fiber length. (5-100 [mm]) Forged carbon is mainly used because of its looks, while fiber mats are optional to use for laminate molds providing a low tooling cost.

### 6.3.2. Woven fibers

There are various fiber weaves, Figure 9 each has their strengths and weaknesses. If the weave is symmetric, wovens have the same characteristics in both the warp (longitudinal) and the weft (lateral) direction. The most popular weave type is 2/2 twill as it easily forms to the mold shape without any warping meaning there is no need to cut the fibers with which the whole laminate can be more homogeneous.



*Figure 9 Different weave types [14]*

There are several other weaves on the market called design fibers that are used as the first visual layer to give the laminate a certain look. These fibers are high fiber count (6k or 12k) spread tow fibers in a plain, twill, triaxial or hexagonal weave style. [15]

## 7. Types of Formula Student chassis

Formula Student chassis could be categorized into two parts, which are either a tubular spaceframe or a monocoque chassis, the latter has several types according to the used materials and manufacturing techniques.

### 7.1. Spaceframe chassis

When it comes to spaceframe chassis Formula Student teams commonly use tubular spaceframes but there are few teams who use square hollow section spaceframes as well due to its availability and price. However cylindrical hollow sections are better to use for such an application because they have a uniform strength in every direction and are easier to work with. Arrabona Racing Team's seventh generation race car's chassis assembly can be seen on Figure 10



*Figure 10 Render of ART\_07 tubular steel spaceframe assembly*

#### 7.1.1. General Chassis requirements

The current Formula Student regulations require to have two braced roll hoops, a front bulkhead (hereafter “FBH”) with a support system and an impact attenuator (hereafter “IA”), lastly side impact structures (hereafter “SIS”) [6]

### 7.1.2. Used materials in spaceframe chassis

There are specified minimum material requirements for each chassis member, which teams have to meet in order to pass scrutineering and have the chance to enter the race. Figure 11 shows the minimum material requirements if the primary structure (hereafter “PS”) members are made from steel tubing.

| Item or application                                                                                                     | Minimum wall thickness | Minimum cross sectional area | Minimum area moment of inertia |
|-------------------------------------------------------------------------------------------------------------------------|------------------------|------------------------------|--------------------------------|
| Main and front hoops, shoulder harness mounting bar                                                                     | 2.0 mm                 | 175 mm <sup>2</sup>          | 11 320 mm <sup>4</sup>         |
| Side impact structure, front bulkhead, roll hoop bracing, driver’s restraint harness attachment (except as noted above) | 1.2 mm                 | 119 mm <sup>2</sup>          | 8509 mm <sup>4</sup>           |
| Front bulkhead support, main hoop bracing supports                                                                      | 1.2 mm                 | 91 mm <sup>2</sup>           | 6695 mm <sup>4</sup>           |

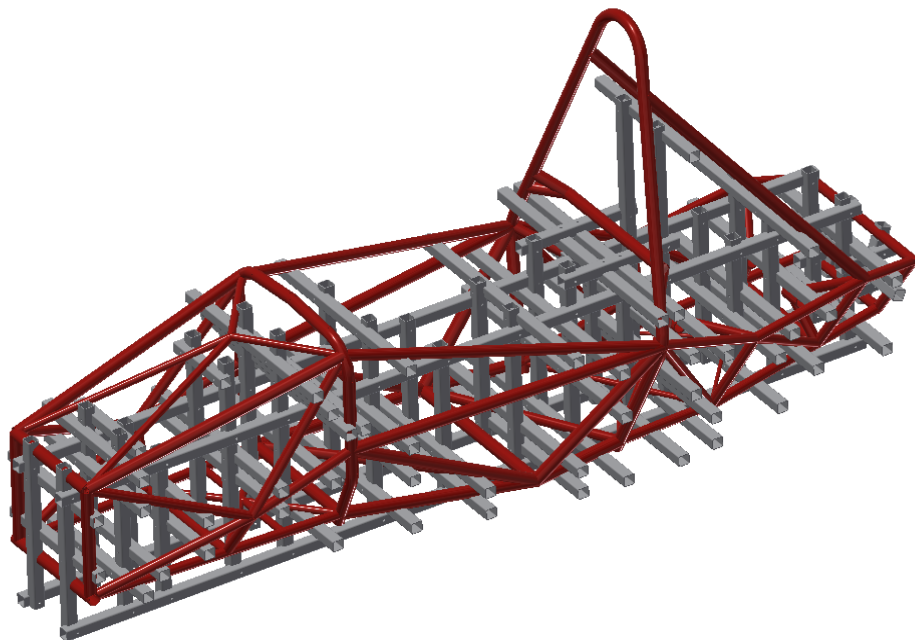
*Figure 11 Minimum Material Requirements [6]*

Moreover, in case of a steel tube structure it is required that the material has to be an unalloyed carbon steel with a maximum content of 0.3% carbon, 1.7% manganese and 0.6% of any other element. [6]

Alternative materials could be used in the primary structure with the exception that the Main Hoop (hereafter “MH”), and the Main Hoop Bracing (hereafter “MHB”) must be steel while the Front Hoop (hereafter “FH”) must be metal. All the welded primary structure members must be steel, however the FH could be a welded aluminum structure as well. If teams are not using steel tubes in the PS or they use a higher alloy content than listed above, they must show equivalency with physical tests and documentations. [6]

### 7.1.3. Mounting points in spaceframe chassis

One of the chassis' most important task is to hold every other part together in a secure way, therefore mounting point must be used. In Arrabona Racing Team's last tubular steel spaceframe chassis the mounting points were welded on as this is the most practical solution. Positioning these brackets are crucial in every sense because not only they have to be implemented in a way that the suspension, engine, and aerodynamic brackets are in place, they also have to withstand all the loads coming from them. In order to achieve this, we have used a frame jig made of laser cut square hollow sections. Figure 12



*Figure 12 ART\_07 Frame jig*

#### 7.1.4. Spaceframe chassis bodywork

The requirement of FS bodywork is that it must not have any opening other than the cockpit opening, where the driver could get in and out of the race car, and minimal cutouts around the front suspension and steering system components. For safety reasons, any edge of the bodywork that could get in contact with a person must have an at least 1 [mm] radius fillet. [6]

The bodywork in case of spaceframe chassis is usually made of carbon fiber reinforced plastic, (hereafter “CFRP”) however some teams use glass fiber reinforced plastic (hereafter “GFRP”) or polymer as well, like FaSTTUBe’s race car from 2021. Figure 13

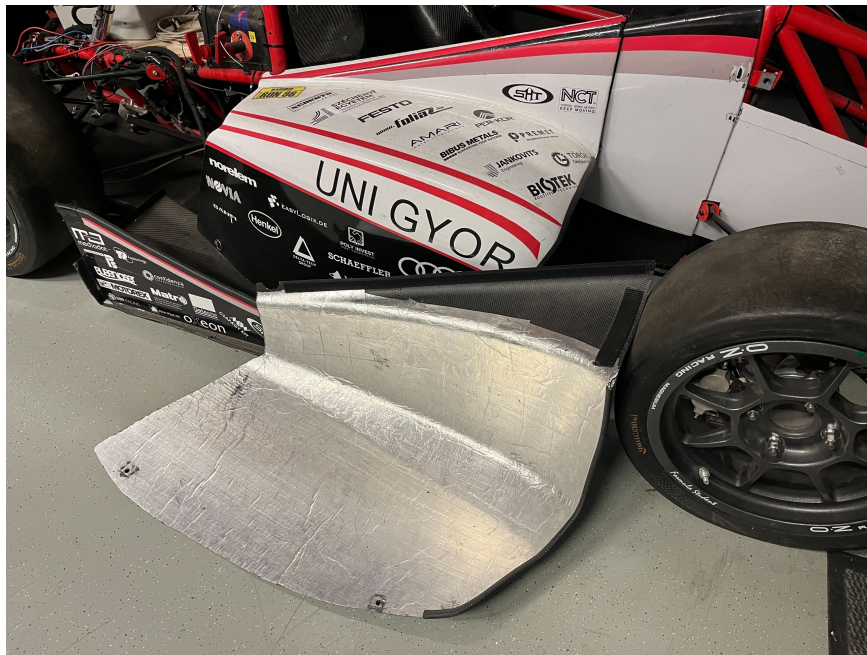


Figure 13 FaSTTUBe FT21 race car [16]

These cover panels must be aerodynamically optimized to have the lowest possible drag coefficient and be designed in a way that is can work effectively with the whole aerodynamic package.

The layup and used materials of each bodywork panel highly depends on its application and shape. On Figure 14 Arrabona Racing Team’s sixth generation race car’s (hereafter “ART\_06”) side-panel and sidepod can be seen. These exact body elements have a relatively great size, simple shape and due to their placement, they have a very low air resistance. The left sidepod’s main task is to cover the exhaust muffler while making sure it does not disturb any airflow of the rear wing. Knowing all

of these we chose to use 2 layers of 2/2 3k twill weave carbon fiber reinforced with epoxy resin. Because of the high temperature generated by the exhaust system it was needed to use some heat reflection material. This is needed because the resin in the composite part softens over its glass transition temperature (hereafter " $t_g$ ") which could lead in a structural failure. In order to protect the composite from thermal radiation, it is the best to use aluminum or gold foil tape, which reflects 95% of the radiant heat that contacts its surface.



*Figure 14 ART\_06 side-panel and sidepod covered with aluminum tape*

## **7.2. Monocoque chassis**

We can consider a chassis a monocoque structure if the body and the frame are combined together and are responsible for carrying any load acting on it.

### **7.2.1. Specific requirements for composite structures**

If composites are used in the PS the flexural rigidity must be calculated and attached in a document called Structural Equivalency Spreadsheet (hereafter "SES") this should be provided to the race event organizers prior to the event. Moreover, the SES must include all the used material types, cloth weights, resin types, fiber orientations, numbers of layers, core materials, layup techniques, 3-point-bending and shear test data. Each team must do laminate tests to show equivalency to specific steel



tube frame members, this should be carried out with 3-point bending and perimeter shear tests. For every different composite PS member, a 275 [mm] x 500 [mm] representative test panel must be manufactured with the same layup, design and manufacturing technique as it is used in the built race car. The distance between the test panel supports must be at least 400 [mm], the load applicator must be a metallic and have a 50 [mm] radius. Figure 15 The other specimen should be a 100 [mm] x 100 [mm] flat panel, the test jig must have a 32 [mm] hole at the bottom and the load applicator must be a 25 [mm] diameter flat punch. Figure 16 [6]



*Figure 15 3-point bending test*



*Figure 16 Perimeter shear test*

All this is needed because this proves that the composite structure is safe for the race car driver and for the race.

