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The Development of a Carbon fiber Aerodynamic Kit for a Formula Student team

Bachelor’s thesis
Mechanical Engineering and Production Technology
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Mohamed Yassine Tasse

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Mechanical Engineering and Production Technology Abstract
Author Mohamed Yassine Tasse Year 2024
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Supervisors Jaakko Vasko

The aim of this thesis work is to allow the reader to have a glimpse into how an Aero Kit is made, while also providing the necessary theory on material engineering, fluid dynamics, and the rules of Formula Student.

The study of the motion of air, or aerodynamics, has to be one of the technological breakthroughs that impacted motorsports most and helped shaping the automotive industry as we know it. Gains in top speed, stability, cornering, and grip can be achieved from a well-designed, well-thought-through Aero Kit. Even within the confines of Formula Student competitions, where the average speeds may seem modest, the impact of aerodynamics is significant.

When engineering any object, picking the right material to use is crucial, especially for our case study. Carbon polymers allowed the next leap forward in motorsports and were an excellent fit; lightweight, high tensile strength, and pretty simple to integrate.

In this thesis, the main focus will be the manufacturing and production. I was lucky enough to be part of the aerodynamics department at Metropolia University and will be shedding light on the techniques, materials, and technologies that he came across.

By combining theoretical foundations with practical work, readers will gain a comprehensive understanding of the intricate craftsmanship and inventive techniques inherent in Aero Kit manufacturing. This synthesis will facilitate a deeper appreciation for the blend of art and innovation that characterizes the development and production of Aero Kits.

Keywords Aero kit, material engineering, formula student, carbon polymers.

Pages 45 pages and appendices 5 pages

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Abbreviations

FS - Formula Student

CFRP - Carbon Fiber Reinforced Polymer

CFD - Computational Fluid Dynamics

CAD - Computer-Aided Design

PLA - Polylactic Acid

AOA - Angle of Attack

DXF - Drawing Exchange Format

N - Newton (unit of force)

FSAE - Formula Society of Automotive Engineers

3D - Three-Dimension

1 Introduction

Formula Student racing is a very competitive and dynamic scene. Students come from different backgrounds and environments to compete against each other. On average, the FS hosts about 90 teams. The competition is complex and is laid out across two different events. The static event is where the teams are judged based on their business pitch, design choices, and budget management. The dynamic event, on the other hand, consists of straight-line acceleration, endurance, and driverless tests.

The dynamic and static events combined add up to a thousand points. Last year, Metropolia had issues getting the car running, which got them zero points from the dynamic events. Still, they accumulated a large number of points from their static events for having a new carbon monocoque and all-wheel-drive powertrain combined with new technologies like Torque Vectoring.

During the season, each team makes the best of its time to make the most performant, most innovative car possible. Numerous innovations and world records came from these seemingly small competitions where only students are allowed. Among the key aspects that can make or break a team’s success on the track is the design and manufacturing of Aerodynamic Kits. These kits, include aerodynamic elements strategically placed on the car that play a crucial role in enhancing speed, stability, and overall handling.

Complementing fluid dynamics is the utilization of carbon fiber materials in Aero Kit manufacturing. Carbon fiber’s exceptional strength-to-weight ratio allows for the creation of lightweight and durable components.

The thesis is partitioned across three sections. The theory section contains all the basics to get up to speed with what we are discussing, with both aerodynamics and CFRP touched on. The design phase is next, where you can find the thought process behind our kit, parts list, and the main Formula Student rules. The manufacturing phase comes last and includes material selection, molding, and part preparation.

The Purpose of this work is to first allow people to have a preliminary look into what Formula really is, and getting familiarized with all its aspects. Then understand the theory of making a kit. Therefore, the aspirations of the thesis are detailed in the following section:

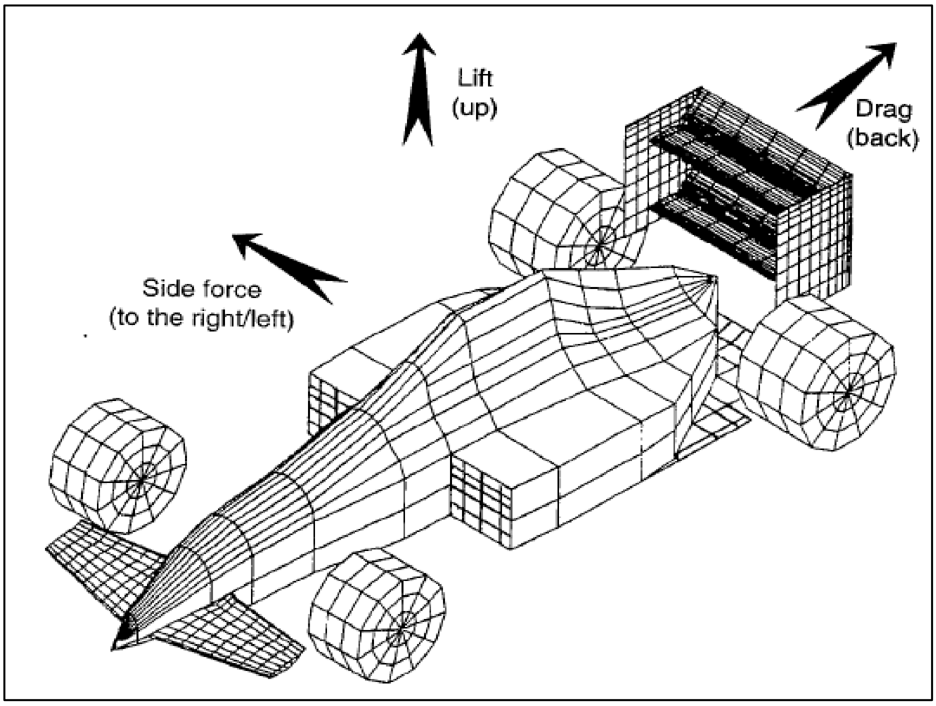
- Learn the main principles of aero and carbon composites.
- Design the different parts of our kit.
- Make the kit and dive into all the techniques and materials used.

A lot of the statements made in this work are from discussions and classes I had with the Metropolia Formula team.

2 Aerodynamics as a Subset of Fluid Dynamics

Drag, lift, and stability are the big three effects of air on a moving vehicle. These aerodynamic moments came to light when designers realized that vehicle stability and handling can be improved by carefully adding lifting surfaces onto, or by modifying, the vehicle's body. This is often seen in the form of aerodynamic elements like wings, spoilers, and diffusers on high-performance cars.

Figure 1. The Main three components of aerodynamic force (J. Katz, 1995)



In motorsports, cars are designed to be the most efficient in one designated category. Since the dynamic events are both on a straight line and on track, compromises are often necessary to balance the different aerodynamic demands of each scenario.

For straight-line speed, the focus is on minimizing air resistance to achieve the highest possible top speed. This is done through having smooth shapes and surfaces. On the other hand, having good cornering performance is crucial at the racetrack, the aero kit must generate enough downforce to maintain traction without excessively increasing drag. Components like wings and diffusers are used to improve grip in corners.

Too much drag makes the car slow in an acceleration test, and little aero makes the car unstable.

Aerodynamic elements must be precisely positioned to distribute downforce evenly across the car to avoid understeer or oversteer.
The compromise between these two needs often leads to an aero kit that is not optimized for either condition but provides a balance that allows for decent performance in both straight lines and the track. We might use adjustable components to tweak the setup for specific events, but there will always be a trade-off between top speed and cornering ability.

The positioning of aerodynamic elements on a race car is where things get complicated, it’s a demanding task due to the complex behavior of airflow dynamics, component interactions, and sensitivity.

Small adjustments can lead to significant changes in performance, as the airflow is nonlinear, and the elements impact one another.

Ground effects, manufacturing challenges, and regulatory constraints further complicate the process, requiring a delicate balance between downforce and drag. Additionally, the car’s motion during acceleration and braking, alters the aerodynamics, necessitating designs that accommodate dynamic changes. It is a must to employ a combination of CFD simulations, real-world testing, and experience to achieve the ideal setup within the budget and time to ensure that the car remains competitive while adhering to the regulations of the racing competition.

2.1 Drag

In short, drag refers to the resistance encountered by an object moving through a certain fluid, air usually, due to friction and pressure differences. In our context of motorsports, aerodynamic drag arises primarily from these two mechanisms:

- Pressure Drag resulting from the pressure differential between the front and rear surfaces of the car.
- Skin friction drag coming from the frictional resistance between the car's surface and the surrounding air.

When the friction and pressure drag coefficients are available, the total drag coefficient is determined by simply adding them: $C_d = C_{d,Friction} + C_{d,Form}$

The presence of drag has a big effect on the behavior of a car, affecting its acceleration, top speed, and cornering. High levels of drag can have a negative effect on acceleration and reduce top speed. Also, excessive downforce, achieved through the aero kit to enhance grip, increases drag and compromises straight-line speed. But this is usually solved by having modular aero elements on the car. Moreover, variations in drag distribution can alter a car's balance, impacting its stability and maneuverability.

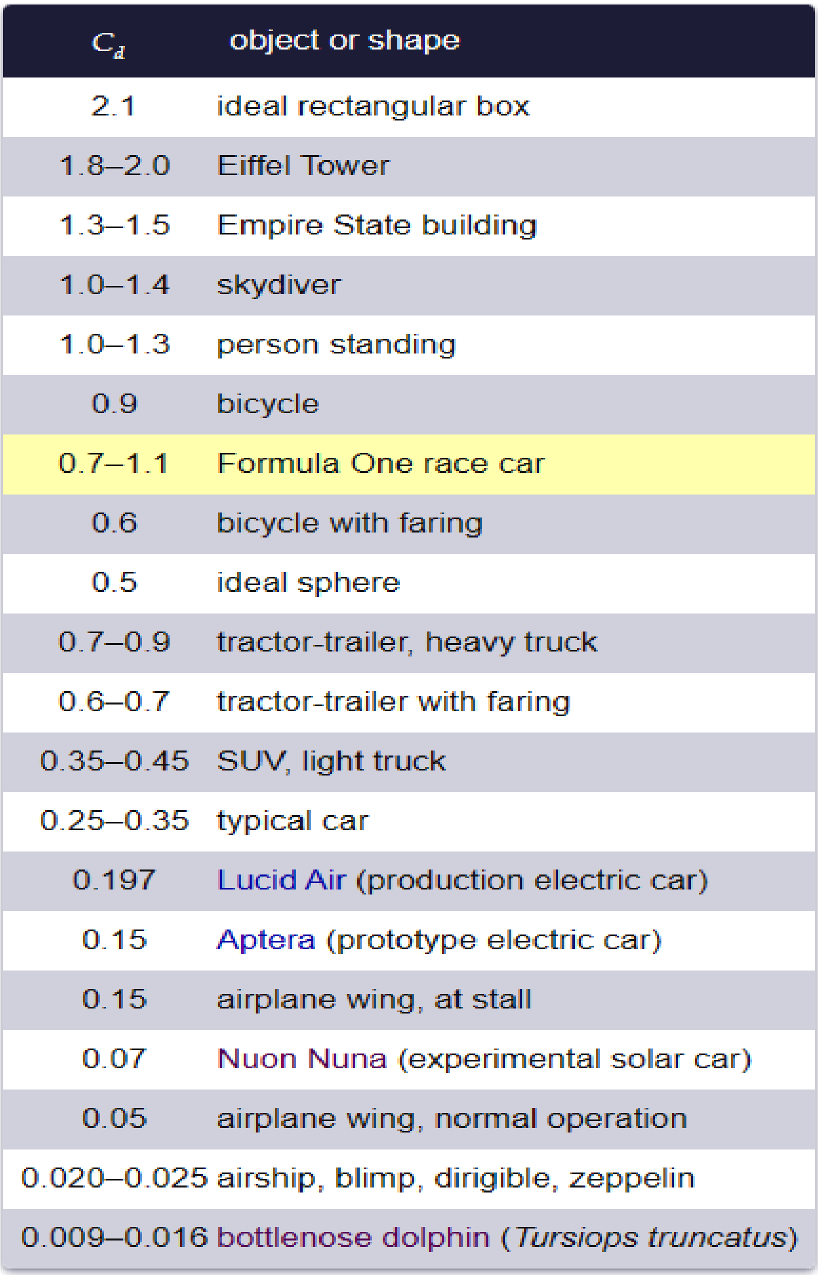
The drag coefficient (Cd) serves as a crucial parameter quantifying the aerodynamic drag experienced by a racing car. It represents the ratio of drag force to the dynamic pressure of the fluid flow.

The drag force (Fd) can be calculated using the formula: $F_d = C_d \times \frac{\rho \times V^2}{2} \times A$

These are the drag coefficients of some vehicles and production cars, you notice that the average formula car has a pretty high drag coefficient of 0.7 and it’s due to the car's high need for grip. Just like Formula 1, our circuits feature a mix of high-speed straights and tight corners, necessitating a balance between high straight-line speed and cornering performance.

From the table, you can also tell that production vehicles try to achieve the lowest drag coefficients in order to be as fuel-efficient as possible

Table 1. Drag Coefficients vs. Type of Objects (Elert, 2024)



C_d	object or shape
2.1	ideal rectangular box
1.8–2.0	Eiffel Tower
1.3–1.5	Empire State building
1.0–1.4	skydiver
1.0–1.3	person standing
0.9	bicycle
0.7–1.1	Formula One race car
0.6	bicycle with faring
0.5	ideal sphere
0.7–0.9	tractor-trailer, heavy truck
0.6–0.7	tractor-trailer with faring
0.35–0.45	SUV, light truck
0.25–0.35	typical car
0.197	Lucid Air (production electric car)
0.15	Aptera (prototype electric car)
0.15	airplane wing, at stall
0.07	Nuon Nuna (experimental solar car)
0.05	airplane wing, normal operation
0.020–0.025	airship, blimp, dirigible, zeppelin
0.009–0.016	bottlenose dolphin (*Tursiops truncatus*)

2.2 Lift

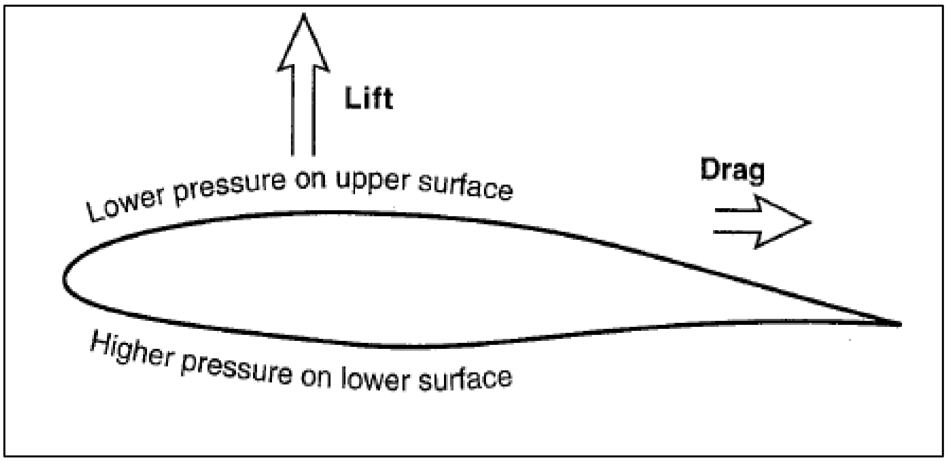
Lift is the aerodynamic force generated perpendicular to the airflow’s direction; it is typically associated with aviation but also is of big importance to high-performance cars.

Understanding lift is crucial for optimizing the aerodynamic performance and handling characteristics of Formula Student vehicles, particularly in achieving high-speed stability and cornering grip. Lift is generated primarily through the differences in air pressure above and below the car or its aerodynamic elements, resulting in an upward force.

This pressure differential is typically achieved through the shape and orientation of aerodynamic surfaces, such as wings, spoilers, and underbody diffusers, which manipulate airflow to produce lift.

The lift equation states that lift L is equal to the lift coefficient Cl times density rho (ρ) times half of the velocity V squared times the wing area A: $L = C_l \times \frac{\rho \times V^2}{2} \times A$

Figure 2. Lift, Drag, and Pressure on An Airfoil (Katz, 1995)



Positive lift refers to the upward force generated on an object that exceeds the gravitational force acting on it. This type of lift is desirable in most situations, as it enables aircraft to achieve lift-off and sustain flight, and it helps Formula Student cars generate downforce to improve traction and cornering grip.