### 7.2.2. Used materials in monocoque chassis

Most Formula Student team's material choice for a monocoque structure is CFRP however there are few teams using aluminum welded construction. Arrabona Racing Team's first composite monocoque chassis was the eighth generation race car. (hereafter "ART\_08") Figure 17



Figure 17 Render of ART\_08 monocoque chassis assembly

In order to achieve the best stiffness to weight ratio it is indispensable to build a sandwich structure, this means that there is a core material between the inner and outer CFRP skins. [17] Figure 18

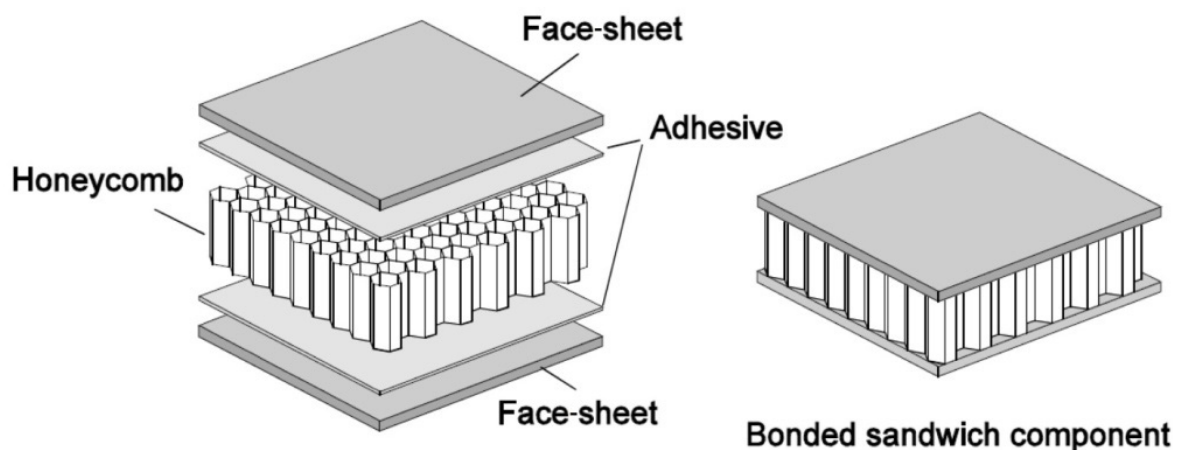


Figure 18 CFRP honeycomb sandwich structure [18]

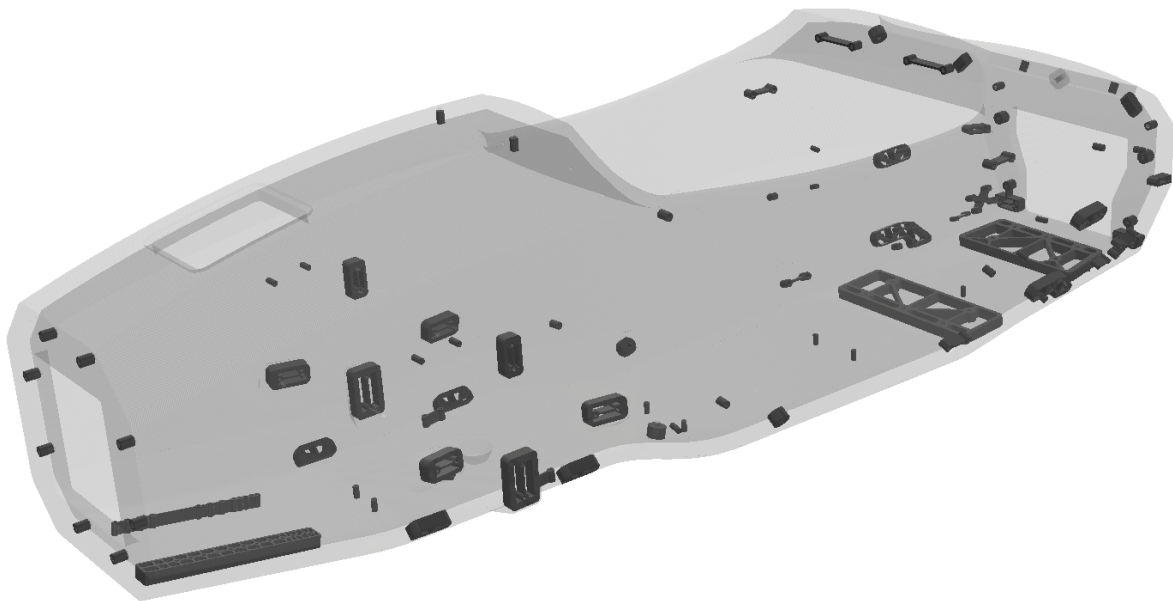
For the two skins the used type of carbon fiber is usually a prepreg carbon, which ensures that the fiber is evenly soaked with resin resulting in a homogeneous laminate. This way it is easier to infer the final torsional stiffness, and mass of the chassis based on FE simulations.



The core material is often either an aluminum or an aramid honeycomb as they have superior strength relative to their mass and have outstanding bonding characteristics. To make sure the skins are adequately bonded to the honeycomb an epoxy resin film must be applied between them. If cured correctly, this adhesive layer runs to the hexagonal walls of the core material providing a greater contact surface for the laminate.

### **7.2.3. Mounting points in monocoque chassis**

At mounting points, monocoques require to put inserts inside Figure 19 the laminate these inserts have holes for bolts, where brackets and backing plates could be attached. The main task of inserts is to hold the bolts in place. When designing inserts, it is crucial to know every load acting on them, because choosing the wrong material could lead in a failure of the structure. Inserts at suspension mounting points must withstand the compression load coming from tightening the nuts to a certain torque, moreover ones near heat sources like the engine or the exhaust must have a specific heat resistance otherwise the material could get soften.



*Figure 19 ART\_08 Insert package*

### **7.2.4. Monocoque chassis bodywork**

In case of a monocoque chassis the structural body serves as the bodywork as well, therefore we consider the nosecone and the cover for the front rockers (if any) the only bodywork elements. To achieve the best construction the structural skin should

be aerodynamically optimized, while still be effective for the suspension. This means that the geometry of the monocoque must be designed hand in hand between the aerodynamics, vehicle dynamics and chassis departments from the first moment.

#### 7.2.5. Types of composite monocoques

We can differentiate 2 main types of composite monocoque Formula Student chassis, the first is called semi-monocoque, which means that there is a subframe connected to the back of the chassis, which holds the engine parts and rear suspension. The other type is a full monocoque which could be one piece or multiple pieces glued or laminated together. Both chassis types have advantages and disadvantages as well, these are detailed in Table 1.

*Table 1 Advantages and disadvantages of different types of monocoque chassis*

|               | Semi-monocoque      | Full monocoque                |
|---------------|---------------------|-------------------------------|
| Advantages    | Serviceability      | Potentially higher T $\theta$ |
|               |                     | Suspension mounting           |
| Disadvantages | More compliance     | Heat management               |
|               | More failure points |                               |

## 8. Driver safety

Driver safety is crucial in every kind motorsport, the possibility of any kind of injury must be minimized. The 5 points listed below shows the importance of every main safety related equipment, component and assembly.

### 8.1. Driver equipment

The driver equipment consists of a well-fitted closed face helmet that meets one of the certifications mentioned in [6] T 13.3.2, a balaclava that covers the head, hair and neck of the driver fire-resistant socks and gloves, all from acceptable fire-resistant material which are Carbon X, Indura, Nomex, Polybenzimidazole or Proban according to [6] T 13.3.11 There are specific certifications referring to race suits, shoes and arm restraint which are SFI or FIA standards. All driver equipment must be worn any time when the driver sits in the car with a running engine and be in a good condition without any tears or significant abrasion. [6]

### 8.2. Driver restraint system

Formula Student cars must be equipped with a 6- or 7-point harness consisting of two shoulder straps (hereafter “SHB”), two lab belts (hereafter “LB”) and two anti-submarine belts. (hereafter “ASB”) Figure 20 In case of a 7-point harness, the ASB has one additional element. They must also meet specified SFI or FIA standards, and be noted with valid date labels and all straps must be connected with a single metal-to-metal latch type quick release. [6]



*Figure 20 6-point FIA 8853 racing harness [19]*

### **8.3. Driver head and helmet protection**

Other than the helmet there are other parts that must be equipped with the car in order to provide a proper protection for the driver. The most important is the head restraint system mentioned previously in 4.1 consisting of an at least 40 [mm] thick energy absorber material that meets SFI 45.2 or listed in FIA n°17 as a type B material. The minimum height and width should be 150 [mm] and be located in a way, that it is not more than 25 [mm] away from the back helmet, moreover the contact point of the helmet and the restraint is no less than 50 [mm] from any edge of the absorber foam. The head restraint must be attached in a way that it sits vertically or near-vertically in side view and must withstand an 890 [N] force in rearward direction at any point of the head restraint or its mounting. [6] [19]

A roll bar padding must be applied to the roll bar wherever the driver's helmet could get in contact with it, furthermore have a minimum thickness of 12 [mm] and meet either SFT 45.1 or FIA 8857-2001. [6]

### **8.4. Firewall**

The task of the firewall is to protect the driver from any dangerous materials in the engine bay area and it must cover the line of sight between the parts mentioned in [6] T 4.8.1 and any part below a plane 100 [mm] above the lowest part of the tallest driver's helmet. It should be manufactured from a fire-resistant material, must be rigid, and rigidly mounted to the race car. In order to give a proper protection, it should now allow any liquids to pass especially in the bottom and sides, however pass through for cables are allowed if the cutout is sealed correctly with grommets. If multiple panels are used as the firewall, there must be at least 5 [mm] overlap between them and be sealed at the seams. [6]