Negative lift, also known as downforce, refers to the downward force generated on an object as a result of aerodynamic effects. While lift traditionally refers to an upward force, negative lift produces a downward force that enhances stability and traction, particularly in high-speed racing applications like Formula Student. Negative lift is commonly generated by aerodynamic elements such as wings, spoilers, and diffusers, which are angled to redirect airflow and create a downward pressure gradient.

3 Carbon theory

3.1 Introduction to Composites

Most Materials can be put into these four distinct categories: Metals, polymers, composites, and ceramics.

Composites are combinations of two or more distinctly different materials, resulting in a product that merges both their unique properties. The components can still be physically identifiable and do not completely dissolve or merge, making composites heterogeneous materials. This heterogeneity often leads to anisotropic behavior, where properties unfortunately vary directionally throughout the material's volume.

Composites primarily consist of combinations of metals, ceramics, and polymers, although naturally occurring materials like wood and bone are also composites.

The origins of modern synthetic composite materials can be traced back to 1937, and while their history is irrelevant to us, the goal after them was to achieve materials with high stiffness, resistance to fatigue at low and high temperatures, and low density, ultimately resulting in an improved strength-to-weight ratio.

3.2 Characterization of Carbon Fiber Properties

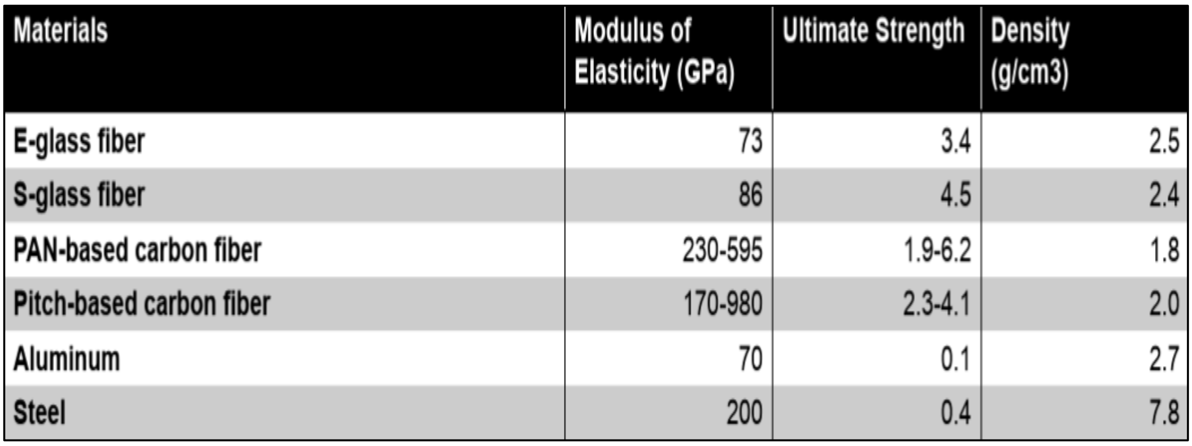
Compared to conventional isotropic materials like steel and aluminum, carbon fiber-reinforced polymer composites are the obvious choice for our use case due to their unique set of properties. Lightweight, great manufacturability, stiffness, and strength that can easily be adjusted by varying the orientation and stacking sequence of the carbon fiber plies or tows.

To put this into perspective we can compare CFRP properties to other materials:

- High strength-to-weight ratio, with tensile strengths up to 10 times greater than steel with only 25% of the density. Enabling a significant weight reduction potential.
- Tensile modulus over 5 times higher than aluminum and steel. This improves component dimensional stability and vibration performance.
- Excellent fatigue and corrosion resistance due to the nature of the carbon fibers and polymeric resin matrix.

- High thermal and electrical insulation properties compared to metals.
- Unique opportunities for parts integration and reduced assembly costs through composite molding processes.
- Tailorable coefficients of thermal expansion by changing the fiber orientations and resin chemistry.
- Easily moldable to complex shapes.

Table 2. Properties of CFRPs and other materials (SAE International, 2014)



Materials	Modulus of Elasticity (GPa)	Ultimate Strength	Density (g/cm3)
E-glass fiber	73	3.4	2.5
S-glass fiber	86	4.5	2.4
PAN-based carbon fiber	230-595	1.9-6.2	1.8
Pitch-based carbon fiber	170-980	2.3-4.1	2.0
Aluminum	70	0.1	2.7
Steel	200	0.4	7.8

3.3 Applications in Motorsports

Carbon Fiber Reinforced Polymer (CFRP) composites have easily found their way into Motorsports due to their exceptional properties. The application of carbon fiber is favored due to its unique strength-to-weight ratio. Compared to more traditional materials such as steel or aluminum, it is significantly lighter and remains extremely strong. This unique combination makes it possible to produce vehicles that weigh less yet are structurally solid.

The reduced weight of these components offers several privileges. First, they improve the power-to-weight ratio leading to great acceleration and overall performance. Second, they help to increase efficiency by enabling vehicles to travel longer distances on one charge. Finally, the lightness of the vehicle makes it more maneuverable and agile on the racetrack, giving drivers precise control and flexibility.

Racing cars generate considerable heat during intense driving conditions, and carbon fiber possesses exceptional heat resistance and thermal stability, making it an ideal selection for such purposes. In contrast to metals that conduct heat, this composite exhibits limited thermal conductivity. This characteristic enables carbon fiber components to maintain a consistent temperature, thereby minimizing the chances of heat-induced deformations or performance degradation. (Motorsportengineer, 2021)

The durability of carbon fiber has a crucial role to play in this challenging environment, and it stands out from the rest. The parts are extremely resistant to impact and have excellent structural integrity, making them suitable for the rigors of this kind of racing. The components retain their shape and strength, which ensures the safety of both drivers and vehicles, unlike conventional materials that may be damaged or broken when subjected to stress. On race day cars are very likely to hit objects; cones, other cars; and obstacles causing body parts to break and mess with the aerodynamic properties of the kit. From personal experience, it is very easy to just tape up or glue the carbon fiber parts back together.

Figure 3. Photo of the 2023 Metropolia car (code name HPF023)

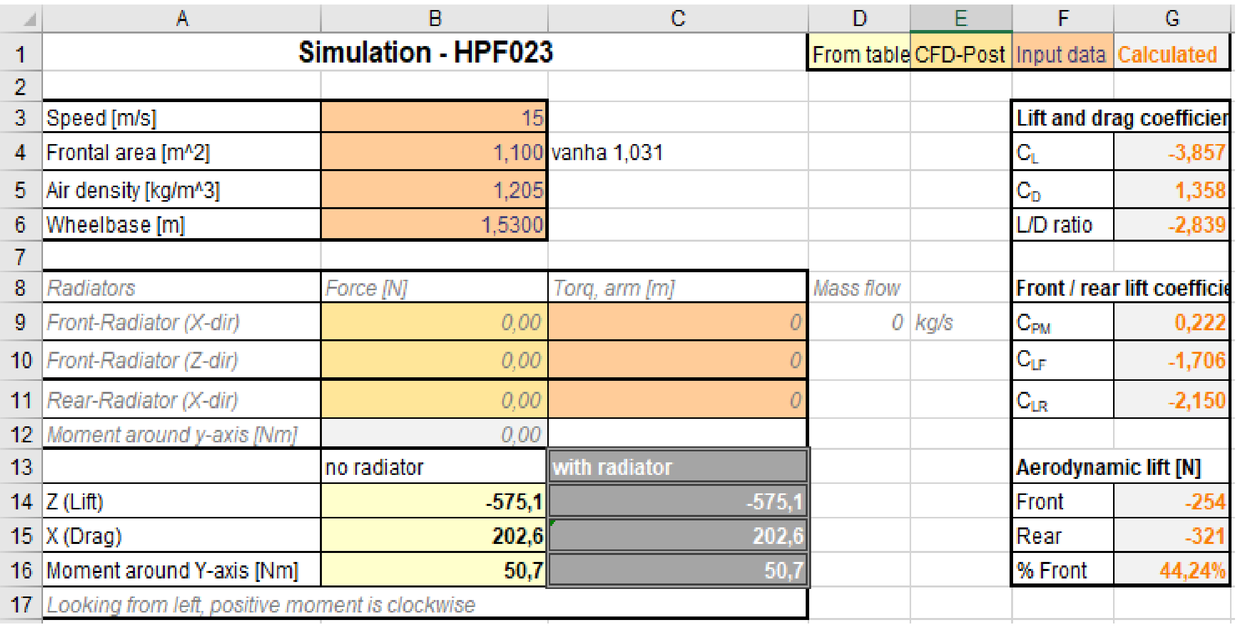
Besides its outstanding performance capabilities, carbon fiber presents a unique aesthetic allure. The woven black weave pattern creates a visually captivating effect that emanates a feeling of velocity and elegance. This is something that values the chance to personalize their cars with carbon fiber elements. The distinctive appearance and customization possibilities empower drivers to express their individuality through their vehicles. (Motorsport engineer, 2021)

4 Designing phase

Before the start of every season, each subsystem would set goals to attain. This can be making the battery lighter, improving steering, or implementing new technologies such as active-aero or driving assistance aids.

To enhance the aerodynamic performance of the 2024 car, code-named HPF024, we set out to increase the coefficient of lift by over 10% by redesigning and modifying aerodynamic elements such as front splitters, side wings, and underbody airflow channels, and by increasing the angle of attack and curvature of aerodynamic surfaces to generate more downforce.

Figure 4. HPF023 Simulation Results



	A	B	C	D	E	F	G
1	**Simulation - HPF023**			From table	CFD-Post	Input data	Calculated
2							
3	Speed [m/s]	15				**Lift and drag coefficier**	
4	Frontal area [m^2]	1,100	vanha 1,031			C_L	-3,857
5	Air density [kg/m^3]	1,205				C_D	1,358
6	Wheelbase [m]	1,5300				L/D ratio	-2,839
7							
8	*Radiators*	*Force [N]*	*Torq, arm [m]*	*Mass flow*		**Front / rear lift coefficie**	
9	*Front-Radiator (X-dir)*	*0,00*	*0*	*0*	*kg/s*	C_{PM}	0,222
10	*Front-Radiator (Z-dir)*	*0,00*	*0*			C_{LF}	-1,706
11	*Rear-Radiator (X-dir)*	*0,00*	*0*			C_{LR}	-2,150
12	*Moment around y-axis [Nm]*	*0,00*					
13		no radiator	with radiator			**Aerodynamic lift [N]**	
14	Z (Lift)	**-575,1**	-575,1			Front	-254
15	X (Drag)	**202,6**	202,6			Rear	-321
16	Moment around Y-axis [Nm]	**50,7**	50,7			% Front	44,24%
17	*Looking from left, positive moment is clockwise*						

Simultaneously, we aimed to lower the coefficient of drag by refining body shapes and surfaces to reduce turbulence and improve airflow attachment, the goal is to achieve a lift-to-drag ratio of 3 or more.

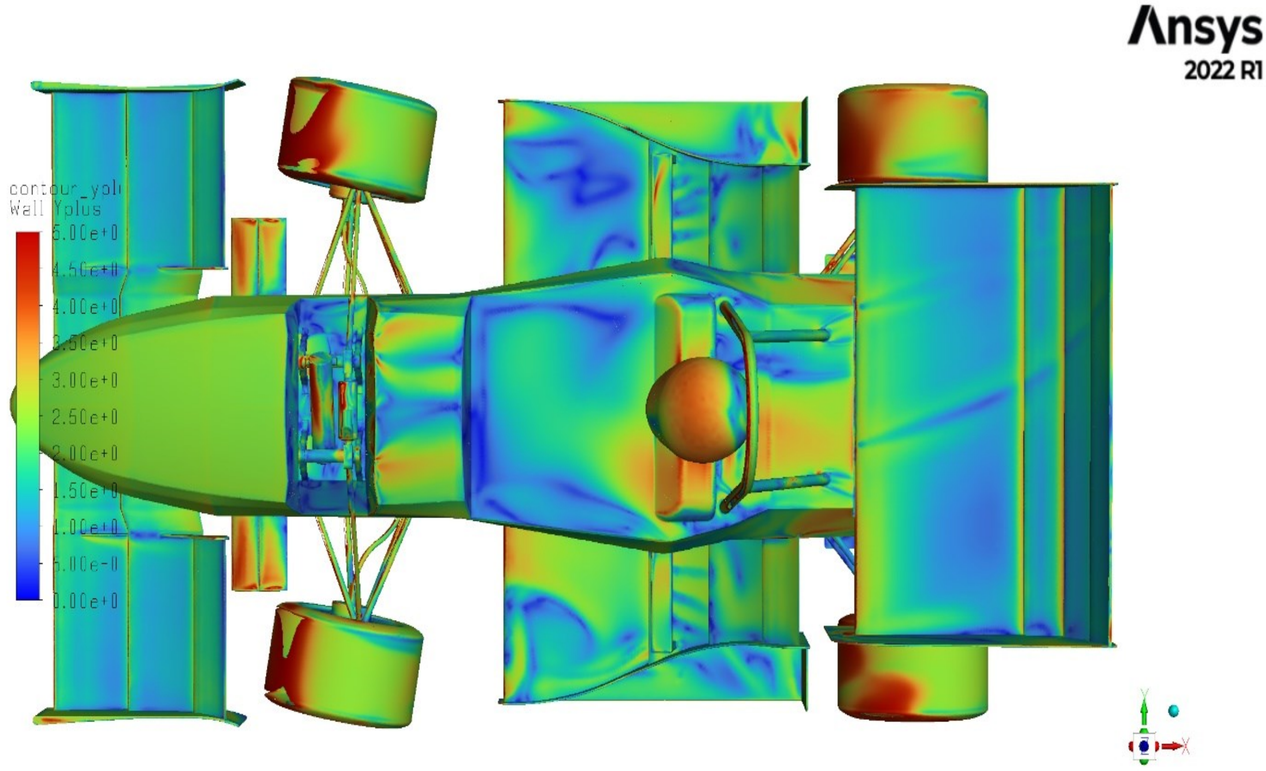
We also targeted a near-perfect weight balance of 50/50 for both static distribution and cornering performance, achieving a package weight of 12 kg by utilizing carbon fiber components and minimizing the use of heavy materials.

Ultimately, we aimed to achieve 600 Newtons of downforce by enhancing the size, angle, and curvature of aerodynamic elements like wings, diffusers, and splitters, utilizing advanced computational fluid dynamics (CFD) simulations to fine-tune downforce generation.

4.1 Parts list

To make things easier we can divide the Kit into 3 separate parts: The front wing and nose cone, the side wing, and then the rear wing.

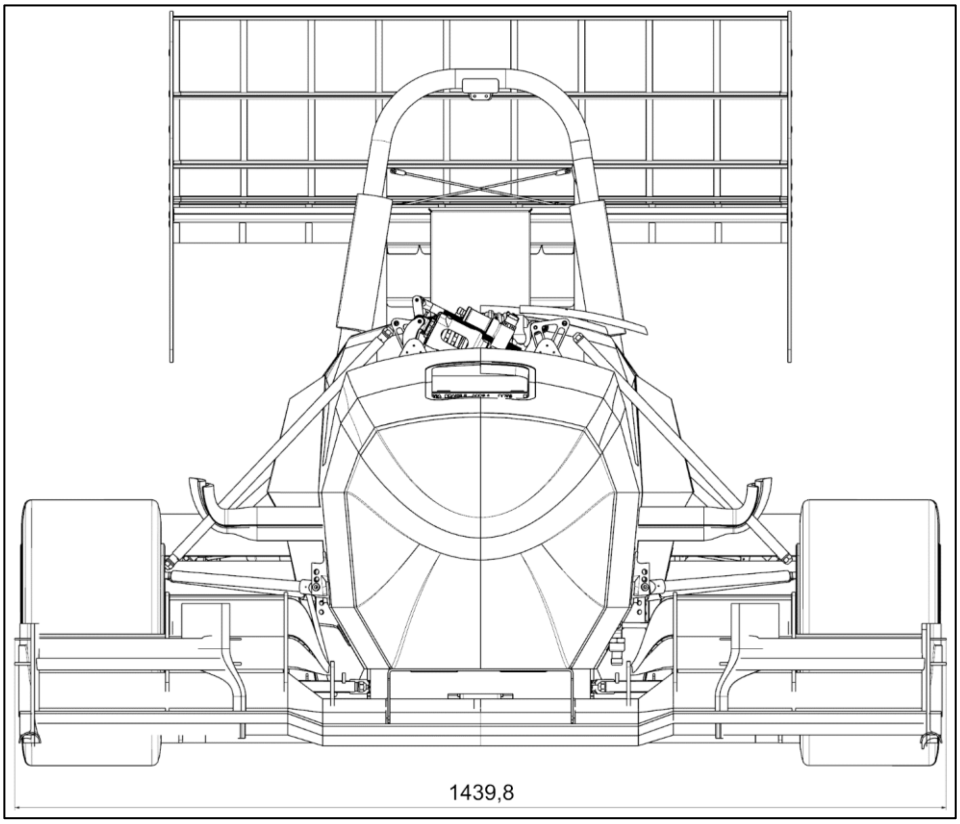
Figure 5. Ansys simulation of the HPF023 car



4.1.1 Front wing and nose cone

Making a front wing is a precise art that requires lots of testing, knowledge, and strict compliance with regulations while also exploring the limits of aerodynamic ingenuity. The front wing of a Formula Student race car is the main pillar for a balanced aero package, since it is the first component to encounter the air, it shapes it for the rest of the vehicle. It consists of numerous bits and pieces, positioned in sequence, each enhancing the car's overall aerodynamic capabilities. (Motorsportengineer, 2021)

Figure 6. Front side view of HPF024



By creating a lower-pressure area beneath the wing and a higher-pressure area above it, the front wing loads the suspension springs and forces the car down, improving traction and stability during high-speed cornering. In the context of Formula Student, where cornering performance can be the difference between winning and losing, the front wing is a vital tool in maintaining control and achieving high-speed precision on more technical circuits. This also improves safety, front-end grip contributes to a more balanced car, reducing the likelihood of understeer during cornering and thereby decreasing the risk of crashing.

The main plane is the primary component of the front wing, it is responsible for most of the downforce generated. It creates the initial pressure differential by interacting with oncoming air. It goes without saying that the faster the car is moving the more downforce we generate. The angle of attack of the main plane is critical, as it determines how aggressively the wing generates downforce. A steeper angle results in higher downforce but also increases drag, which can slow the car on straight sections of the track. In Formula Student, where the balance between downforce and drag is paramount, the design of the main plane must be carefully considered to avoid excessive drag while still generating sufficient downforce.

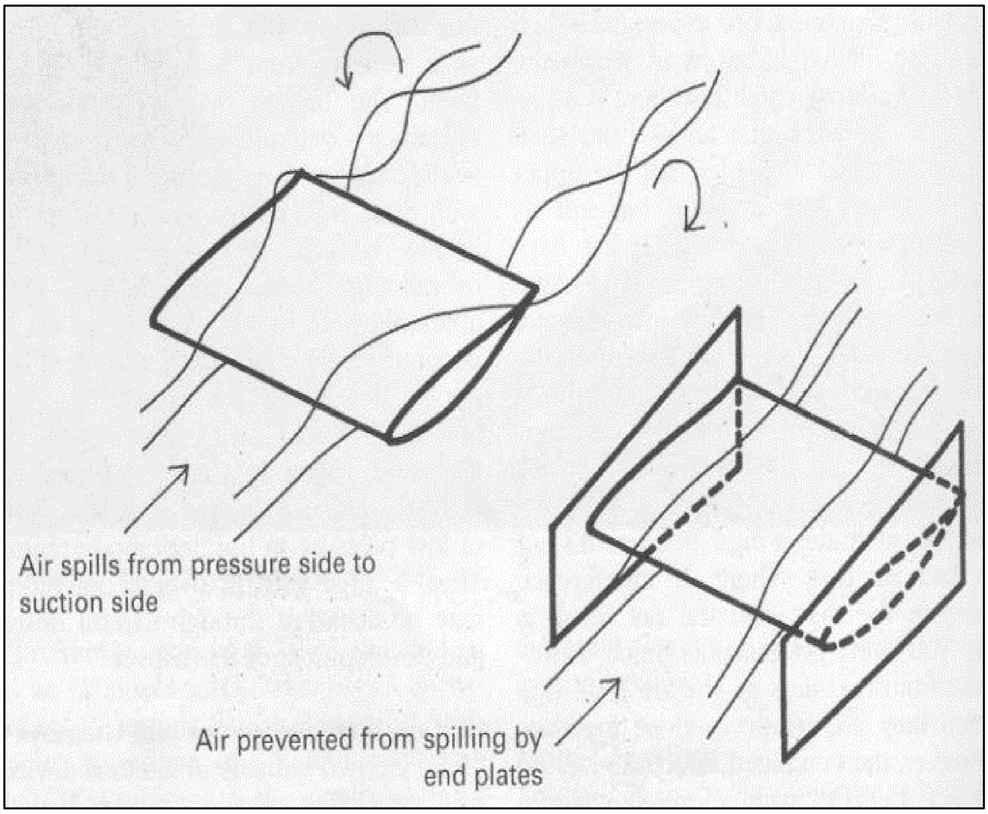
Figure 7. HPF023

The secondary elements, such as flags, cascades, and winglets positioned above the main plane enhance the overall effectiveness of the front wing by fine-tuning the airflow. By adjusting their AOA, we can increase or decrease the overall downforce depending on the specific requirements. They help redirect and smooth the flow of air and optimize its distribution across the front of the car. They also influence the aerodynamic balance between the front and rear of the car, helping to stabilize the vehicle at high speeds and through tight corners.

The endplates, located at the outer edges of the front wing have a very important role in managing both pressure and airflow. They prevent high-pressure air at the top of the wing from going over to the low-pressure area under it. Take the endplates off and this air would create turbulence and make the downforce-generating elements basically ineffective.

The endplates also help get rid of “dirty air” around the front tires, reducing drag and minimizing the turbulence created by the wheels. the reduction in turbulence contributes to the overall aerodynamic efficiency of the car, allowing it to be more stable at higher speeds while still having enough downforce for the tight corners.

Figure 8. the effect of endplates (McBeath, 1998)



4.1.2 Side Wing

Traditionally, side pods in FSAE vehicles served two main functions. Firstly, they housed radiators and cooling intakes essential for managing the heat generated by internal combustion engines. This was crucial knowing that all competitions are held during summertime in various countries. Secondly, they needed to accommodate a large portion of the exhaust systems, which needed to be carefully routed to manage heat without interfering with the vehicle's aerodynamic performance.

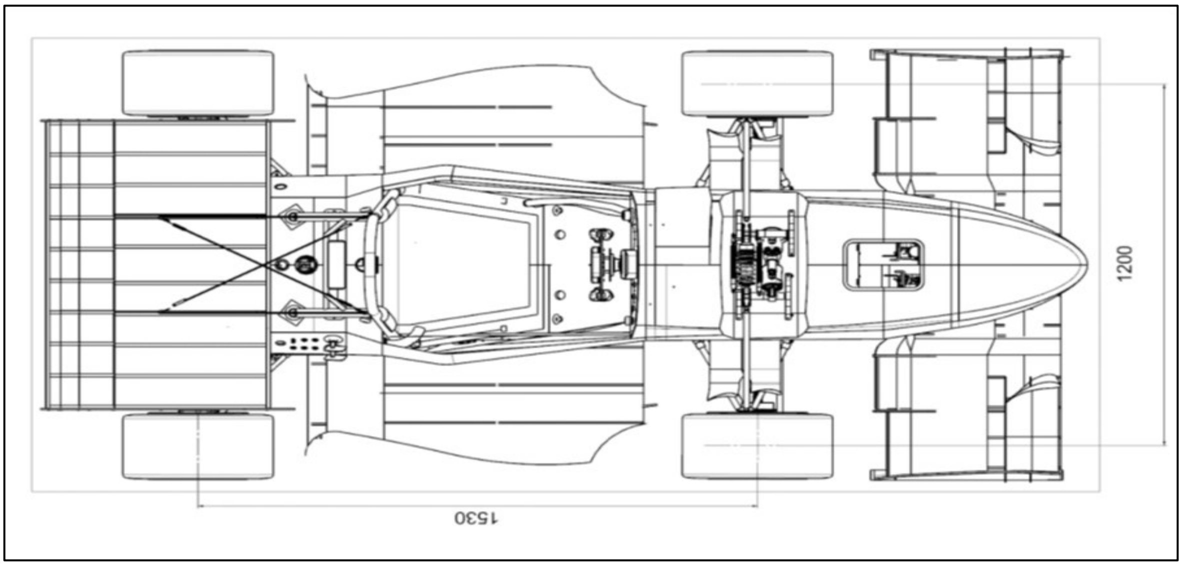
The side pods were quite large, and their design was heavily influenced by the need to balance aerodynamic efficiency with thermal management requirements. With the adoption of fully electric drive trains, notable changes have been made to get the most out of the vehicle's new potential. This shift has led to the use of side wings in the design of electric Formula Student vehicles.

Figure 9. the University of Liverpool 2016-year car (University of Liverpool, 2015)

Side wings began to play a big role in enhancing the overall vehicle performance by improving downforce distribution, aerodynamic balance, and airflow management. They generate a significant amount of lateral downforce increasing greatly tire grip during cornering thus allowing for higher cornering speeds and improved stability.

They also influence airflow toward the rest of the aerodynamic elements, such as diffusers and rear wing, enhancing their efficiency. Similarly to the front wing, the main plane generates downforce the airflow passing over and under the wing, creating a pressure differential that pushes the car toward the ground. Multi-element wings are then positioned and added to fine-tune the airflow and provide additional downforce at specific speeds or angles of attack.

Figure 10. Upper side view of HPF024



4.1.3 Rear Wing

At last, the rear wing is designed to complement the downforce levels and aerodynamic balance of the front wing. The rear wings on FSAE are very visually imposing, they sit quite high compared to the rest of the aero package and contribute to more than 20% of the total car’s downforce accounting for approximately one-third of it.

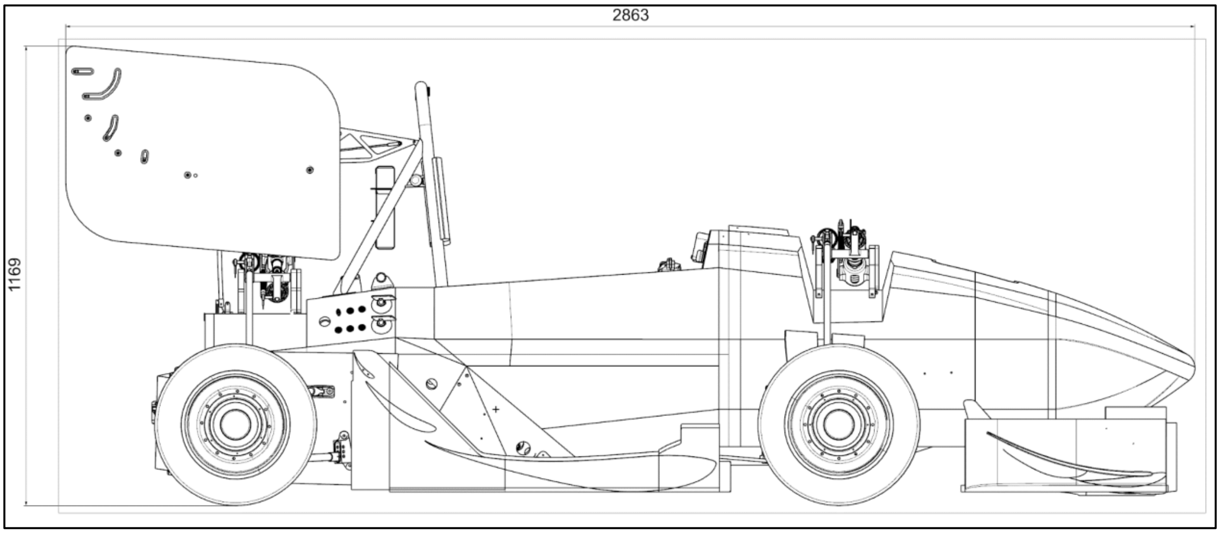
Figure 11. Tallinn Formula Student Team Car (Magagni, 2024)

Due to its placement, the rear wing is subject to the dirty airflow from the rest of the car, therefore it must be designed carefully, taking into account orientation and measurements to negate the turbulent conditions.

Typically, rear wings feature multiple airfoils, consisting of three or four sets of elements. These elements can be either manually or electronically (DRS) adjusted to lower or raise the drag coefficient for either straight line or cornering performance. On each side, large endplates are mounted to prevent “spillage” and reduce drag.

To further aid with airflow attachment, a simple length of aluminum or carbon fiber in a right-angle profile can be rigidly bolted, riveted, or glued to a wing's trailing edge. Called a Gurney Flap it increases pressure on the pressure side of the wing, decreasing pressure on the suction side, and helping the boundary layer flow stay attached all the way to the trailing edge on the suction side of the airfoil. At the same time, a long wake downstream of the flap containing a pair of counter-rotating vortices can delay or eliminate the flow separation near the trailing edge lower surface (racing car wing). Thus, the total suction on the airfoil is increased. (Formula 1 dictionary, n.d.)

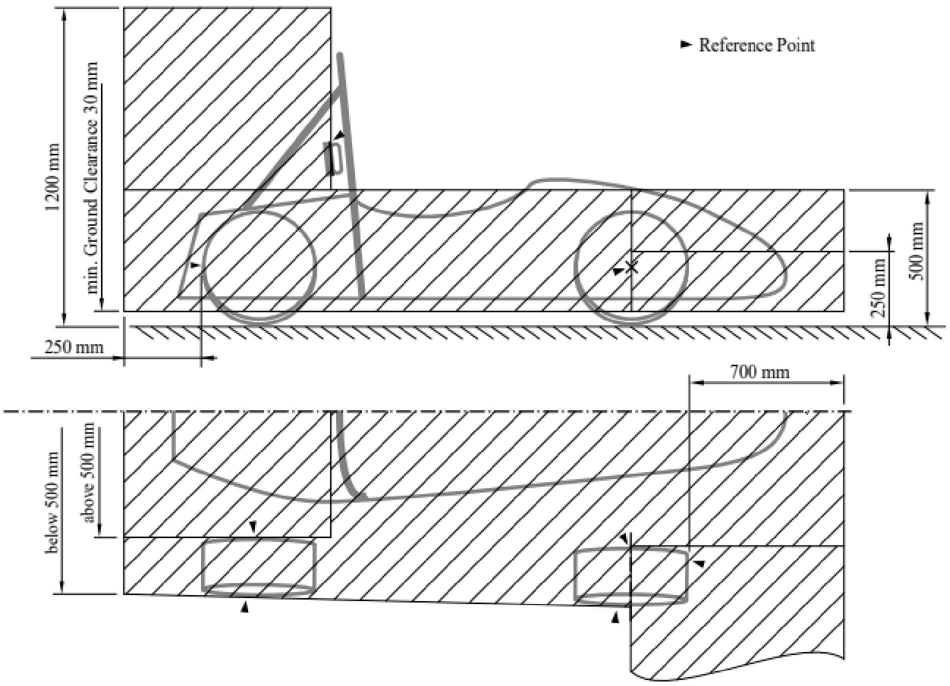
Figure 12. Right Side View of HPF024



4.2 FS regulations

The FS rule book has a few restrictions regarding the “Aerodynamic Device”, these rules can be split into 2 separate sub-sections, Dimensional and Durability restrictions. Adhering to these rules is of utmost importance, judges test and measure the different aspects of the car to ensure its compliance. Cars who fail to pass the tests are banned from competing. The first appendix has all the rules listed.

Figure 13. Maximum Dimensions and Positioning of Aerodynamic Devices (FSAE International, 2024)



4.3 Planning and Considerations

When tackling a project as big as this one, which spans several months and involves numerous people working simultaneously, it is essential to address several critical considerations to ensure the final product is flawless.