### **8.5. Impact system**

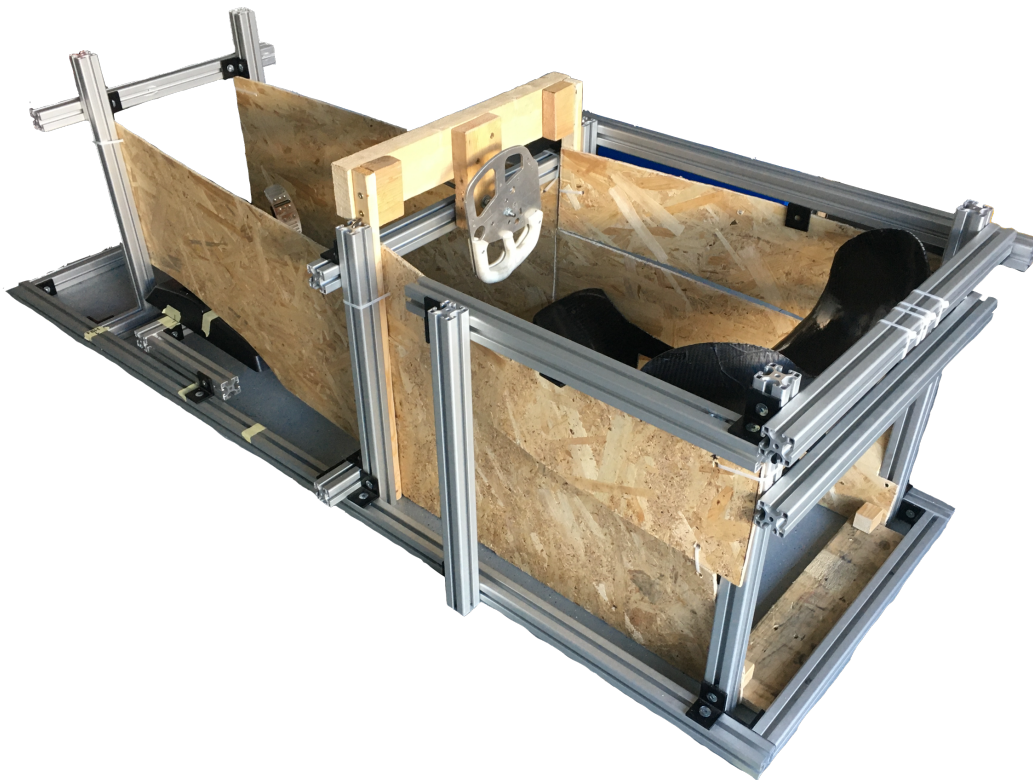
All FS cars must be equipped with two impact systems, the Side Impact Structure and the Impact Attenuator Assembly. The SIS of a composite chassis is the region between the FH and MH and from the lowest inside surface point to 320 [mm] up from the bottom of the inner surface of the monocoque. This area must have a flexural rigidity and an absorbed energy equivalent or greater than two baseline steel tubes,

while its perimeter shear strength has to be higher at least 7.5 [kN]. [6]

The IA assembly consists of the Impact Attenuator and the Anti Intrusion Plate (hereafter “AIP”), these components’ task is to protect the driver in case of a frontal crash. The IA must have a height of 100 [mm] with a width and depth of 200 [mm] and can be a standardized FSAE foam or aluminum honeycomb, however alternative materials could also be used. It should be securely attached to the AIP and must not penetrate through the FBH in the event of an impact. The Anti Intrusion Plate can be made of a 1.5 [mm] thick steel plate or a 4 [mm] thick but can be manufactured from alternative materials for example CFRP, if equivalency is proved with mechanical tests. All data and measurements of the IA assembly must be reported in the Impact Attenuator Data (hereafter “IAD”) and be submitted to the organizers prior to the race event. [6]

## 9. Seating position

To determine the drivers' seating position, I had to take into consideration the three main components which they interact with. Designing a cockpit that is functional yet comfortable for each driver is a hard task because not all drivers are the same, they have different preferences, therefore it is subjective. First, I have made measurements of our shortest and tallest drivers' body parts to see the difference, then made a mockup of Bosch Rexroth strut profile and Oriented Standard Board (hereafter "OSB") which allowed me to steplessly adjust it to each of the drivers' needs. Figure 21 After that I have attached previous year's car's components and with all that I have started the designing phase with regular consultations with all the drivers from iteration to iteration. The perfect seating position can only be found if the three components are in accordance with each other, moving only one part can ruin the whole setup.



*Figure 21 ART\_08 mockup*

## **9.1. Seat**

As the driver is the greatest mass in a Formula Student car it is indispensable to put the seat near to the ground, to achieve the lowest possible center of gravity (hereafter “CoG”) which is crucial when designing the suspension geometry. The distance between the roll axis and the CoG of the car defines a lever arm which has an essential role in the weight transfer of the race car. In ART\_08’s race season we had a problem with the CoG, that it was 38 [mm] higher than the designed value. Because of this, the forces acting on the Anti Roll Bar (hereafter “ARB”) blades were 4 magnitudes larger. Because of this, a much heavier ARB blade was needed to be used.

Other than the position on the vertical axis, the angle of the seat also impacts the CoG. With tilting the seat to a more reclined position, we can make the driver’s upper body to be lower, however we cannot do this until he is in a horizontal position, because it would put a lot of unnecessary stress on the neck, spine and pelvis, while also limiting visibility. Furthermore, we must limit the length of the cockpit so the chassis has the lowest possible moment of inertia to get an agile race car.

## **9.2. Pedal box**

The pedal box must be positioned in a way that no parts of it except sensors be forward of the rearmost plane of the FBH and they must be at least 25 [mm] rearward from the back of the AIP. Based on drivers’ feedbacks, they can drive the vehicle for a long period of time in a 90° toe angle, but any angle lower than that puts a constant tension to their feet. Positioning the pedals along the z vertical axis influences the position of the steering wheel as well, because the thighs could get in contact with it resulting in a difficulty during turning. [6]

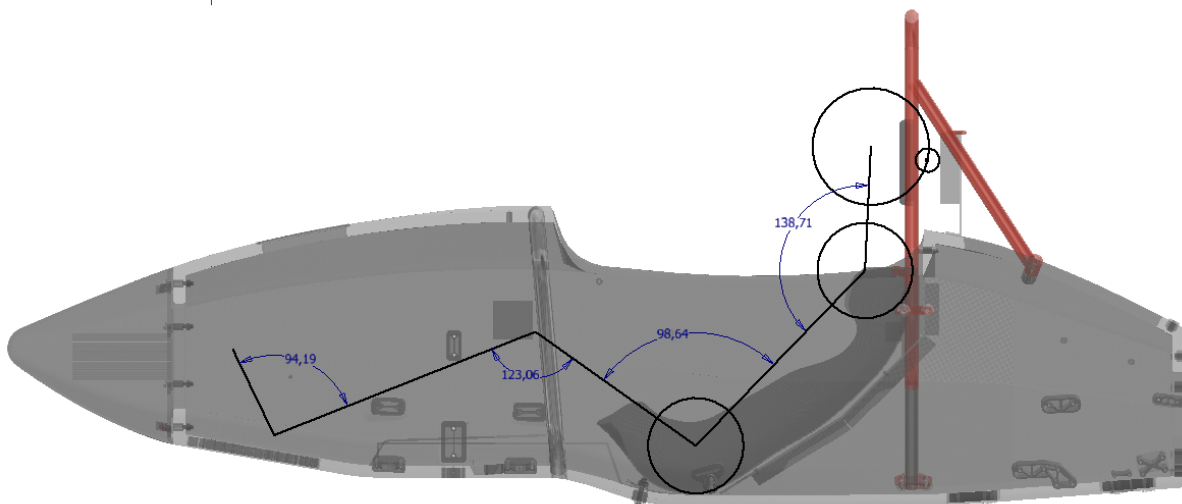
## **9.3. Steering Wheel**

There are two FS rules present limiting the position of the steering wheel, one says the foremost point of the steering wheel must not be more than 250 [mm] (measured horizontally) rearward from the rear surface of the front hoop. The other limits the vertical position in a way that in any steering wheel angle there must not be any point of it that sits above the topmost surface of the FH. [6]

There are very few positions of the SW where it is ergonomic for all the drivers. Because of the position of the legs, in order for the steering wheel not to touch the thighs it must be positioned either more to the rear or to the top. Because of the rules regarding the Front Hoop I pushed the SW as high as possible to have the greatest playroom for the other factors. Therefore, the only way to adjust it to the correct position is either to bring it closer to the driver's chest and tilt it around the y lateral axis. In a turn where the SW rotates 90° the wrist which stays lower gets near to a -100° angle that puts a lot of stress on the joint. Unfortunately, this is unavoidable with these restrictions related to the steering wheel, so the drivers must adapt to it and train their wrists hard to be able to drive on the track without any distractions.

#### 9.4. Alignment of components

Knowing all this I was able to create the final seating position of ART\_08, it can be seen on Figure 22. Modifications were needed from the NBP because there were lots of other factors listed above that I had to consider. With the perfect seating position, we can maximize the drivers' confidence with the car and make sure they can focus on the driving without any disturbances.

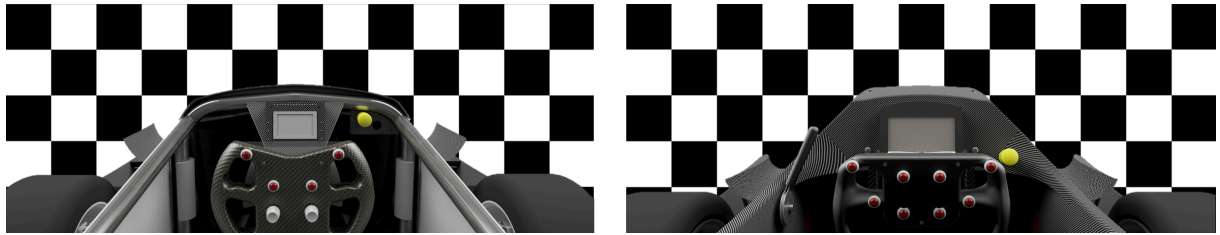


*Figure 22 ART\_08 Final seating position angles*



## 9.5. Visibility

On Figure 23 the difference between the designed visibility of our seventh and eighth race car can be seen. As in an average FS race track, around 80% of the time, the car is in a turn, visibility to the sides are crucial. We have enlarged the Field of View (hereafter “FOV”) and gained a lot of visibility via applying relatively large 45° chamfers on the dashboard. This way the drivers’ see the cones sooner and more accurate meaning there is a smaller chance of hitting one.



*Figure 23 Render of ART\_07 and ART\_08 visibility*

## 10. Seat Design

When choosing the materials and manufacturing techniques for the seat and its lamination tool I have made a decision matrix Table 2 Decision matrix for ART\_08's seat mold material to see which method is the most beneficial.

*Table 2 Decision matrix for ART\_08's seat mold material*

| Construction possibilities |                  |                  |
|----------------------------|------------------|------------------|
| View points                | Milled foam mold | Glass fiber mold |
| Mold manufacturing time    | 4                | 2                |
| Accuracy                   | 4                | 2                |
| Price                      | 4                | 3                |
| Surface quality            | 5                | 3                |
| Manufacturing knowledge    | 3                | 5                |
| Sponsorship resources      | 3                | 1                |
| Overall                    | 23               | 16               |

In conclusion, the accuracy and the surface quality were the most important factors that we wanted to improve therefore we chose the milled PU foam mold over the 2-part Styrofoam mastermold - Glass fiber mold combination.

### 10.1. Seat mold design

#### 10.1.1. Materials used in the seat mold

The biggest step in the design from last year in that I have only used a milled single mold. This hardly improves the manufacturing accuracy and -time with keeping the same material costs. There are numerous materials that could be used for the mold, in the past we have used both extruded (hereafter "EPS") and expanded polystyrene (hereafter "XPS") for the mastermolds and hand laminated glass fiber on it to form the laminate mold. This year the chosen material was a closed cell 80 [g/m<sup>3</sup>] polyurethane foam, which means that the air bubbles are filled hydrofluorocarbon that provides a more effective thermal barrier, but most importantly in our case the compressive strength is greatly improved, ensuring there will not be any problems during vacuuming. As it is a thermosetting polymer, manufacturing it via a hot wire cutter was not an option, it can only be made via machine cutting. [20] The cost calculation for the

milled mold compared to the 2-part hand-made mastermold-mold combination is detailed in Table 3 and Table 4.

*Table 3 Cost calculation for PU foam seat mold*

|             | Amount | Unit           | Unit cost [€] | Total cost [€] |
|-------------|--------|----------------|---------------|----------------|
| PU foam     | 0.23   | m <sup>3</sup> | 650           | 149.5          |
| PU adhesive | 0.6    | kg             | 12            | 7.2            |
| Putty       | 0.35   | kg             | 12            | 4.2            |
| Topcoat     | 0.2    | kg             | 11            | 2.2            |
| Sum         |        |                |               | 163.1          |

*Table 4 Cost calculation for XPS seat mastermold and GFRP seat mold*

| Mastermold    | Amount | Unit           | Unit cost [€] | Total cost [€] |
|---------------|--------|----------------|---------------|----------------|
| XPS foam      | 0.38   | m <sup>3</sup> | 298.72        | 113.5          |
| XPS adhesive  | 2.3    | kg             | 12            | 27.6           |
| Putty         | 0.8    | kg             | 12            | 9.6            |
| Topcoat       | 0.2    | kg             | 11            | 2.2            |
| Mold          |        |                |               |                |
| Twill GF      | 4.62   | m <sup>2</sup> | 5             | 23.1           |
| Core material | 0.25   | m <sup>2</sup> | 20            | 5              |
| Resin         | 1.6    | kg             | 19            | 30.4           |
| Sum           |        |                |               | 211.4          |

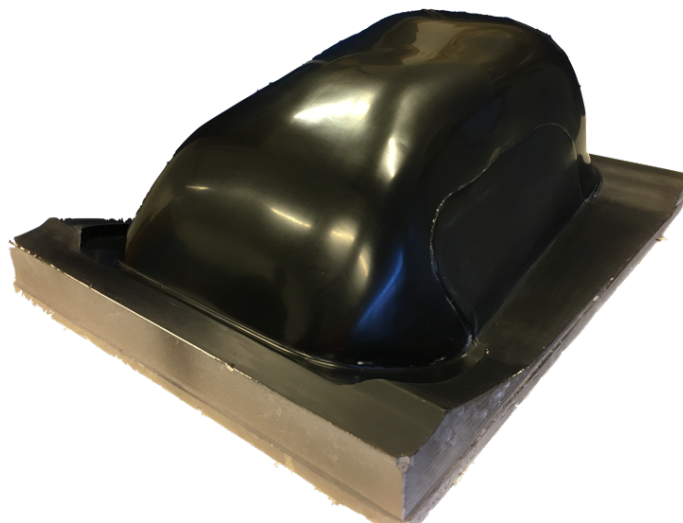
The milling machine had a limited vertical workspace, therefore the was needed to be cut in multiple sections. They were milled and glued step by step until the whole seat mold geometry is reached.

### 10.1.2. Seat mold manufacturing

The raw milled mold can be seen on Figure 24. The next step after milling is surface preparation, the major defects were fixed with soft putty. The final surface which we laminate onto has to be covered with a material that is hard enough to be polished, has small pores and easy to apply. A polyester based topcoat is a perfect option for this as it is easy to sand and polish but dense enough to cover the whole surface. Then a release agent must be applied so the laminate could be removed after curing, we chose to use a two-step semi-permanent system which consists of a mold sealer and a mold release, because if there is need for manufacturing another seat this step can be skipped resulting in a faster manufacturing time. Figure 25 shows the final seat mold before the lamination process.



*Figure 24 ART\_08 seat mold after milling*



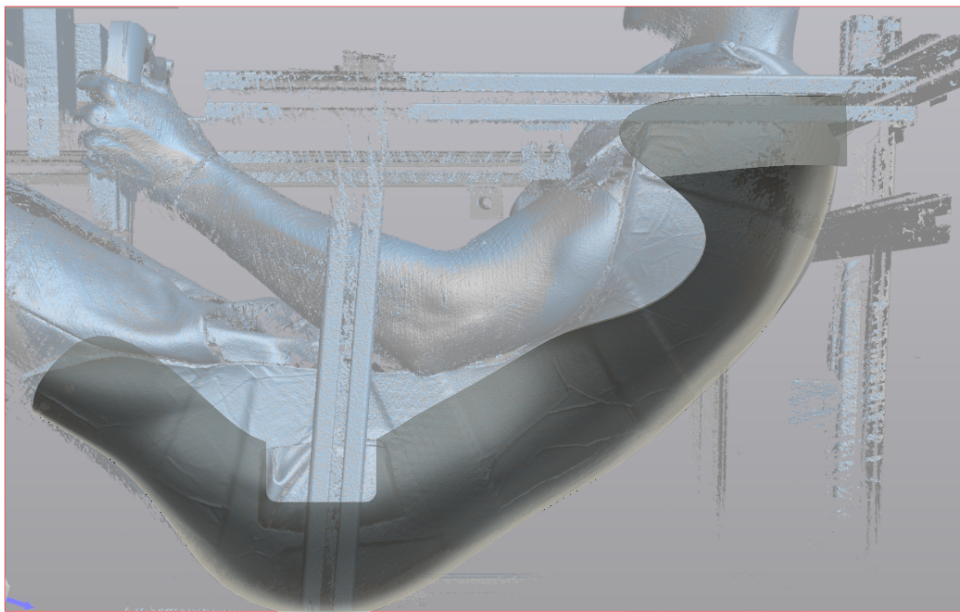
*Figure 25 Mold for ART\_08's CFRP seat*

## 10.2. Seat design

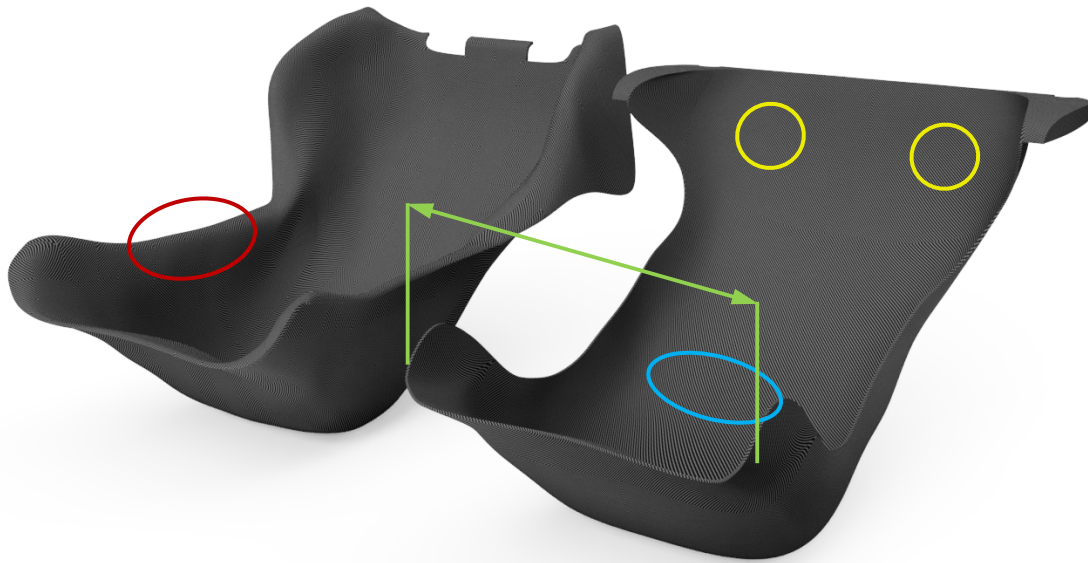
### 10.2.1. Seat geometry

The design process of the seat started with 3D scanning our tallest driver in the final mockup. Figure 26 There was no need to change the seat's main geometry because the same drivers drove ART\_08 than who drove ART\_07, but there were some areas where it could be improved based on the drivers' feedbacks gathered throughout the season. Figure 27

The 3D scan showed the unnecessary areas at the side of the seat, mainly at the pelvis where material was previously added in order to gain stiffness but based on FE simulations there was no need for it in thanks to the used core material. The other area was a part at the upper arm, where movement was partially blocked when steering. This area got weakened because of the larger cutout but the stiffness was gained back due to the geometry of the shoulder support.