It is common to get carried away with complex designs that give excellent results on paper but are impractical or even impossible to manufacture. It is essential to align the design with the available tools, materials, and fabrication techniques. This alignment starts at the very beginning of the season where teams go through their material’s inventory (carbon fiber, aluminum alloys, foams) and equipment (CNC machines, 3D printers, tools) to get a better grasp on the limitations of their resources. By acknowledging these limitations early on, less time is spent going back on design choices and modifying them to better suit the team’s capabilities. This goes hand in hand with budgetary Constraints, limiting teams with smaller budgets and favoriting the ones with more spending power. Our team had to deal with a substantial budget cut this year which led us to be more creative with our manufacturing approach, reusing existing components when possible and reducing product waste by lowering the number of prototypes.

The skill set available is another big point of consideration, experience of the team members plays a huge role in achieving perfection. Recruiting a wide range of profiles and recognizing their respective skills allows for an adequate task repartition, add that to a collaborative environment and you get a team that not only strives for more but also maximizes the chances of learning new things and introduces new perspectives that can refine the design.

The design process is inherently iterative, involving continuous testing, evaluation, and refinement. Trial and error play a significant role, especially when experimenting with the placement of components and selecting appropriate airfoil profiles

Another key aspect is leveraging the previous design's strong points and building upon them. For example, we retained the rear wing and the main plane of the front wing from the prior year's design due to their proven efficacy. This continuity allows the team to focus on optimizing other aspects of the aero kit.

4.4 CAD modelling

In our design workflow, we use two different software platforms for CAD modeling, each serving distinct purposes in the development of the aero package. For preliminary simulations, we use Ansys Space Claim. Here we create models focused specifically on the aerodynamic package, minimizing unnecessary details such as the monocoque, control arms, wiring, etc. Ansys is notorious for being very power-demanding, so this simplification helps improve computational efficiency during the straight line and cornering simulations while maintaining enough detail to yield accurate results for the aero package's performance.

Once the simulation phase is complete and the aero package design is finalized, we transition to NX, a more detailed assembly software. In this phase, the entire team integrates their respective parts into a single, cohesive model. Siemens NX allows us to include detailed elements for the aero package such as the skins, internal geometries, and the structural skeleton of the car but also the drive train, suspension geometries, and wiring.

The static events indirectly require accurate car models, teams have to present detailed justifications for their vehicle's design, materials, and manufacturing processes. These models ensure that the teams can explain how their design choices impact performance and manufacturability, influencing the judges' evaluation of their work.

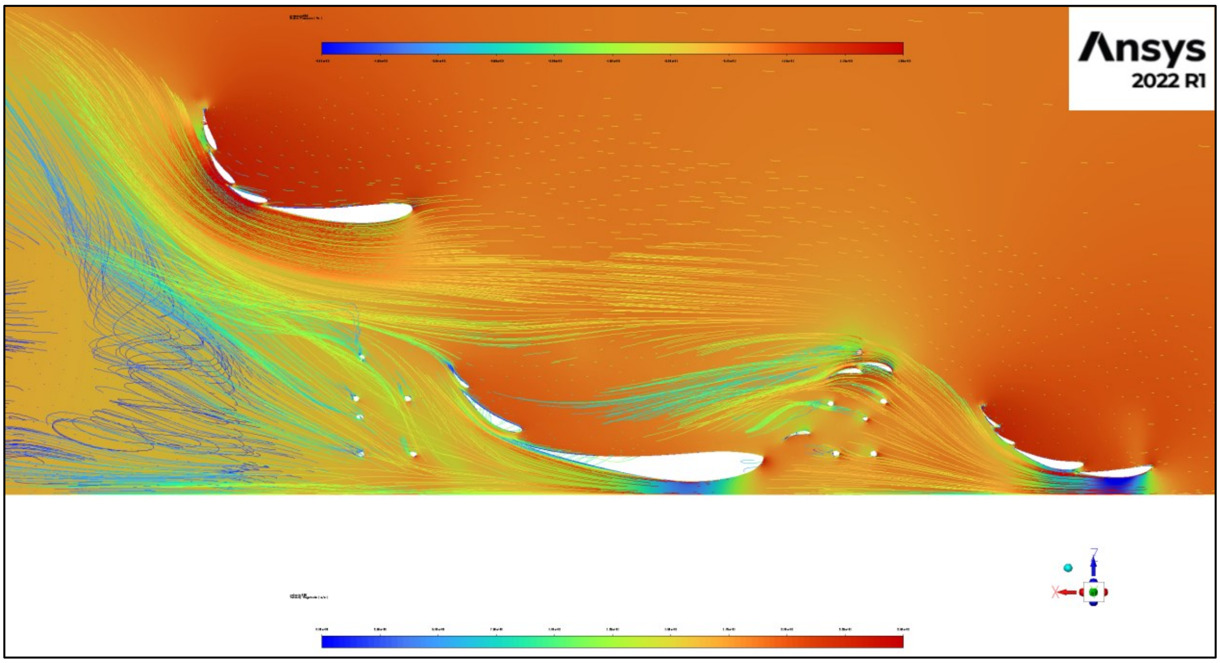
This comprehensive assembly ensures that all components, including the aerodynamic package, fit together perfectly with the rest of the vehicle before moving into manufacturing.

4.5 Rendering and Simulations

I call this our testing grounds, and it is so important in creating a successful aerodynamic device in my opinion. Here we materialize the goals we gave ourselves earlier by experimenting with new ways of delivering those improvements within the regulations we have.

These simulations allow us to see the differences our adjustments make in real-time and from different angles. Computational Fluid Dynamics simulations reveal airflow patterns, pressure distribution, and turbulence around the car. These insights help identify areas of drag, downforce, or airflow separation, enabling targeted improvements. It's all about testing new and different options to understand how we can manipulate the flow field in the best way suitable for us, even though this process is time-consuming and takes most of our effort and resources, it remains essential to achieve our desired outcomes.

Figure 14. airflow patterns and turbulence areas around foils



We usually start from the previous year’s design as a baseline, it provides us with a solid foundation while allowing us to experiment freely. This year the focus was on making a better front wing than the previous one that was used for three seasons and was outdated. In addition to the front wing, substantial attention was given to refining the side wing and rear wing endplates. I had very little involvement in this phase due to the little knowledge I have when it comes to race car aerodynamics. However, I closely followed the progress and results of this phase, as it played a critical role in shaping the final design and performance of the aerodynamic package.

In total more than 50 different iterations were made, all simulated with different parameters and drive heights. I chose three different concepts that seemed most interesting to me. We can see different rear wing airfoil shapes being tried to help with the turbulence and wake created by the driver and cockpit area. Also, different endplate configurations were tested to see if any gains in drag reduction could be made but just making simple cutouts or adding 3D bits that didn’t cost a lot to manufacture. The front wing setups involved adding strakes to the bottom of the main plane, changing the cascade setups and angle of attack. We are mainly looking to smooth out the air for the rest of the car by eliminating turbulence.

Figure 15. First Concept Ansys Simulation Example

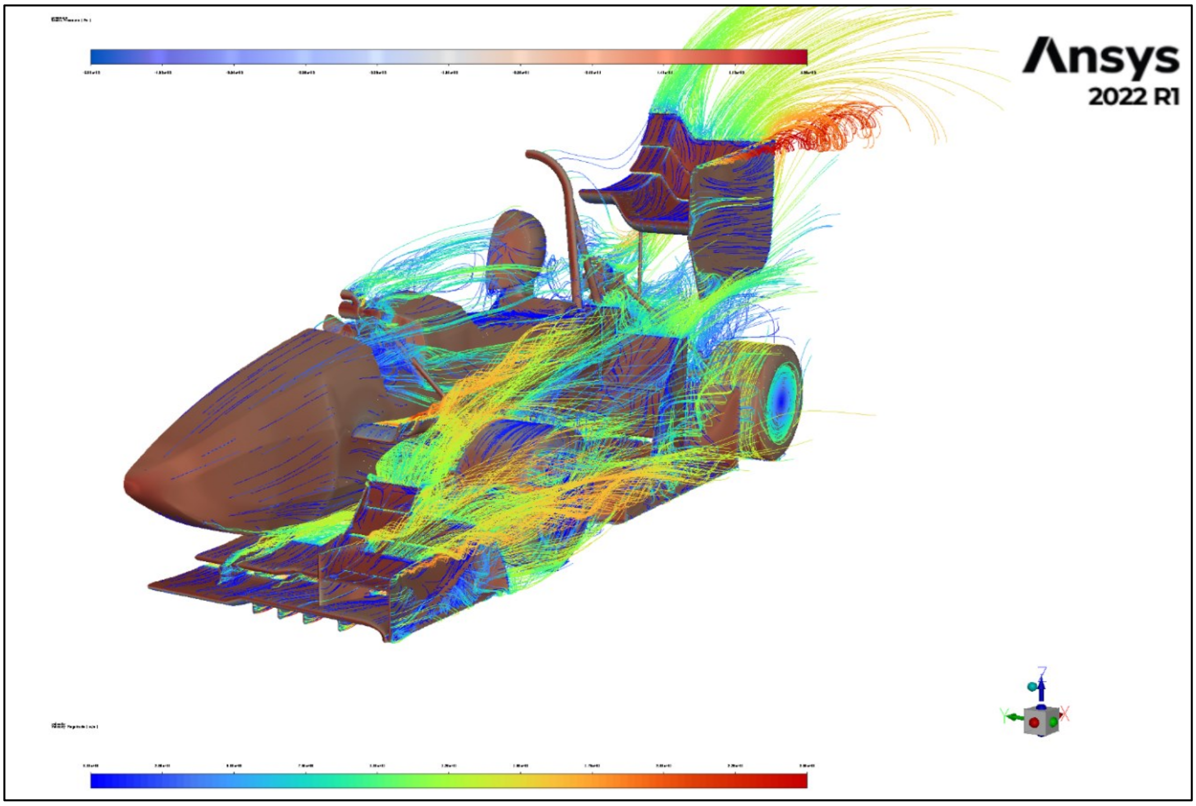


Figure 16. Second Concept Ansys Simulation Example

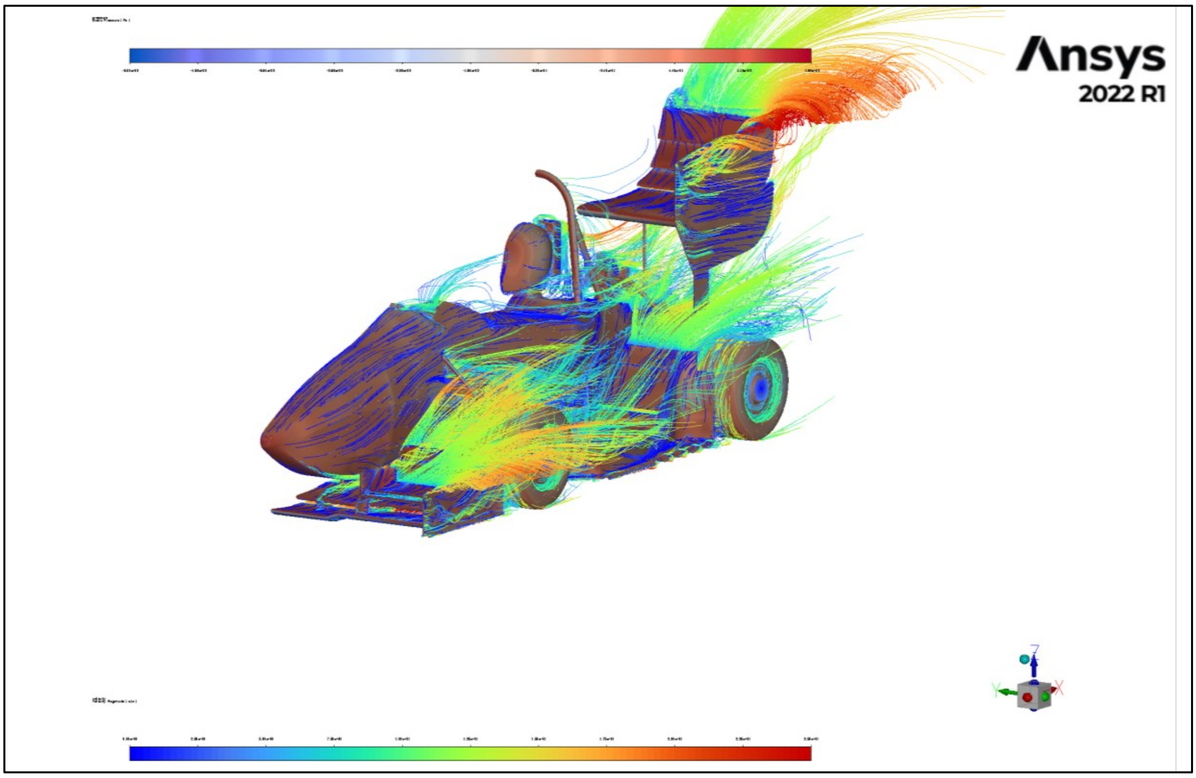
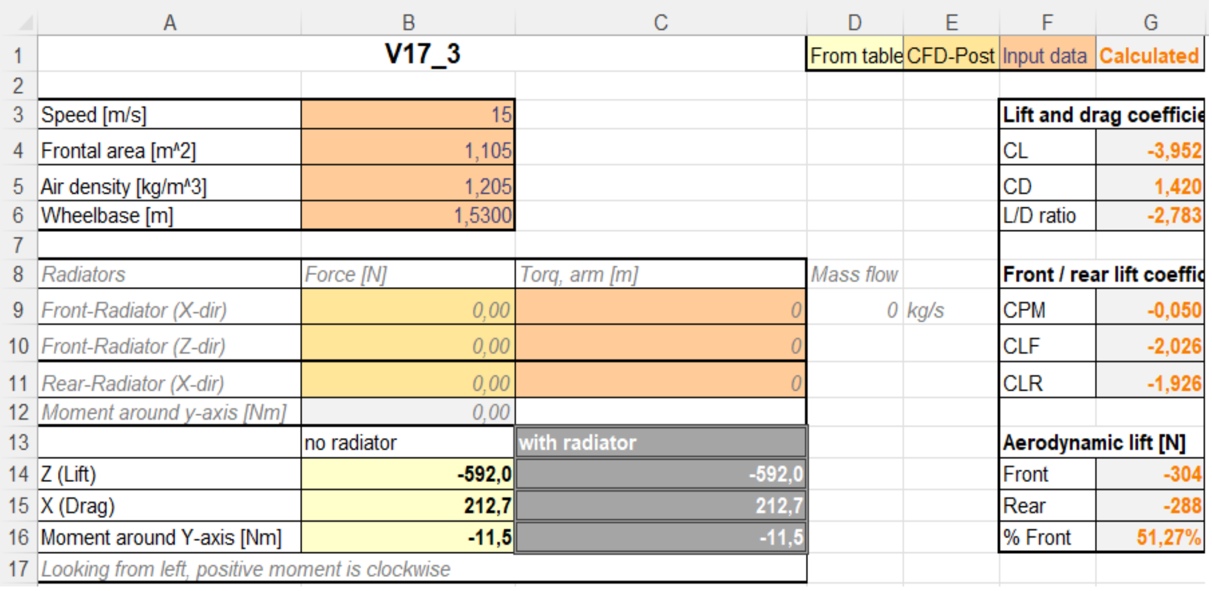


Figure 17. Second Simulation Results



	A	B	C	D	E	F	G
1	**V17_3**			From table	CFD-Post	Input data	**Calculated**
2							
3	Speed [m/s]	15				**Lift and drag coefficie**	
4	Frontal area [m^2]	1,105				CL	**-3,952**
5	Air density [kg/m^3]	1,205				CD	**1,420**
6	Wheelbase [m]	1,5300				L/D ratio	**-2,783**
7							
8	*Radiators*	*Force [N]*	*Torq, arm [m]*	*Mass flow*		**Front / rear lift coeffic**	
9	*Front-Radiator (X-dir)*	*0,00*	*0*	*0*	*kg/s*	CPM	**-0,050**
10	*Front-Radiator (Z-dir)*	*0,00*	*0*			CLF	**-2,026**
11	*Rear-Radiator (X-dir)*	*0,00*	*0*			CLR	**-1,926**
12	*Moment around y-axis [Nm]*	*0,00*					
13		no radiator	**with radiator**			**Aerodynamic lift [N]**	
14	Z (Lift)	**-592,0**	**-592,0**			Front	**-304**
15	X (Drag)	**212,7**	**212,7**			Rear	**-288**
16	Moment around Y-axis [Nm]	**-11,5**	**-11,5**			% Front	**51,27%**
17	*Looking from left, positive moment is clockwise*						