*Figure 26 Tallest driver 3D scanned in mockup*



*Figure 27 Modified areas on ART\_08's seat (right) from ART\_07's seat (left)*

Other than the pelvis area (marked with red on Figure 27.) the drivers needed a more functional waist support (marked with blue.) so a protrusion was created to prevent hunching the back. This was defined by putting different sized paddings during tests, then the modification was made in Computer Aided Design (hereafter “CAD”) model environment as well. The scapula support (marked with yellow) was too tight for all drivers, pushing their shoulders forward to an uncomfortable position. This put unnecessary stress on the shoulder joint that was disturbing during longer drive sessions. The last major change was done at the thigh support (marked with green) which got narrower. The problem with the previous construction was that the cockpit was too wide at the Front Hoop because of the front suspension geometry. There was no option to put a leg support that was great enough to hold the knees in an ergonomic position. Because of this, the drivers’ feet rotated out with around 25° from vertical, and they needed to twist their feet back in order to operate the pedals. Thanks to the new monocoque, there was an option to change the chassis geometry near the front suspension so both the cockpit at the FH and the seat got slimmer.

### **10.2.2. Seat mounting**

As for the mounting, two self-positioning pins were used on the top to taper-lock the seat, in addition with two 3D printed cylinders limiting the lateral movement at the thighs. These mounts made putting the seat in and out and fixing it to the race car incredibly quick compared the previous method, where two zip-ties were used on the top.

### 10.2.3. Materials used in the seat

The materials and layup of the seat was defined by FE simulations, the goal was to decrease the mass and improve the stiffness so it does not twist as much in the cockpit. In Formula Student, the resources and time are limited so a cost plan was made to see the expenses for the seat for different available materials. The first thing was to measure the area of the seat so the amount of needed materials can be calculated, then estimated the price using the core material and carbon fiber that we have a material card for and compared it to a glass fiber seat with the same stiffness. Table 5 shows the costs of the carbon composite seat.

*Table 5 Cost calculation for CFRP seat*

|               | Amount | Unit           | Unit cost [€] | Total cost [€] |
|---------------|--------|----------------|---------------|----------------|
| Twill CF      | 2.48   | m <sup>2</sup> | 28            | 69.44          |
| Biaxial CF    | 0.03   | m <sup>2</sup> | 17            | 0.51           |
| Core material | 0.18   | m <sup>2</sup> | 20            | 3.6            |
| Resin         | 0.6    | kg             | 19            | 11.4           |
| Sum           |        |                |               | 84.95          |

Knowing that the tensile strength of glass fiber is about 40% less than carbon fiber, if the seat would have been made of glass fiber, 4 more layers would be needed additionally to have an acceptable failure factor. The price estimation is detailed in Table 6.

*Table 6 Cost calculation for GFRP seat*

|               | Amount | Unit           | Unit cost [€] | Total cost [€] |
|---------------|--------|----------------|---------------|----------------|
| Twill GF      | 4.96   | m <sup>2</sup> | 5             | 24.8           |
| Biaxial GF    | 0.03   | m <sup>2</sup> | 3             | 0.09           |
| Core material | 0.18   | m <sup>2</sup> | 20            | 3.6            |
| Resin         | 1.2    | kg             | 19            | 22.8           |
| Sum           |        |                |               | 51.29          |

The layup and different laminate structure thicknesses of the seat can be seen on Figure 28.

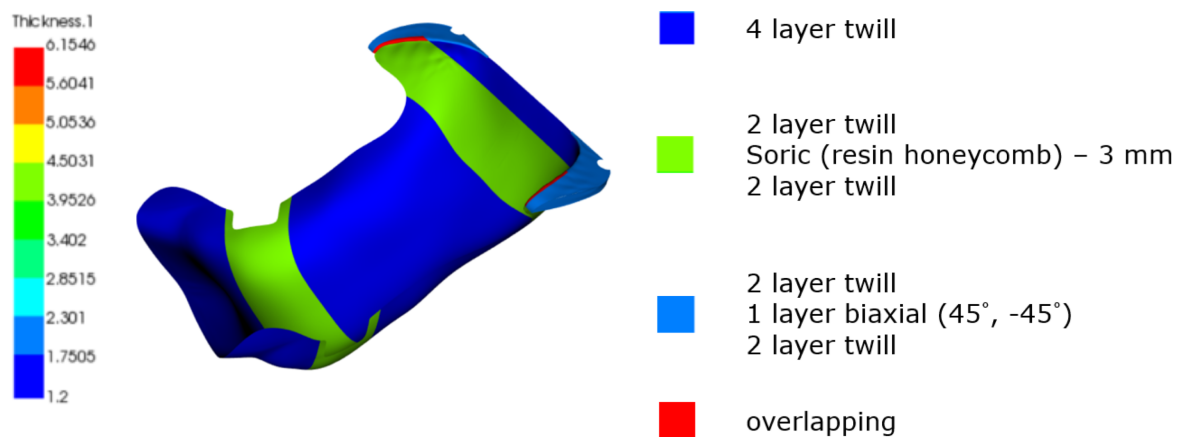


Figure 28 ART\_08 seat layup [5]

One of the most important parameter to consider when sizing a fiber reinforced plastic component is the failure factor. This was the authoritative information during the simulations next to the tensile stress local peaks. Figure 29 shows the failure factor analysis of the seat during acceleration in a corner which is the greatest load, it receives. The highest failure factor is at the outer corner of the shoulder holder support area, other local peaks appear at sharp geometrical changes at the start and endpoints of the core material. In the real life, these points have lower failure number because the epoxy resin flows into the edge of the fiber and core material creating a fillet, that helps to distribute the load.

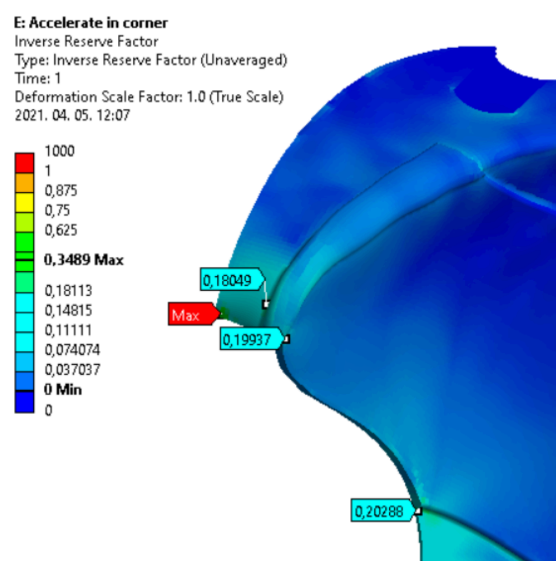


Figure 29 ART\_08 CFRP seat failure factor analysis [5]



Based on the FE simulation the chosen material for the reinforcement was a Toray T300 2/2 3k twill weave carbon fiber with an MGS LR 235 + MGS LH 235 epoxy resin matrix system and Lantor Soric XF 3 core. The material card was created and validated in the previous years for these combination of materials, therefore it can be stated that if there are no problems during manufacturing, the laminated seat is in accordance with the simulation.

#### **10.2.4. Manufacturing of the seat**

The manufacturing of the seat starts with surface preparation, which is detailed in 10.1.2. Then in order to achieve a perfect finish a thin layer of resin must be applied to the mold, this also helps to hold the first carbon fiber layer in place. After that a continuous resin-carbon layup must be followed, it is essential to soak each reinforcement layer evenly with the matrix so the laminate gets as homogeneous as possible. Applying pressure to every section of the fiber helps to eliminate the trapped air which if it would stay inside the crosslinked resin, can cause delamination. After the two carbon layers, the core material follows, Soric XF has a hexagonal channel where the resin can flow and in order to achieve an effective bonding between the reinforcement and the core material, it should be fully filled with epoxy. The next step is to apply the consumables, which consists of a release film that gives the laminate the desired surface finish, a breather layer which helps to evenly distribute the vacuum, lastly the vacuum bag that closes the whole structure. There are several options for these materials, some are combined, for example Compoflex that is available in both smooth and coarse release film finishes, and the topmost sublayer is a breather. Using such materials, not only time, but money can be saved as well. As the back surface of the laminate is cosmetic and it needs to be smooth, so the appropriate Compoflex is used to achieve this. The other important task of Compoflex is to absorb the unnecessary resin, this is controlled in a way, that neither the laminate gets dry nor there is too much epoxy left in the structure. With this, the last step is to choose the vacuum bag, knowing the manufacturing technique, which is hand lamination there is no need to find a high temperature resistant bag, but there are several options, that could help the lamination process. It could be beneficial if we use for example STERTCH-VAC 350 because it has a high elongation of 800% compared to its original size, this way we can minimize the chance of overstretching the vacuum bag which

can result in a torn foil. In order to form the vacuum, a tube with vacuum spiral should be used, it helps to distribute the pressure between the mold and the vacuum bag so there is a decreased chance of local vacuum formations. The consumables and vacuum formation can be seen on Figure 30.



*Figure 30 ART\_08 CFRP seat during manufacturing*

As an experiment, we have decided to use forged carbon as the first visible layer as a design layer in addition to the 4 ply of twill carbon. Using this material is beneficial because it is made of hand laminated leftovers, meaning the material gets a second line resulting in an overall more sustainable laminate. However, there were drawbacks of using this material as well. The density of the fiber was too high so it required additional resin to be evenly soaked and after crosslinking there were still lots of pinholes on the surface which had to be filled with epoxy.

The simulated mass of the seat was 1530g however the final mass went up to 2225g because of the additional surface post-processes.

## 11. Resonance measurements

The two measurements below show the difference between two types of engine mounts. Figure 31 and Figure 32 Arrabona Racing Team's 3<sup>rd</sup> race car (hereafter "ART\_03") was made with fixed mounting points, but the 5<sup>th</sup> generation car (hereafter "ART\_05") had a rubber bushing for vibration damping.