Figure 18. Final Ansys Simulation

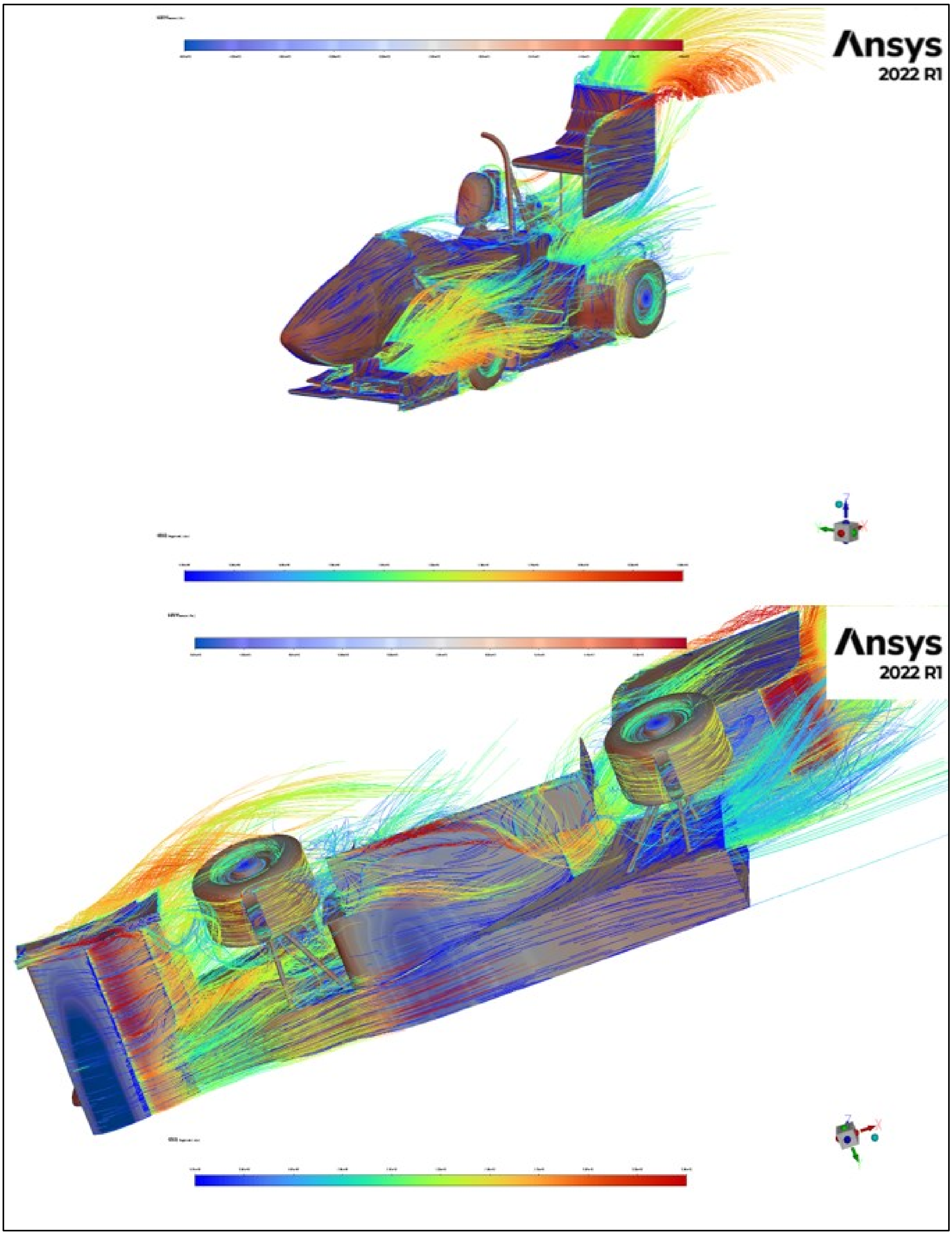
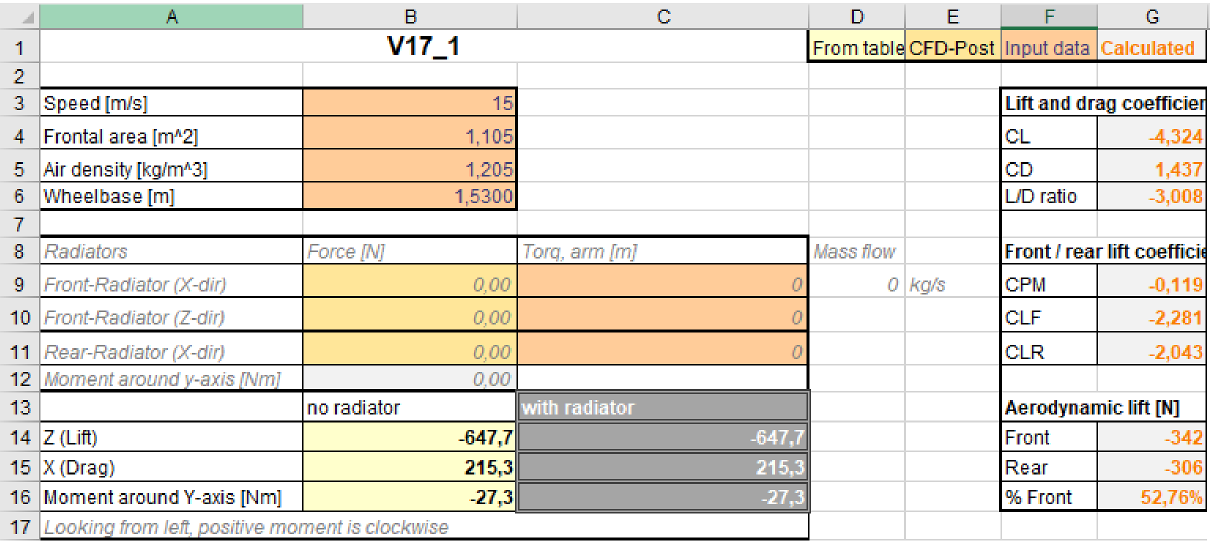


Figure 19. Final Simulations Results



	A	B	C	D	E	F	G
1	**V17_1**			From table	CFD-Post	Input data	Calculated
2							
3	Speed [m/s]	15				**Lift and drag coefficier**	
4	Frontal area [m^2]	1,105				CL	-4,324
5	Air density [kg/m^3]	1,205				CD	1,437
6	Wheelbase [m]	1,5300				L/D ratio	-3,008
7							
8	*Radiators*	*Force [N]*	*Torq, arm [m]*	*Mass flow*		**Front / rear lift coefficie**	
9	*Front-Radiator (X-dir)*	*0,00*	*0*	*0*	*kg/s*	CPM	-0,119
10	*Front-Radiator (Z-dir)*	*0,00*	*0*			CLF	-2,281
11	*Rear-Radiator (X-dir)*	*0,00*	*0*			CLR	-2,043
12	*Moment around y-axis [Nm]*	*0,00*					
13		no radiator	with radiator			**Aerodynamic lift [N]**	
14	Z (Lift)	**-647,7**	-647,7			Front	-342
15	X (Drag)	**215,3**	215,3			Rear	-306
16	Moment around Y-axis [Nm]	**-27,3**	-27,3			% Front	52,76%
17	*Looking from left, positive moment is clockwise*						

4.6 CAD Mold modelling

Each part comes with its unique parameters that must be considered during mold design. This means that mold creation is inherently a case-by-case process, requiring different solutions to address the geometries, size, and placement issues. However, there are a couple of general principles to follow.

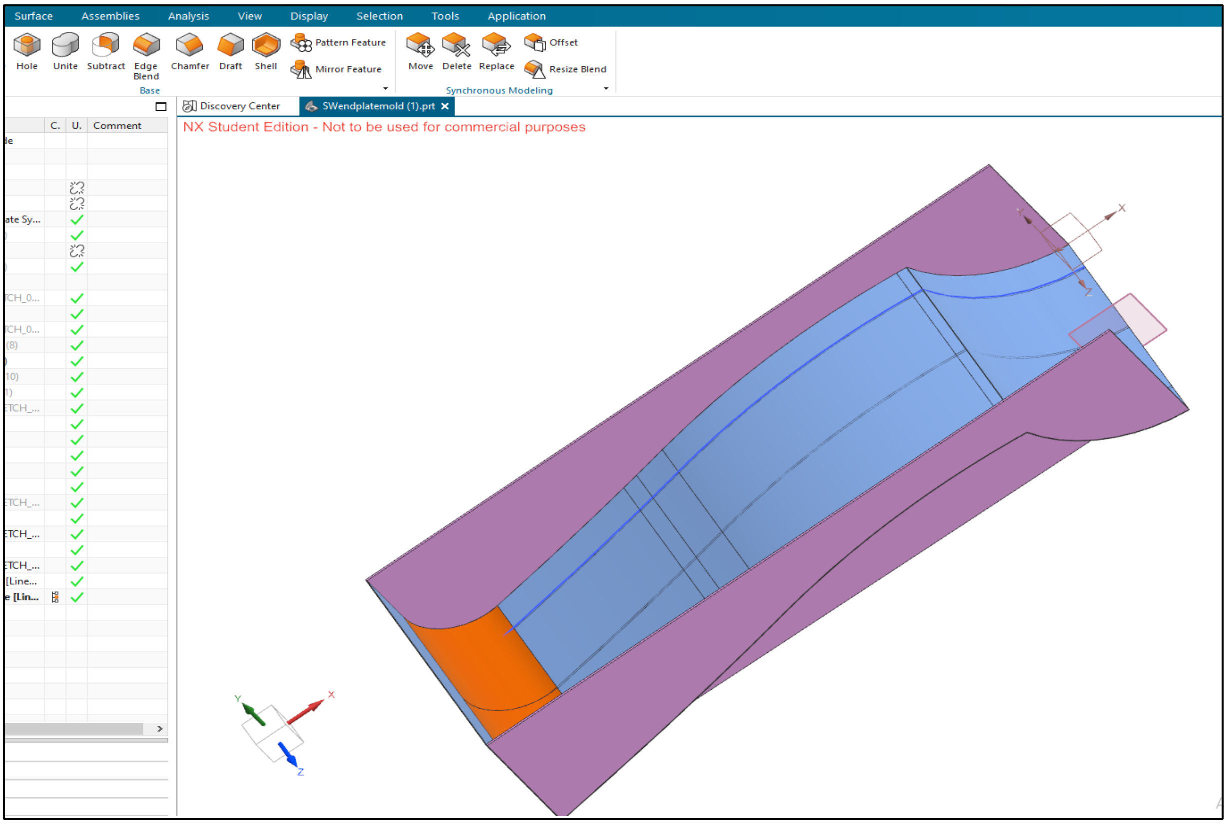
The first step of creating the molds happens on the CAD software, the process begins by copying the existing part geometries into a new file and modifying them to meet the specific requirements of the mold.

It is quite a tedious task and requires meticulous planning. All the molds that we are making are one-piece molds, they combine simplicity, cost-effectiveness, and speed. With fewer materials, assembly steps, and experience requirements, they significantly reduce production costs and setup time while also giving a better and smoother surface quality. The demolding process is way easier and faster as well, especially beneficial for the bigger and more fragile parts.

The geometry of the part plays a big role in determining the mold manufacturing process. Parts with simple 2D curves like the end plates are made using simple processes such as bent sheet metal in our, as they require bending around a single axis. In contrast, parts with complex 3D curvatures such as the inverted wings or front wing main plane necessitate more advanced manufacturing techniques, like CNC machining, 3D printing, or stamping. These methods are generally more expensive and complex.

In addition to geometry, several practical design features can greatly enhance the Mold’s functionality and ease of use. Extending edges, avoiding undercuts, and allocating space for necessary equipment ensure that the Mold is not only easier to produce but also more efficient to use in practice. Tolerances must be accounted for depending on parts positioning on the mold and the number of carbon fiber layers used.

Figure 20. Side wing End plate CAD model mold



5 Manufacturing Phase

Once the final kit design is ready and the molds have been properly planned, we proceed to the manufacturing phase. Transforming sketches and 3D models into tangible parts is a very delicate and time-consuming task that requires expertise and patience.

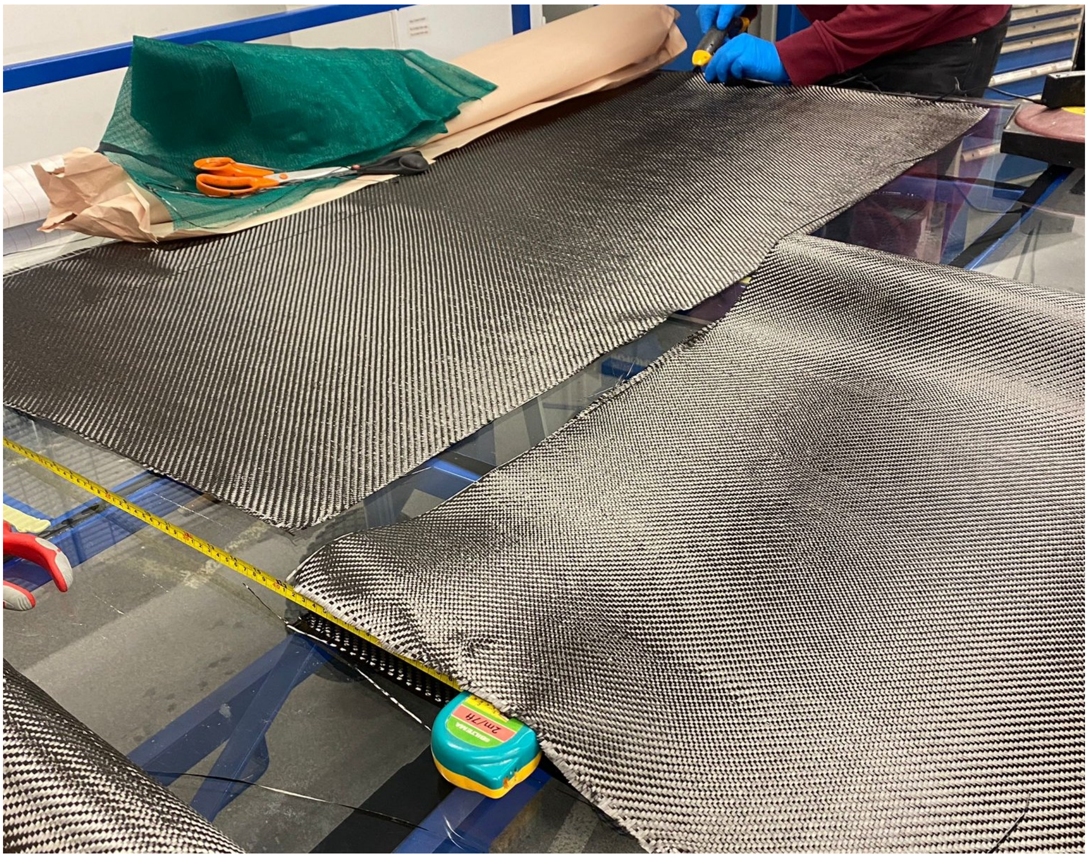
5.1 Material selection

When aiming to set new records and achieve top scores in competitions, selecting the right materials becomes essential. FSAE has seen a lot of different trends since its inception. In the early years steel and aluminum were the only two options available due to their low cost and ease of fabrication. As the automotive sector evolves materials like fiberglass and carbon fiber become easier to get a hold of and use. This shift has led to a huge reduction in weight, resulting in lighter and faster cars. The innovations did not stop there, each year new materials are being introduced such as titanium 3D-printed components, hemp fibers, and more.

5.1.1 Materials for Parts

Kevra® is one of the teams' sponsors and supplies us with a 2/2 twill weave with an aerial weight of 200 g/m². It offers high tensile strength and a superior modulus of elasticity while also reducing the weight of the car due to its low density. The twill pattern offers excellent "drapability" and maintains strength even when forming complex shapes. It also adds that attractive exposed carbon fiber look. (Kevra Oy, n.d.)