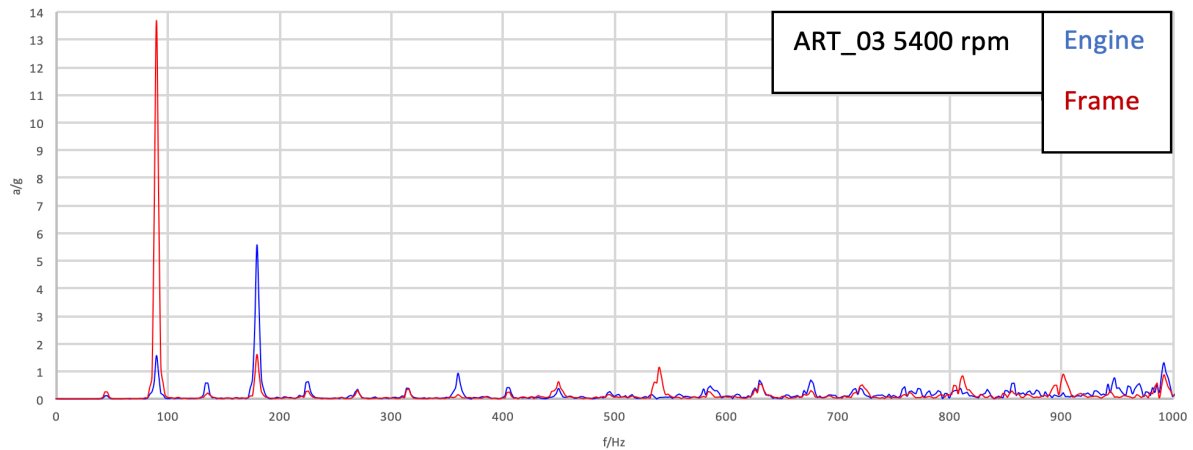


Figure 31 Frequency spectrum analysis on ART\_03 at 5400 [rpm] [5]

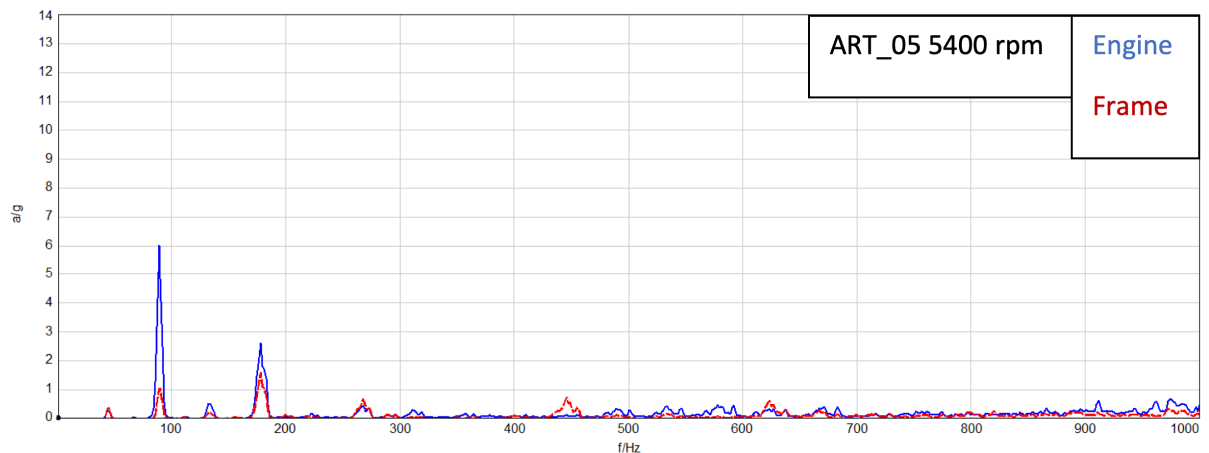
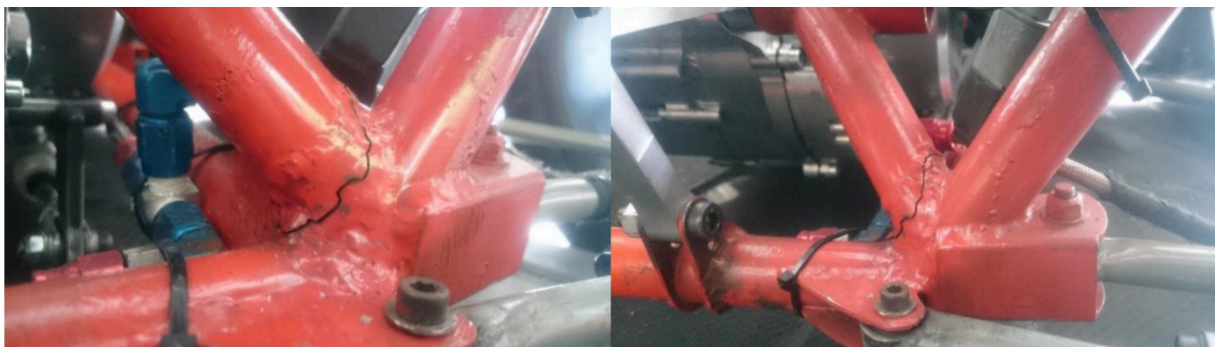


Figure 32 Frequency spectrum analysis on ART\_05 at 5400 [rpm] [5]

It can be seen on the two figures that there are two peaks, one at 90 [Hz] and another at 180 [Hz], the acceleration measured on the frame at 90 [Hz] went down from 13.5 [g] to 1.1 [g], the second-order accelerations at 180 [Hz] were the same but this is not the natural frequency of any human organ, therefore it is not a problem for us. The test was also done at 6200 [rpm], the first-order accelerations went from 15.4 [g] to 1.7 [g] while the second-order accelerations from 2.6 [g] to 2 [g]. The differences between the two engine mounts are crucial considering the human body and components. The test shows, that the bushing with a correct hardness was found and

the accelerations at harmful frequencies were minimized. Both the ART\_03's and ART\_04's fixed engine mount and chassis components near the engine suffered from constant breakage throughout the whole season, which were needed to be repaired. Figure 33 [21]

This is a serious problem, because if the tubes are cracked, the torsional stiffness of the chassis is significantly lower than the designed value. The chassis cannot withstand the loads coming from the suspension and it acts like a torsional spring that is far from optimal regarding the driving characteristics of the car.



*Figure 33 Cracks along ART\_04's welds at the engine compartment [21]*

### **11.1. Drivers' feedbacks**

If we look back to the eigenfrequency of different body parts on Figure 3 we can see that the eyeballs and the chest wall are the two organs that the resonance of ART\_03 and ART\_05 could be harmful to. The range of both the eyeball's and chest wall's natural frequency covers a relatively wide range which depends on their mass and shape, therefore it is hard to determine an exact number. [22]

Looking deeper into this field, these resonance frequencies give us answer, and correlate with drivers' feedbacks that they experience vision and coughing problems during driving. This was a constant problem for lots of years because of the lightened balance shaft in the engine, which main task is to reduce vibrations generated by unbalanced forces. The previous high-amplitude low frequency vibrations were eliminated in the eighth generation race car which had a new KTM 690 [cm<sup>3</sup>] engine with two unmodified balance shafts. As the time of now there are not any resonance measurements with ART\_08, however based on the drivers' feedbacks they do not feel the same strong vibrations than before.

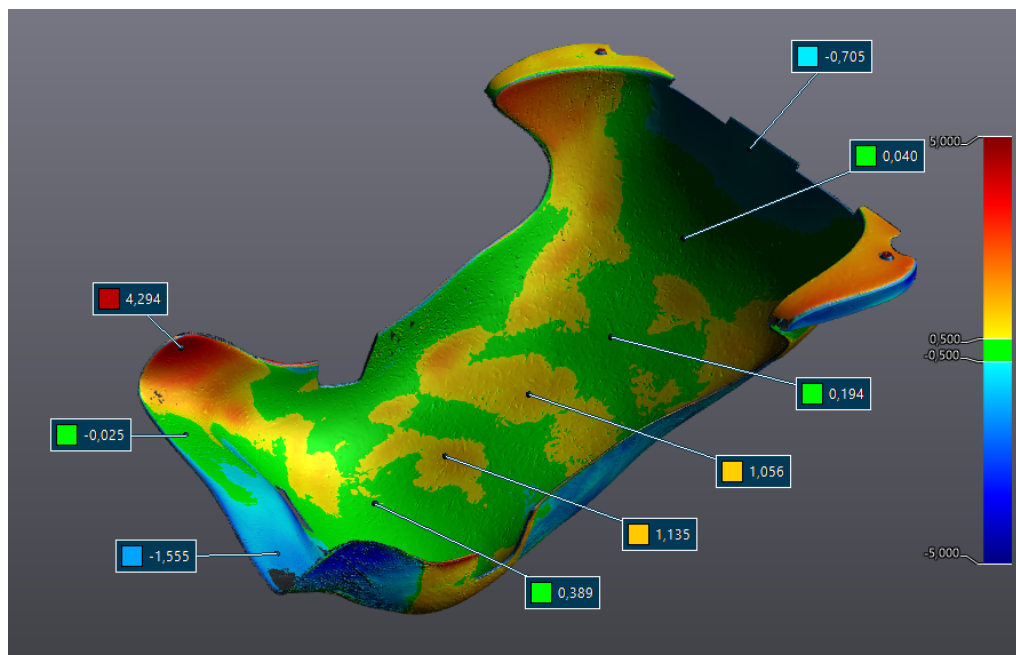
## 12. Validation

### 12.1. 3D scanning

In order to validate our manufacturing accuracy, we have scanned the final seat steering wheel and metal 3D printed brake pedal. This is useful for future design process refinements and manufacturing improvements. The 3D scanning was done by using Creaform MertaSCAN 3D measuring device which has an accuracy of 0.025 [mm]. The scanned parts were put into VXElements software to be compared with the CAD model and the differences were defined via the color map function, that gives an easily readable visual representation of the accuracy.

#### 12.1.1. Seat

On the color map, Figure 34 it can be seen that at the major geometry the difference is between 0-1.2 [mm] which is presumably caused by the surface finish coats that were sanded and polished by hand. However, at the shoulder- and thigh supports it approaches to 5 [mm], the cause of this could be thermal warping during crosslinking which usually happens if the layup is asymmetric. [23]



*Figure 34 ART\_08's CFRP seat 3D scanned and compared to CAD model using color map analysis*

We do not consider these differences a problem, because the major defects, only occur at the four corners on top and bottom, where the seat is positioned with the taper locks and spacers.

If we look at the color map of ART\_07's CFRP seat on Figure 35, we can state that the manufacturing accuracy has improved by much from last year thanks to the milled single mold system.

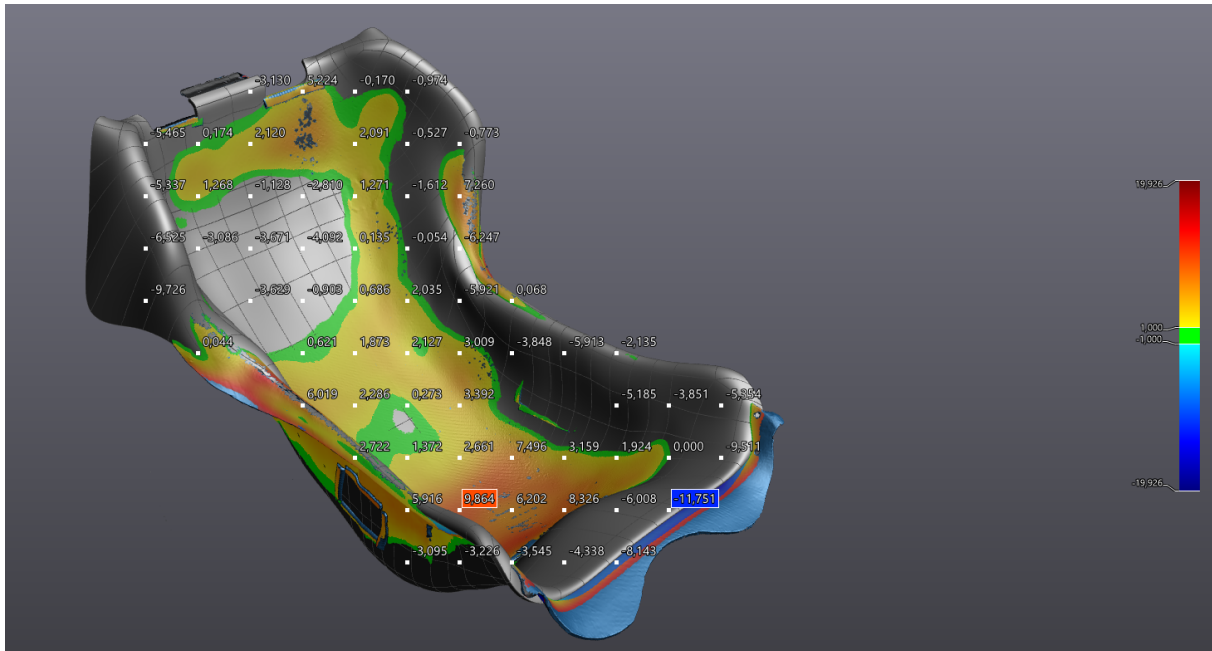


Figure 35 ART\_07's CFRP seat 3D scanned and compared to CAD model using color map analysis

### 12.1.2. Steering wheel

In the 2021 race season, ART\_08's steering wheel was a 2-piece injection mold ABS. The 3D scan Figure 36 shows that at the molded surface, the deviation between the model and the manufactured steering wheel is between  $\pm 0.5$  [mm]. Larger surface alteration can be noticed at the Alcantara grip which thickness is 0.7 [mm], so the steering wheel looks exactly as designed.

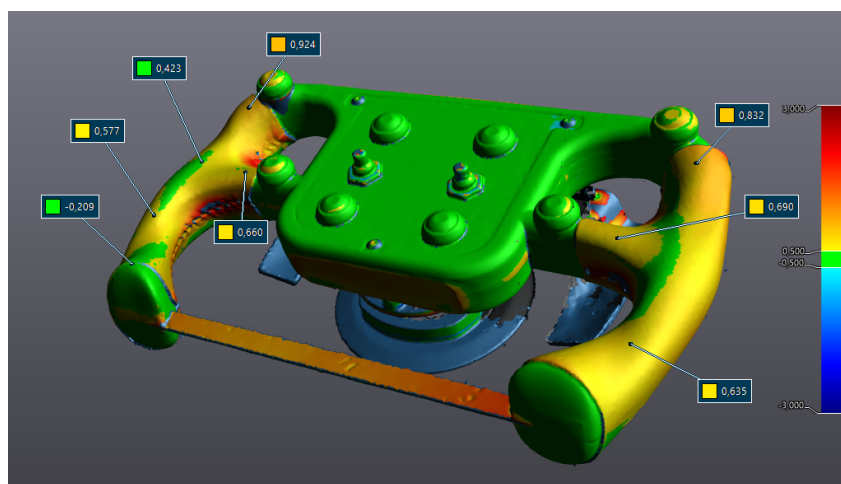


Figure 36 ART\_08's steering wheel color map analysis



### 12.1.3. Brake pedal

With ART\_08's brake pedal, the metal 3D printing manufacturing technique's accuracy was wanted to be tested. Figure 37 The deviation was  $\pm 0.10$ - $0.17$  [mm] which is acceptable in case of additive manufacturing, however post-processing was needed at the attachment points for the perfect fitment.

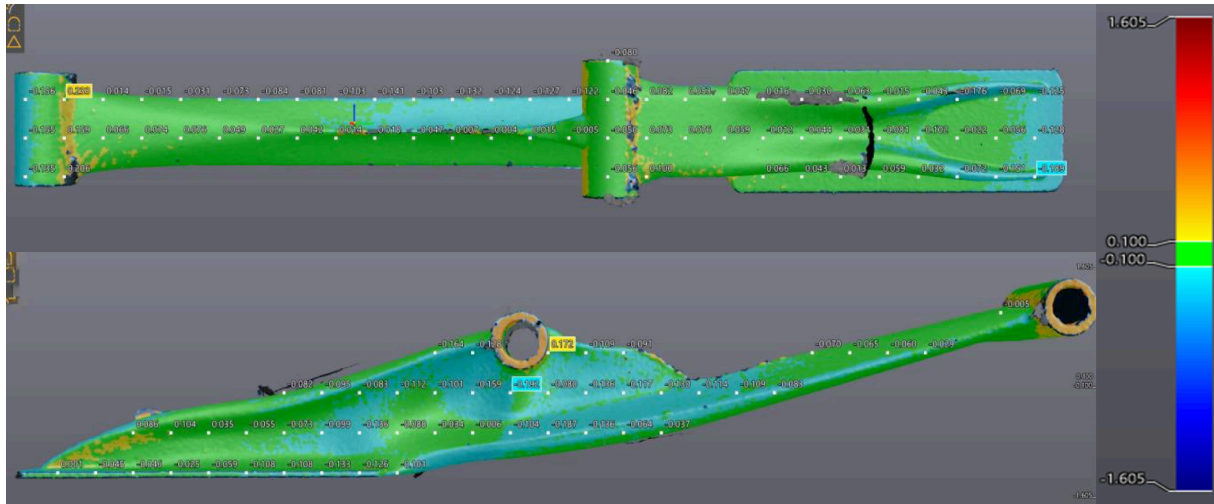


Figure 37 ART\_08's brake pedal color map analysis

## 12.2. Failure Mode and Effects Analysis (hereafter “FMEA”)

FMEA is as approach to identify all possible failures and risks in a component, design or manufacturing process. In an optimal case failure modes are collected from the beginning of the design phase of the part and continues throughout is whole lifecycle. With this, lots of possible problems could be prevented or in case of a failure, interpreted. An FMEA for ART\_08's seat can be seen below. Figure 38

| Component |                                                                    | Function                         | Potential Failure Mode                          |           | Potential Failure Cause                         |                                                                                                                  | Potential Failure Effect                                         |                                   |
|-----------|--------------------------------------------------------------------|----------------------------------|-------------------------------------------------|-----------|-------------------------------------------------|------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------|-----------------------------------|
|           |                                                                    |                                  |                                                 |           |                                                 |                                                                                                                  | Local                                                            | Global                            |
| Seat      |                                                                    | Connects the driver with the car | Structural failure at mounting points, abrasion |           | a) Vibration<br>b) Rubing against the monocoque |                                                                                                                  | Delamination at mounting point<br>Hole at the bottom of the seat | The seat moves inside the cockpit |
| Severity  | Severity Reasoning                                                 | Possibility                      | Possibility Reasoning                           | Detection | Failure Detection                               | Detection Reasoning                                                                                              | Risk                                                             |                                   |
| (S)       |                                                                    | (P)                              |                                                 | (D)       |                                                 |                                                                                                                  | (S*P) + (D)                                                      |                                   |
| 4         | Driver is in great danger at any time after mounting point failure | 1                                | Real life testing in ART_08                     | 1         | Visual inspection before and after tests        | Major delamination can be easily noticed at the mounting point. Holes at the rubbing surfaces are easy to notice | 5                                                                |                                   |

Figure 38 FMEA of ART\_08's CFRP seat

The lifecycle of the seat can be considered to be 1 year with around 500 [km] development- and performance tests. During this time, the seat got in contact with other parts in 4 areas. Abrasion was noticed right at the first test at these areas, so we put adhesive foam onto it. Two bigger indentations can be seen at the bottom, where the undertray's mounting screws almost poke through the laminate. After noticing we put 3D printed bolt caps onto them to prevent further abrasion. A slight wear can be seen at the edge of the core material, but this is not considered to be problem. Figure 39



*Figure 39 ART\_08's CFRP seat bottom abrasion*



## **13. Conclusion**

### **13.1. Seat**

In conclusion about ART\_08's seat, other than the abrasion wear mentioned in 12.2 there were no any problems during the race season. Looking back from now, the additional forged carbon layer was not a great idea, because while from one hand, it is a great material for its recyclability, on the other hand it has a relatively low torsional and shear strength relative to its mass due to the short fiber lengths. The other drawback of using such a material (as detailed in 10.2.4) was that it was heavy and needed additional resin for an acceptable surface finish after crosslinking.

### **13.2. Resonance measurement**

Hearing the positive feedbacks from the drivers about the reduced resonances on ART\_08 makes me even more curious about the frequency spectrum and acceleration measurements that will be done in this season.

## **14. Future plans**

### **14.1. Seat design**

For future recommendations for the seat design, it can be stated from the simulation that the core material is the densest material in the seat layup, therefore the largest weight reduction can be achieved if it is made of a different core. Such suitable option is PVC foam, that does not absorb as much resin as Soric XF resulting in an overall lighter laminate. As the time of now, ART\_09's seat has also been laminated using an 80 [kg/m<sup>3</sup>] PVC foam core material and without the forged carbon layer, the final mass went down to 1050 [g]. It is in an early state of its life and different tests should be made with it before stating it is sufficient for the race season. There were manufacturing difficulties with the core material as it is hard to form onto curved surfaces, therefore this is a field where other materials should be considered and tested.