Figure 21. Carbon Fiber Twill Cutting Process



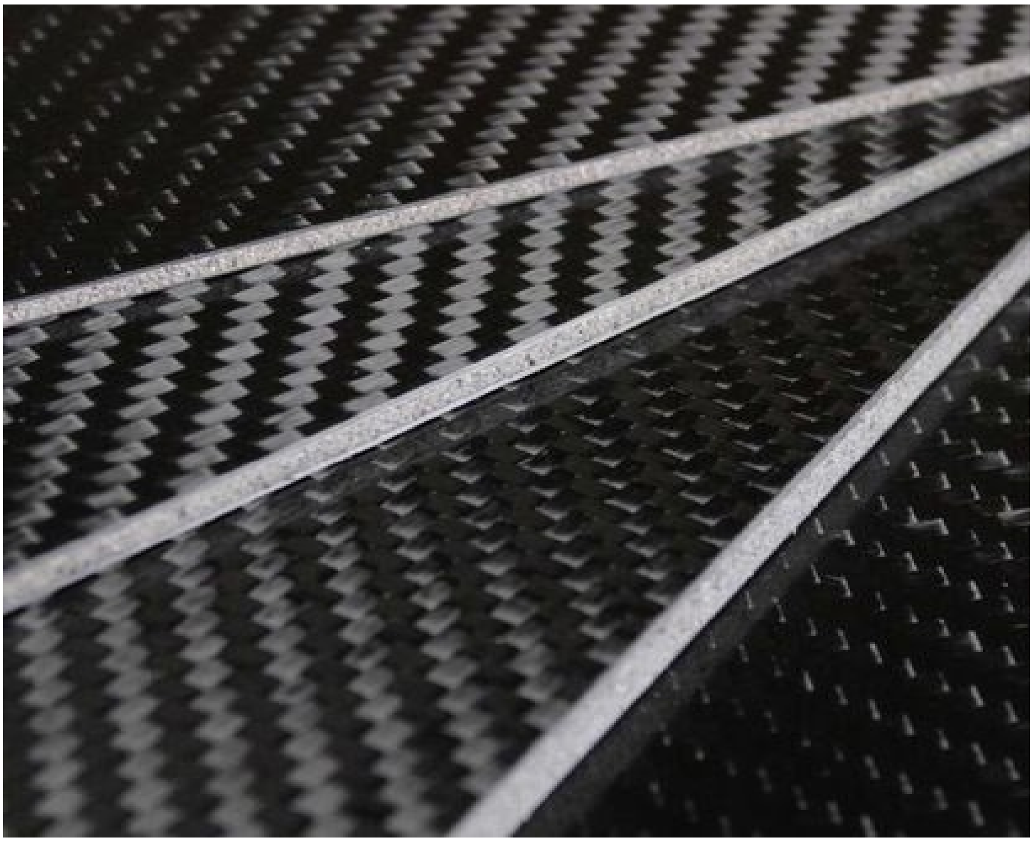
Rohacell ® foam is used as the core material, with a density of approximately 32 kg/m³, this lightweight foam significantly reduces the weight of sandwich composite structures. Its closed-cell structure prevents resin absorption during the manufacturing process, avoiding unnecessary weight gain and ensuring consistency in the final product. The foam exhibits sufficient compressive strength to withstand processing pressures and maintains dimensional stability during high temperature curing cycles (Evonik, n.d.).

To bind the materials together The Epoxy Ampreg 30 H+K STD resin system is used. The synergy between these materials results in composite components that exhibit exceptional performance characteristics.

The carbon fiber provides high tensile strength and stiffness, the Rohacell ® foam core brings in rigidity and reduces weight, and the Epoxy ensures structural binding and durability.

For the internal structure of the wings, a combination of carbon fiber fabric, 5mm Rohacell ® foam sheets, and an Epoxy Ampreg 37 resin system have been selected. These materials work in synergy to produce composite panels that are lightweight yet exhibit high strength and stiffness.

Figure 22. Sandwich Panels (Rock West Composites, n.d.)



5.1.2 Materials for Molds

For the creation of the molds, a couple of different materials and techniques were used. This variation was mainly due to the complexity of certain parts or their size.

The first thing on the list was the front wing Main Plane, with a length of 1,5 meters and very complex curvatures we had to opt for the SikaBlock ® M700 N. This polyurethane tooling board has been used extensively in the FSAE realm and has become a pillar for mold manufacturing in recent years. It offers excellent machinability and allows for intricate designs and precise dimensions through CNC. Computer Numerical Control machining has the advantage of ensuring consistency and quality while cutting down on lead time (Sika Services AG, n.d.).

Figure 23. SikaBlock® M700 N Sample

The side wing and undertray molds were mainly made out of 3mm generic aluminum sheets. Aluminum provides a rigid mold structure essential for parts requiring tight tolerances and its high thermal conductivity ensures uniform heat distribution during the curing process of composite materials, crucial for achieving consistent quality in the final products.

The accessory components such as the inverted wings, cascades, winglets, and flaps are either 3D printed and then laminated or used as is if the weight savings are not great.

Figure 24. 3D Printing Filament

5.2 Mold manufacturing

5.2.1 CNC

The molds that required CNC machining were for the front wing main plane and multi-element airfoils, even though the designs were kept from last year’s car and the existing molds were in decent condition, we had to remake them to achieve the high-quality results we aim for.

With the CAD files previously converted to G-Code, the task was straightforward. We imported the files to the CNC machine, carefully aligned the sika block, and locked it in place, any movement can cause errors and when making aerodynamic devices there is no room for that. Next, we selected the appropriate cutting tools, calibrated the machine, and began the process. Although this step takes a considerable amount of time, constant supervision is needed. For instance, the vacuum system needs to be running flawlessly to make sure the excess dust doesn’t cause jamming.

We then verified the dimensions and surface finish to ensure they met our requirements. If minor adjustments are needed, we may go through additional light finishing passes or even manual sanding to achieve the perfect result. SikaBlock ® is an expensive and delicate material and needs a careful approach

The final steps consist of, manually sanding the mold, then painting and clear coating it. Finally, we applied multiple coats of beeswax to ensure an easy release from the mold.

Figure 25. Front Wing Main Plane Mold

5.2.2 Laser and Waterjet Cutting

Laser cutting requires a slightly easier approach. The DXF files required are made from the already existing CAD models and then sent over with the sheet metal to Aalto University where they are cut into the designated shapes. Once that is done, they are brought back to our workshop to be bent and assembled to form the full mold shape.

Folding the sheet metal to the required dimensions needs a lot of skill, especially for the harder bends. It is also worth mentioning that hard curves can be 3d printed and glued onto the sheet metal. The last step is assembly, we chose epoxy resin glue for its ease of use compared to welding or mechanical fasteners.

Finally, the completed molds are tested and adjusted to ensure the mold's accuracy and that the finished part aligns with design specifications. Minor adjustments can be made, such as re-assembling the mold, re-cutting specific sections, or re-bending.

To reduce cost and material waste the molds are symmetrical and designed to make both the right-side and left-side wing parts.