### **14.2. Sustainable composites**

There is a high pressure from the government in the motorsport industry as well to try to move to sustainable materials. We are currently testing flax and cellulose fiber reinforced bio epoxy composites and if we can produce non-structural elements like covers of it instead of CF sufficiently, without too much mass gain, we may use it in other parts as well, like the seat, head restraint and smaller aero profiles.

### **14.3. New monocoque and cockpit geometry**

We are planning to modify the monocoque geometry in our next race car, which opens a new field both in the cockpit design and ergonomics of the seat and seating position. Lifting up the nose of the chassis helps both the aerodynamics and vehicle dynamics departments and we can make small changes at the leg area so even if it gets closer to the steering wheel, the legs are in a straighter position, therefore not blocking any movement.

## 15. List of figures

|                                                                                                        |    |
|--------------------------------------------------------------------------------------------------------|----|
| Figure 1 ART_08 at Formula Student Austria 2021 .....                                                  | 1  |
| Figure 2 Human neutral body posture [2] .....                                                          | 2  |
| Figure 3 Eigenfrequency of human body parts [5] .....                                                  | 3  |
| Figure 4 Arrabona Racing Team's eighth generation race car's cockpit.....                              | 4  |
| Figure 5 Cockpit Opening Template (left); Cockpit Internal Cross Section Template<br>(right) [6] ..... | 6  |
| Figure 6 Dimensions and placement of 95 <sup>th</sup> percentile male [6] .....                        | 7  |
| Figure 7 Typical autoclave curing cycle for prepreg [9] .....                                          | 9  |
| Figure 8 Non-crimp biaxial fiber [13] .....                                                            | 10 |
| Figure 9 Different weave types [14].....                                                               | 11 |
| Figure 10 Render of ART_07 tubular steel spaceframe assembly .....                                     | 12 |
| Figure 11 Minimum Material Requirements [6].....                                                       | 13 |
| Figure 12 ART_07 Frame jig .....                                                                       | 14 |
| Figure 13 FaSTTUBe FT21 race car [16].....                                                             | 15 |
| Figure 14 ART_06 side-panel and sidepod covered with aluminum tape .....                               | 16 |
| Figure 15 3-point bending test.....                                                                    | 17 |
| Figure 16 Perimeter shear test.....                                                                    | 17 |
| Figure 17 Render of ART_08 monocoque chassis assembly.....                                             | 18 |
| Figure 18 CFRP honeycomb sandwich structure [18] .....                                                 | 18 |
| Figure 19 ART_08 Insert package.....                                                                   | 19 |
| Figure 20 6-point FIA 8853 racing harness [19] .....                                                   | 21 |
| Figure 21 ART_08 mockup.....                                                                           | 24 |
| Figure 22 ART_08 Final seating position angles .....                                                   | 26 |
| Figure 23 Render of ART_07 and ART_08 visibility .....                                                 | 27 |
| Figure 24 ART_08 seat mold after milling .....                                                         | 30 |
| Figure 25 Mold for ART_08's CFRP seat .....                                                            | 30 |
| Figure 26 Tallest driver 3D scanned in mockup.....                                                     | 31 |
| Figure 27 Modified areas on ART_08's seat (right) from ART_07's seat (left) .....                      | 32 |
| Figure 28 ART_08 seat layup [5].....                                                                   | 34 |
| Figure 29 ART_08 CFRP seat failure factor analysis [5] .....                                           | 34 |
| Figure 30 ART_08 CFRP seat during manufacturing .....                                                  | 36 |
| Figure 31 Frequency spectrum analysis on ART_03 at 5400 [rpm] [5] .....                                | 37 |

|                                                                                                     |    |
|-----------------------------------------------------------------------------------------------------|----|
| Figure 32 Frequency spectrum analysis on ART_05 at 5400 [rpm] [5] .....                             | 37 |
| Figure 33 Cracks along ART_04's welds at the engine compartment [21].....                           | 38 |
| Figure 34 ART_08's CFRP seat 3D scanned and compared to CAD model using color<br>map analysis ..... | 39 |
| Figure 35 ART_07's CFRP seat 3D scanned and compared to CAD model using color<br>map analysis ..... | 40 |
| Figure 36 ART_08's steering wheel color map analysis.....                                           | 40 |
| Figure 37 ART_08's brake pedal color map analysis .....                                             | 41 |
| Figure 36 FMEA of ART_08's CFRP seat .....                                                          | 41 |
| Figure 39 ART_08's CFRP seat bottom abrasion .....                                                  | 42 |

## 16. List of tables

|                                                                                  |    |
|----------------------------------------------------------------------------------|----|
| Table 1 Advantages and disadvantages of different types of monocoque chassis.... | 20 |
| Table 2 Decision matrix for ART_08's seat mold material .....                    | 28 |
| Table 3 Cost calculation for PU foam seat mold.....                              | 29 |
| Table 4 Cost calculation for XPS seat mastermold and GFRP seat mold .....        | 29 |
| Table 5 Cost calculation for CFRP seat.....                                      | 33 |
| Table 6 Cost calculation for GFRP seat.....                                      | 33 |

## 17. Abbreviations and symbols

|          |   |                                                   |
|----------|---|---------------------------------------------------|
| AOV      | – | Angle of View                                     |
| ART_06   | – | Arrabona Racing Team's sixth generation race car  |
| ART_08   | – | Arrabona Racing Team's eighth generation race car |
| CF       | – | Carbon fiber                                      |
| CFRP     | – | Carbon Fiber Reinforced Plastic                   |
| FBH      | – | Front Bulkhead                                    |
| FH       | – | Front Hoop                                        |
| FMEA     | – | Failure Mode and Effects Analysis                 |
| FOV      | – | Field of View                                     |
| GF       | – | Glass fiber                                       |
| GFRP     | – | Glass Fiber Reinforced Plastic                    |
| IA       | – | Impact Attenuator                                 |
| MH       | – | Main Hoop                                         |
| MHB      | – | Main Hoop Bracing                                 |
| PS       | – | Primary Structure                                 |
| rCF      | – | Recycled Carbon Fiber                             |
| RTM      | – | Resin Transfer Molding                            |
| SIS      | – | Side Impact Structure                             |
| $t_g$    | – | Glassing transition temperature                   |
| $\theta$ | – | Torsional stiffness (Theta)                       |

## 18. Bibliography

- [1] C. Marek and K. Siebertz, Encyclopedia of Automotive Engineering - Ergonomics for Passenger Cars, 2014, pp. 1-24.
- [2] NASA, "Evaluation of Neutral Body Posture on Shuttle Mission STS-57 (SPACEHAB-1)," Huston, Texas, 2003.
- [3] Wikipedia, "Natural frequency," [Online]. Available: [https://en.wikipedia.org/wiki/Natural\\_frequency](https://en.wikipedia.org/wiki/Natural_frequency).
- [4] K. Y., W. T. and F. T., "Study on the Reduction of the Resonant Stress of Turbine Blades Caused by the Stage Interaction Force (Simultaneous Optimization of Blade Resonant Stress and Amount of Unbalance)," 2021.
- [5] Arrabona Racing Team, "ART\_06 Ergonomics Design Document," Győr, 2019.
- [6] Formula Student Germany, "FS-Rules\_2022\_v1.0," 2022. [Online]. Available: [https://www.formulastudent.de/fileadmin/user\\_upload/all/2022/rules/FS-Rules\\_2022\\_v1.0.pdf](https://www.formulastudent.de/fileadmin/user_upload/all/2022/rules/FS-Rules_2022_v1.0.pdf).
- [7] R. Figueiro, Fibrous and Composite Materials for Civil Engineering Applications, Woodhead, 2011, pp. 389-401.
- [8] SHD Composites, "MTC510 Epoxy Component Prepreg Technical Datasheet," 01 02 2018. [Online]. Available: <https://shdcomposites.com/admin/resources/mtc510-tds.pdf>.
- [9] s. y. & C. W. & C. H. S. Park, "A comparative study on the properties of GLARE laminates cured by autoclave and autoclave consolidation followed by oven postcuring," 2010.
- [10] N. Saba, A. Y. Othman, M. Jawaid, P. M. Tahir and A. Hassan, Recent advances in epoxy resin, natural fiber reinforced epoxy composites and its applications. Journal of Reinforced Plastics and Composites., 2015.
- [11] F. Manis, G. Stegschuster, J. Wölling and S. Schlichter, "Influences on Textile and Mechanical Properties of Recycled Carbon Fiber Nonwovens Produced by Carding.," 2021.

- [12] T. G. F. Kruse, Non-Crimp Fabric Composites - Standardisation of production technologies for non-crimp fabric composites, 2011.
- [13] V. R. Patlolla, J. George, S. Loo and R. Asmatulu, Effects of UV light and moisture absorption on the impact resistance of three different carbon fiber-reinforced composites, 2014.
- [14] CA Composites, [Online]. Available: <https://cacomposites.com/dry-fabrics-reinforcements/carbon-fiber-reinforcements/carbon-fiber-fabric/>.
- [15] H. El-Dessouky, "6 Spread Tow Technology for Ultra Lightweight CFRP Composites," 2017.
- [16] FaSTTUBe, [Online]. Available: <https://fasttube.de/boliden/>.
- [17] J. & A.-A. E. Moheb, "Study of the Bending Characteristics in Composite Sandwich Structures," 2020.
- [18] A. Al-Fatlawi, K. Jármay and G. Kovács, "Optimization of a Totally Fiber-Reinforced Plastic Composite Sandwich Construction of Helicopter Floor for Weight Saving, Fuel Saving and Higher Safety," Miskolc, 2021.
- [19] SCHROTH, "SCHROTH Profi 6-Point 3x2 FIA 8853 Racing Harness," [Online]. Available: <https://www.schroth.com/en/racing/racing/details/show/profi-3x2/>.
- [20] Thomasnet, "Differences Between Open Cell and Closed Cell Polyurethane Spray Foam," [Online]. Available: <https://www.thomasnet.com/articles/plastics-rubber/closed-cell-open-cell/>.
- [21] B. Hered, "Differenciálmű tartó tervezése Formula Student versenyautóhoz," Győr, 2018.
- [22] P. W. S. S. Y. Shih, "Eye orbit effects on eyeball resonant frequencies and acoustic tonometer measurements," 2022.
- [23] V. Brúnó and C. Tibor, "ALAKVÁLTÓ KOMPOZITOK TERVEZÉSE ÉS GYÁRTÁSA AUTOKLÁVVAL," 2020.