Figure 26. Side Wing Mold

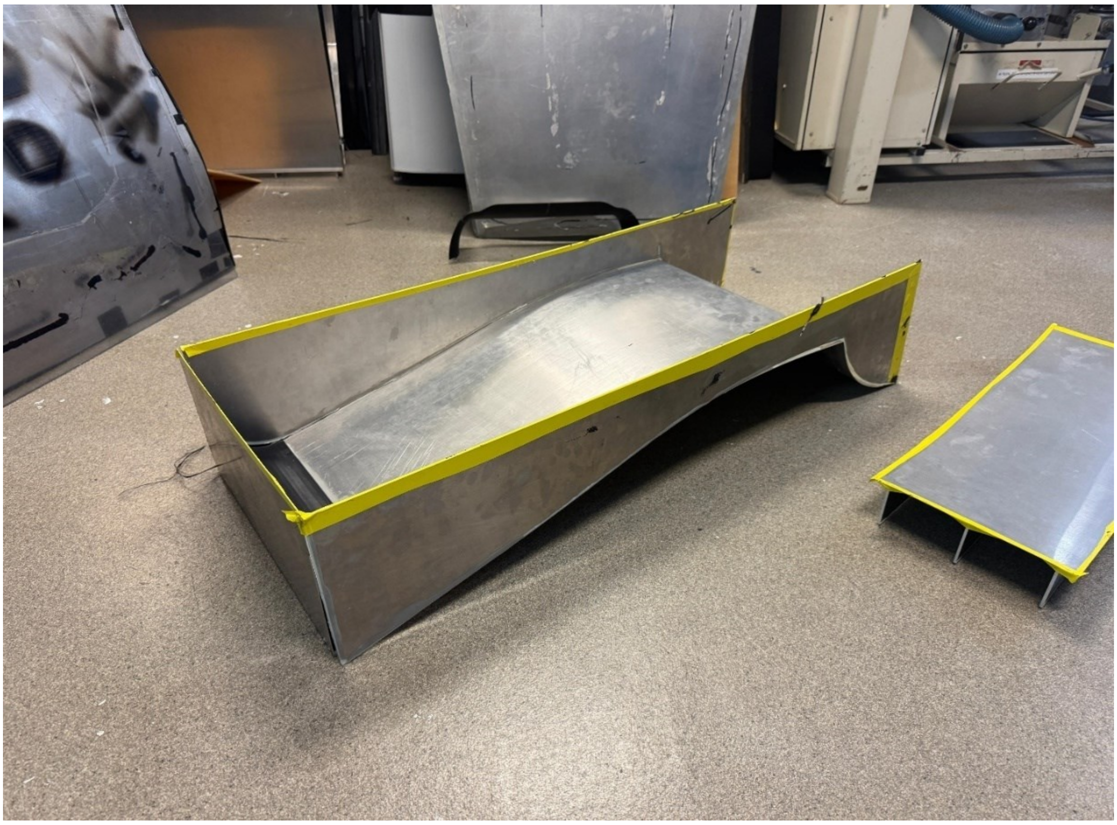


Figure 27. Side Wing Bottom Side Profile

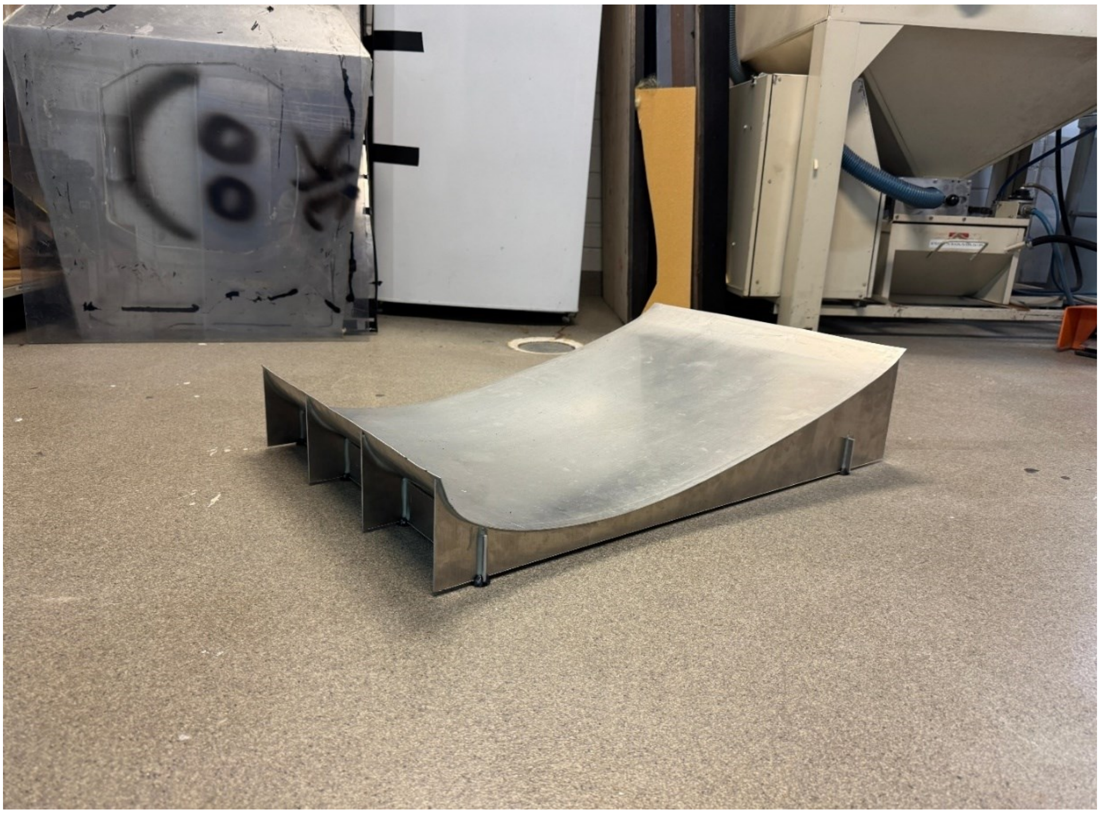


Figure 28. Side Wing Upper Side Profile

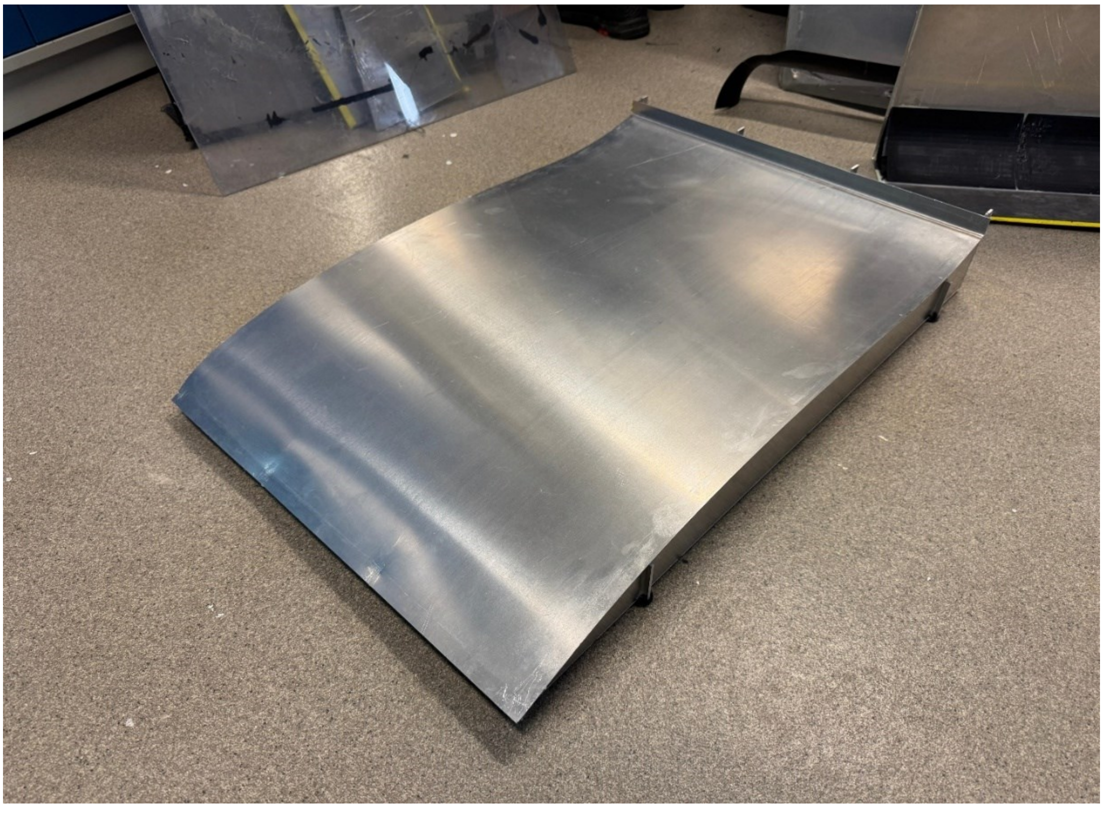


Figure 29. Front Wing End Plates Mold

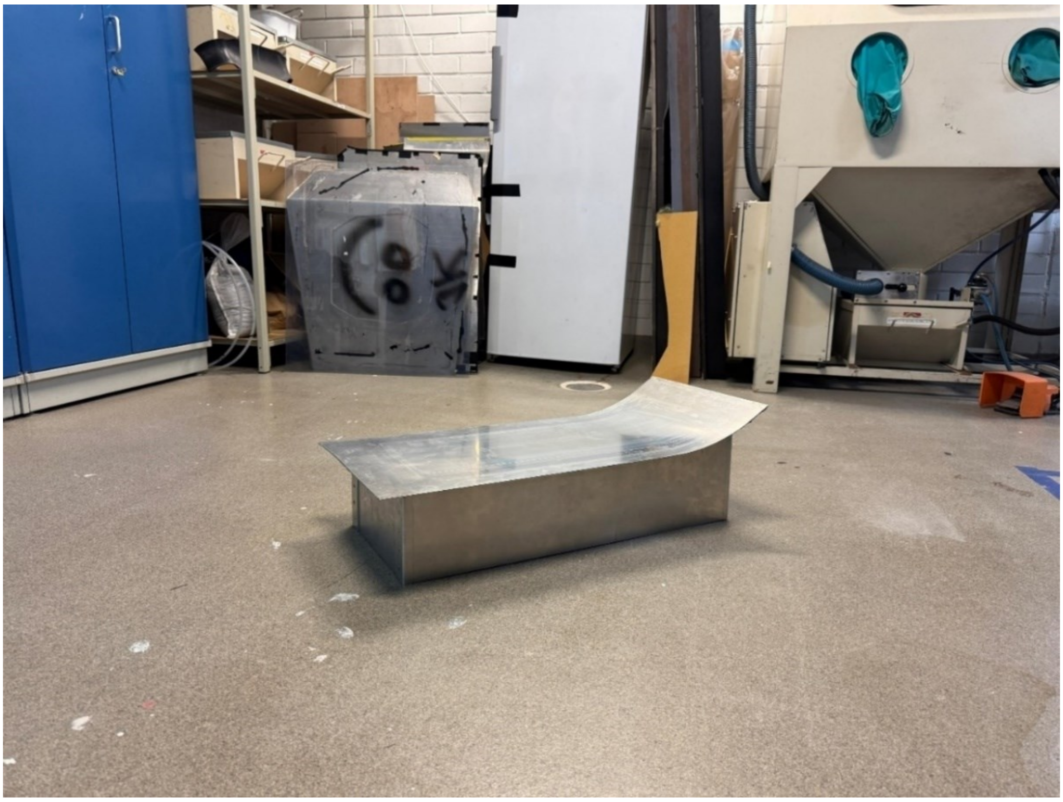
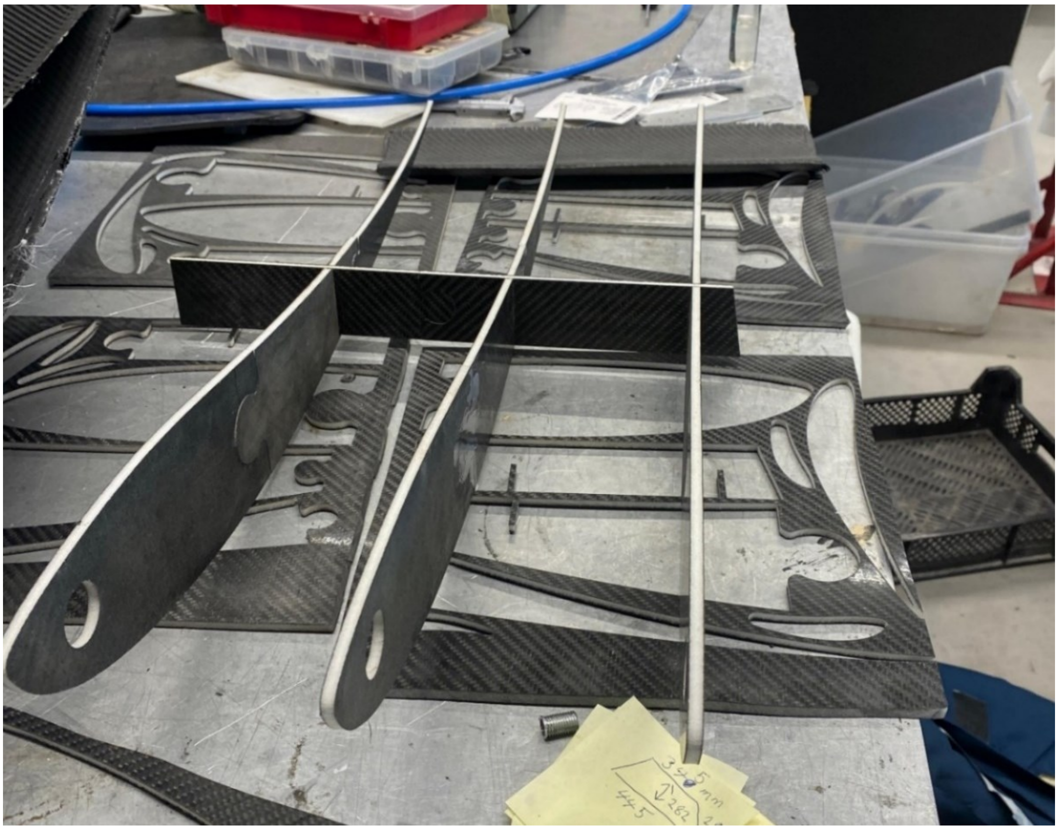


Figure 30. Carbon Fiber Wing Skeleton



For the internal skeleton of the wings, the large 2m² sandwich panels we made were cut into smaller 60cm² sections to fit in the machine. The DXF files provided precise cutting instructions for the waterjet rig.

5.2.3 Additive Manufacturing

In our case, 3D printing offered numerous advantages in producing aerodynamic parts and molds for our kit. Rapid prototyping was the primary benefit, allowing us to experiment with more intricate designs and geometries. We could create parts directly from CAD models and have them ready within hours or days, rather than weeks. 3D printing also proved to be more economical than other methods, meaning we can try numerous iterations without exceeding our budget.

The issue is that due to size and weight limitations, not all parts can be made from PLA, limiting our options to only molds or small aero devices such as canards and inverted wings in our case.

Figure 31. Inverted Wings

The 3D-printed parts can be very brittle and will shatter if they collide with a cone at high speeds. To fix this issue the parts are laminated with a single layer of carbon fiber to ensure their durability and impact resistance.

5.3 Laminating

For the actual laminating process, I chose two different parts to talk about, the side wing end plates and the front wing main plane. They both necessitate a nearly similar approach but with some key differences.

With the mold previously Coated with beeswax to ensure an easy release, we apply double-sided gum tape or sealant tape around the flange to ensure an airtight seal. We measure the desired dimensions and make sure to not leave too much or too little material, a carbon strand is pulled to give us a guiding line to follow with our cutting sheers. This step minimizes waste and ensures the fibers remain properly aligned during layup.

We mix up the right ratio of the Epoxy Ampreg resin and the hardener and apply the mix on the laid down carbon fiber with a brush while making sure the whole surface is thoroughly covered. One must be careful not to apply too much resin to the edges of the carbon to prevent unraveling. We then quickly layer on the peel ply sheet, it’s a nylon cloth treated with a release agent that absorbs a small amount of resin during the curing process and will ensure an even, grease-free surface that does not need extensive sanding. This layer is critical for creating a surface that will bond well with other skins during assembly.

Next, we cut and apply our Breather/Bleeder Cloth, which will absorb and retain the excess resin drawn from the part through the perforated layer and also allow vacuum pressure to distribute evenly across the entire laminate. Vacuum lines are then installed in place and are positioned on each side of the mold to allow air and excess resin to flow without creating blockages or uneven pressure distribution throughout the entire surface.

The last step is vacuum bagging, we peel off the adhesive from the gum tape and carefully stick it all around the plastic bag while making sure to seal off all the surface area to prevent pressure leaks. Here, we perform a test by turning on the vacuum pump and monitoring the pressure gauge. If leaks are detected, adjustments are made by resealing or applying additional tape.

Figure 32. Carbon Fiber Fabric Layering

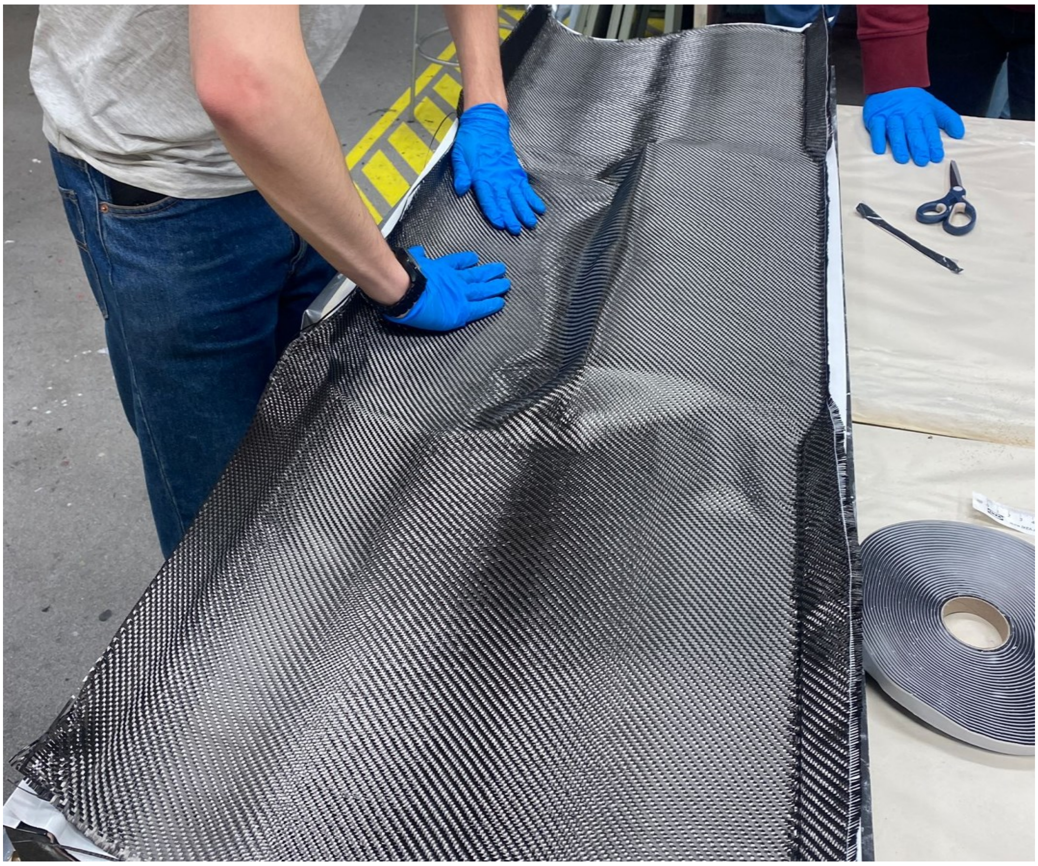


Figure 33. Bleeder Material Application

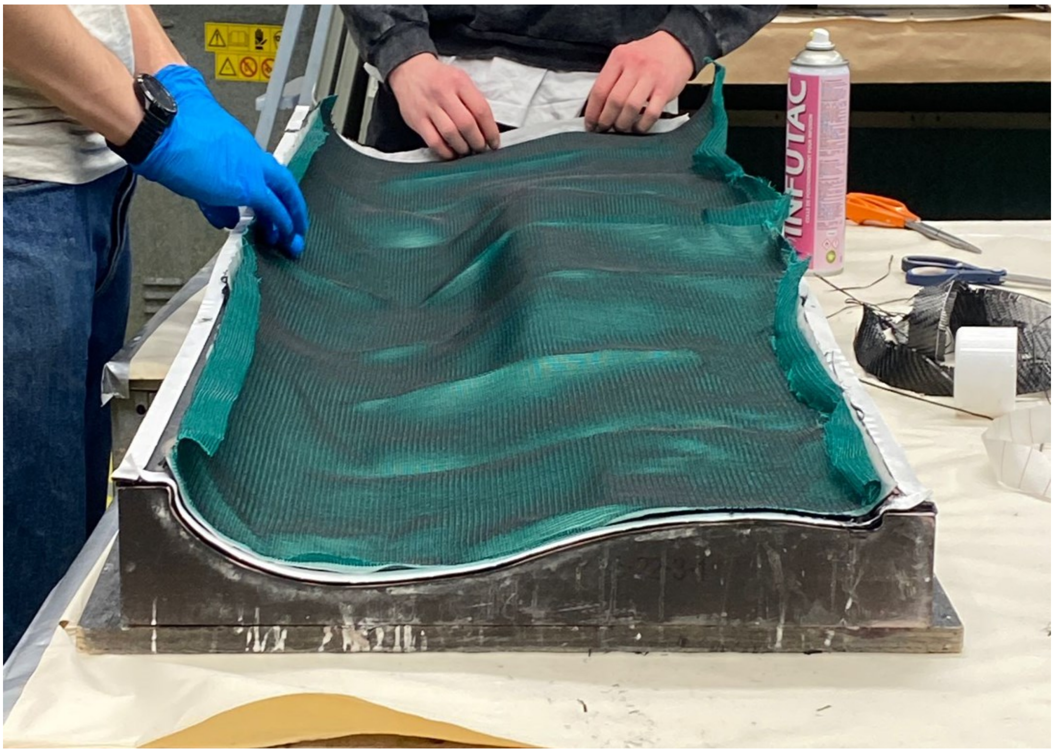


Figure 34. Vacuum Lines Installation

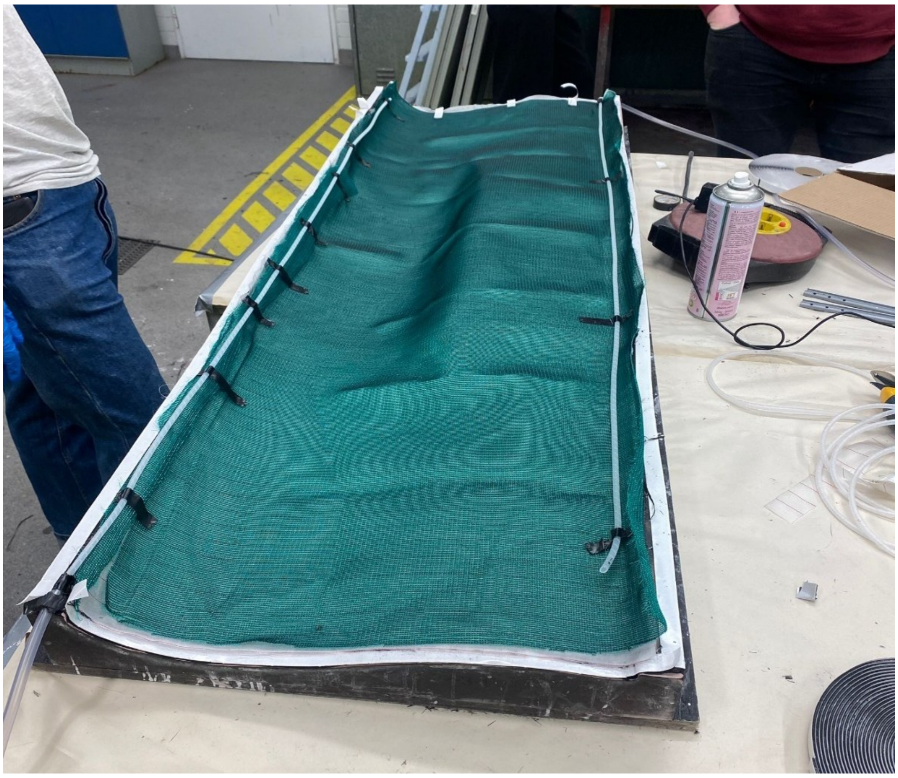


Figure 35. Vacuum Bagging Setup

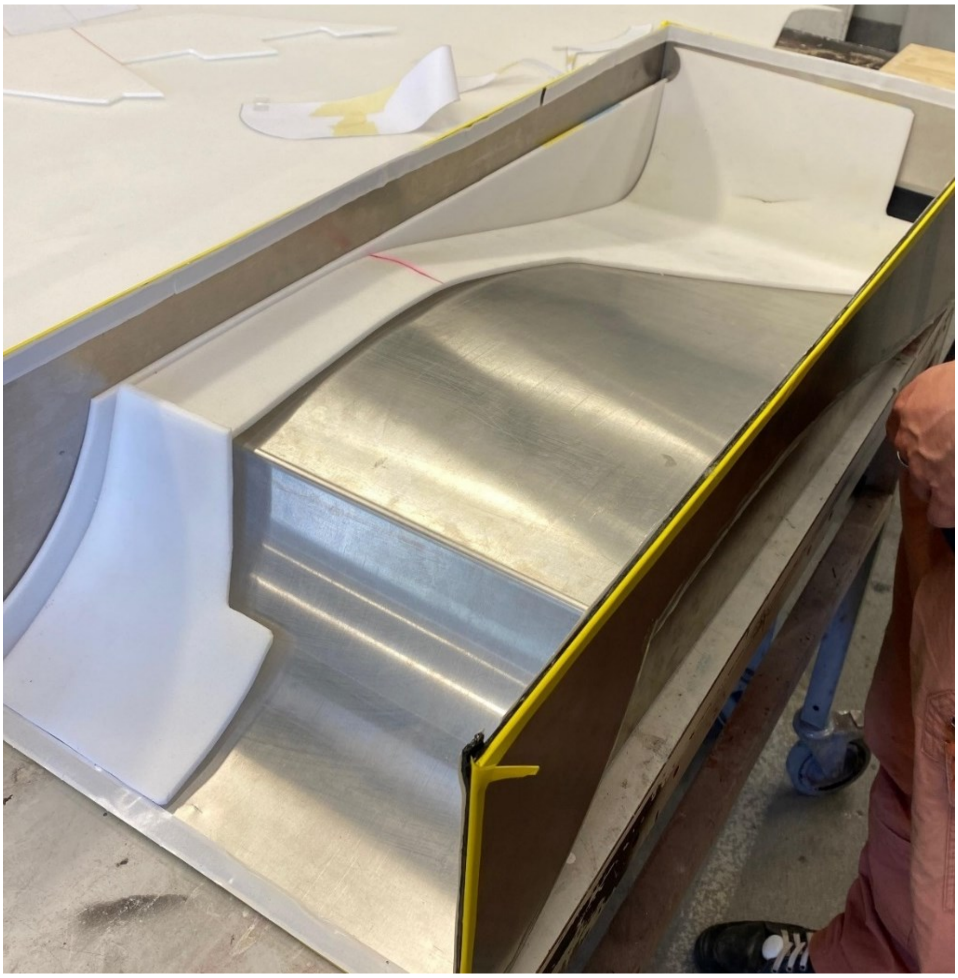
Once the vacuum is secured and the part is under the right pressure, it is left to cure overnight in the autoclave.

The same steps are applied to the side wings. We prepare the Molds, cut the materials into the appropriate sizes, and mix the resin and hardener in the specified ratios. The key difference is the addition of Rohacell® foam as a core material, which transforms the laminate into a sandwich panel. We mark the contours on the foam based on the CAD files and cut using a hot wire cutter.

Rohacell ® foam is thermoformable, meaning it can be heated to become pliable and shaped to match the mold's geometry. To achieve the desired curves, we heat the foam to around 190°C using a heat gun, so that it becomes flexible enough to be manually formed against the mold. After the foam has cooled, we place it between two layers of carbon fiber and bond it using the epoxy resin mix.

Figure 36. Twill Cutting Templates

Figure 37. Shaped Rohacell ® Core



5.4 Part Preparations

After curing, we carry out an initial visual test fit to ensure the dimensions are accurate to the CAD models and that the monocoque mounting points align correctly. This preliminary fitting is crucial as it allows us to detect any mismatch in the part's dimensions before further trimming and drilling.

Once the initial fit is verified, we proceed with trimming the carbon fiber components, this process requires a meticulous approach to avoid deeming the parts unusable. Cutting the cured carbon fiber poses serious health risks, the fine dust particles are very harmful when inhaled and can cause chronic respiratory conditions and irritations. It is essential to be in a well-ventilated space and use the right protective equipment, respirators with HEPA filters, safety goggles, and protective suits.

Once done, we are left with the final profile of the component, which includes clean edges and accurately defined shapes that fit within the design tolerances.

Drilling the mounting holes comes after and is done by aligning the parts so that each hole matches the CAD model and the corresponding points on the monocoque. After confirming the fit and alignment, the interior skeleton is assembled, and the trimmed edges are sealed using a layer of epoxy resin. Carbon fiber parts are highly susceptible to wear and potential damage due to moisture and UV light, proper surface finish is thus very important for parts longevity.

Figure 38. Pre-trimmed Side wing End plate

Figure 39. Side Wing Skeleton and End Plates Attached Together

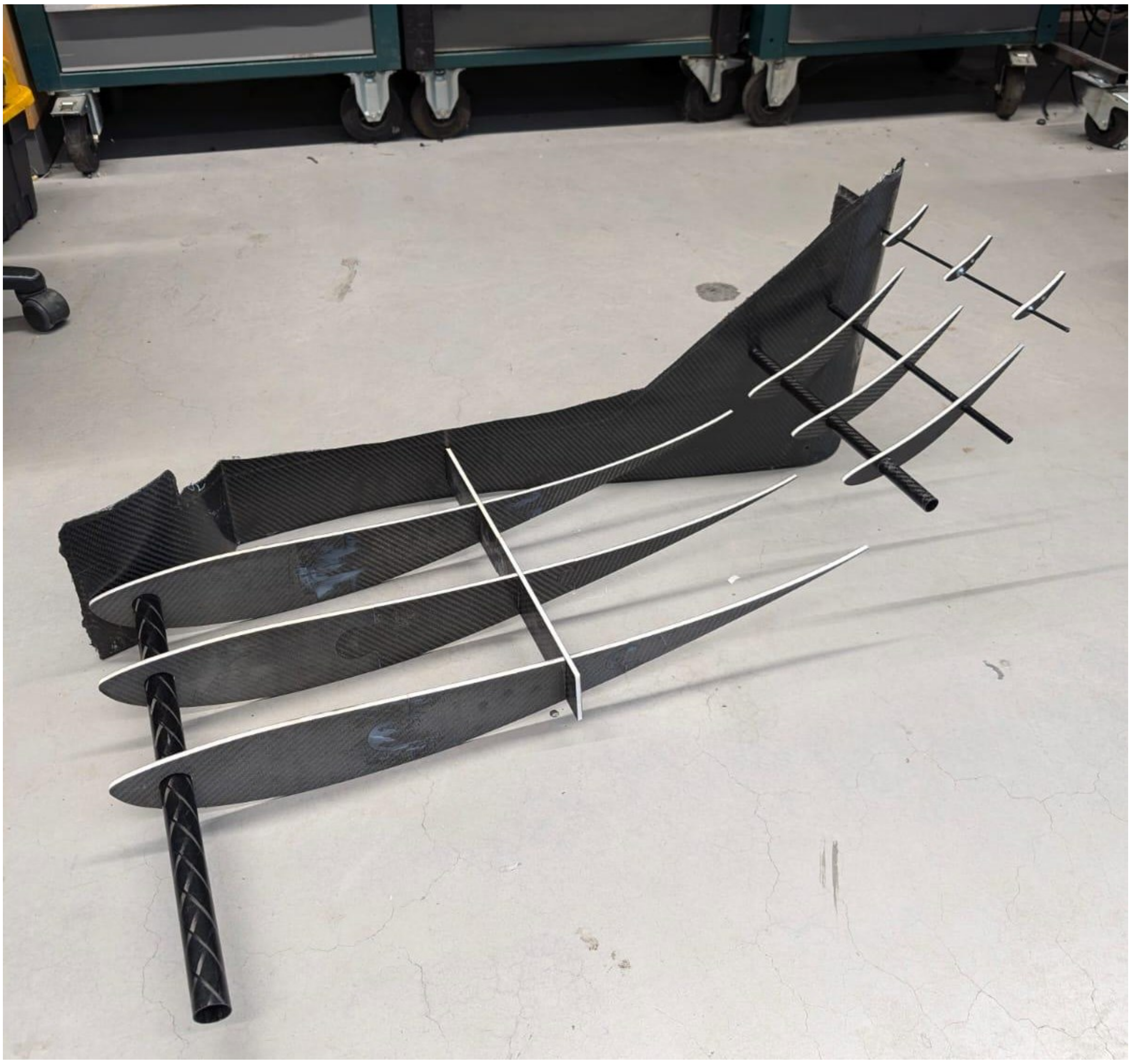


Figure 40. Complete Side Wing

5.5 Assembly

The Last and final step is the assembly, where the front, side, and rear wings are mounted on the monocoque using different methods.

The front wing is attached to the monocoque using laser-cut mounting brackets, while two steel cables are connected to each side of the wing using 3D-printed anchor points to reduce flexing in both ways. For the side wing, large carbon fiber tubes run through the chassis to provide rigidity while rivets keep everything secured in place. Same way as the front wing, steel cables are used to reduce side wing flex. Finally, the Rear wing is put in place using Laser cut brackets and carbon fiber rods. With all this, the final weight of the kit was 12 kg.

During the competitions, the cars must go through multiple Technical Inspections to ensure that they comply with structural safety regulations. For aero, the front, side, and rear wings need to pass the physical test independently. Force up to 200 N is applied near the mounting points and along the wings to observe deflection or flexing. Failing these tests means that the car cannot participate in any of the events, this is why particular attention is given to the assembly and mounting.
The finalized car with all the subsystem additions can be found in the Second appendix.

Figure 41. Last Stages of Assembly

6 Conclusion

To conclude, my journey with the Formula Student team, which began in late 2023, has been a very valuable learning experience. This project provided me with ample hands-on experience in both design and manufacturing, strengthening my acquired knowledge even further.

For the first time, I was involved in a large-scale project spanning over a year and operating with big a budget, and as a big motorsports fan, this was a dream come true. Finding the balance between being with the team and my studies was tough but also extremely rewarding. Even though we didn’t manage to participate in all the races this summer due to technical issues I was very excited to see my contributions come to life.

Looking forward, I am committed to staying as an active part of the Metropolia Formula Student team, even after graduating. While I have gained substantial knowledge and skills during this project, I know there is still a lot for me to learn especially when it comes to fluid dynamics and CFD simulations. With the start of this new season, we already have plenty of inspiring ideas for the HPF025 car and I cannot wait to start this new chapter.

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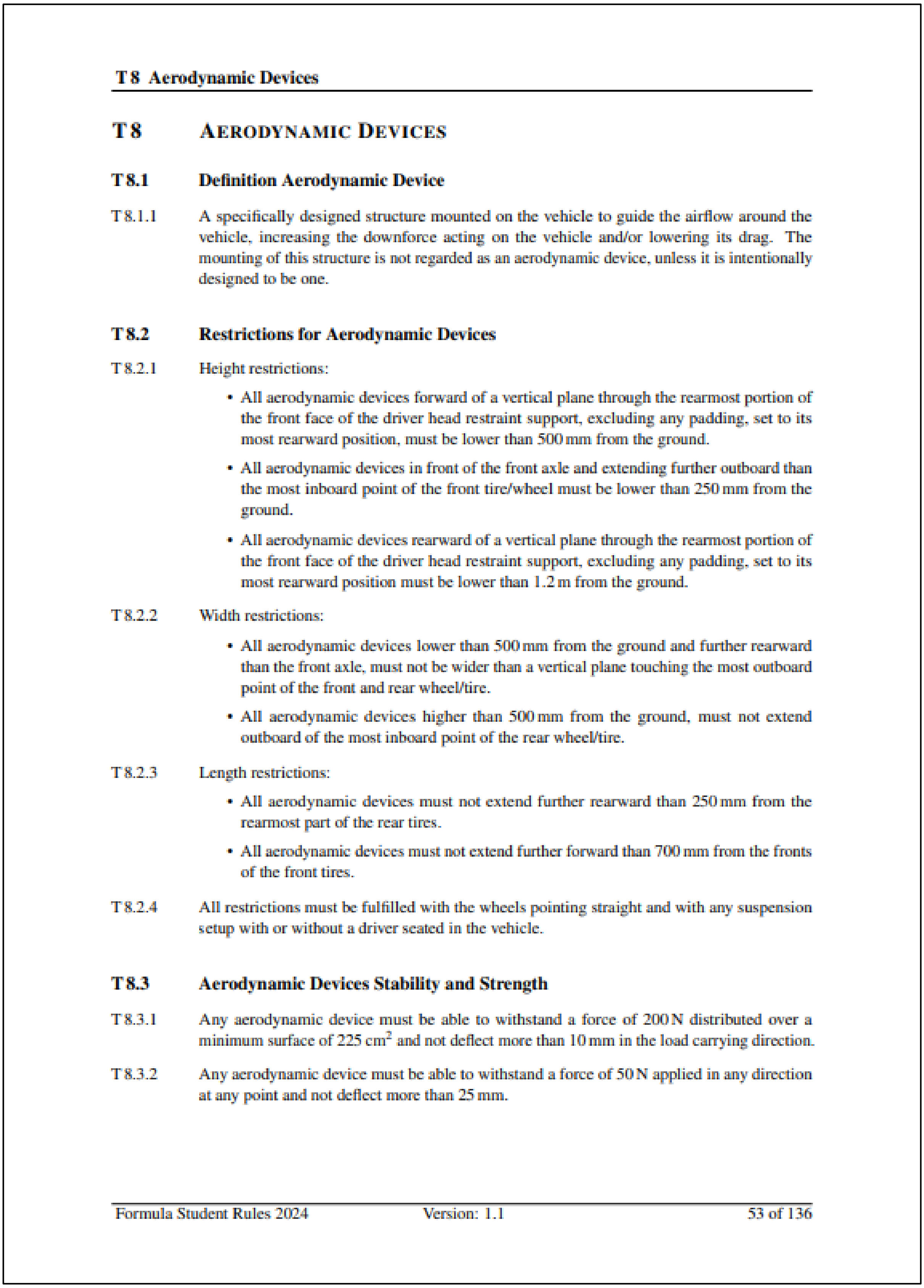
Rock West Composites (n.d.) https://www.rockwestcomposites.com/cftfs10-full-mg-dl.html

Appendix 1. FS 2024 rules



T 8 AERODYNAMIC DEVICES

T 8.1 Definition Aerodynamic Device

T 8.1.1 A specifically designed structure mounted on the vehicle to guide the airflow around the vehicle, increasing the downforce acting on the vehicle and/or lowering its drag. The mounting of this structure is not regarded as an aerodynamic device, unless it is intentionally designed to be one.

T 8.2 Restrictions for Aerodynamic Devices

T 8.2.1 Height restrictions:

- All aerodynamic devices forward of a vertical plane through the rearmost portion of the front face of the driver head restraint support, excluding any padding, set to its most rearward position, must be lower than 500 mm from the ground.
- All aerodynamic devices in front of the front axle and extending further outboard than the most inboard point of the front tire/wheel must be lower than 250 mm from the ground.
- All aerodynamic devices rearward of a vertical plane through the rearmost portion of the front face of the driver head restraint support, excluding any padding, set to its most rearward position must be lower than 1.2 m from the ground.

T 8.2.2 Width restrictions:

- All aerodynamic devices lower than 500 mm from the ground and further rearward than the front axle, must not be wider than a vertical plane touching the most outboard point of the front and rear wheel/tire.
- All aerodynamic devices higher than 500 mm from the ground, must not extend outboard of the most inboard point of the rear wheel/tire.

T 8.2.3 Length restrictions:

- All aerodynamic devices must not extend further rearward than 250 mm from the rearmost part of the rear tires.
- All aerodynamic devices must not extend further forward than 700 mm from the fronts of the front tires.

T 8.2.4 All restrictions must be fulfilled with the wheels pointing straight and with any suspension setup with or without a driver seated in the vehicle.

T 8.3 Aerodynamic Devices Stability and Strength

T 8.3.1 Any aerodynamic device must be able to withstand a force of 200 N distributed over a minimum surface of 225 cm^2 and not deflect more than 10 mm in the load carrying direction.

T 8.3.2 Any aerodynamic device must be able to withstand a force of 50 N applied in any direction at any point and not deflect more than 25 mm.

Appendix 2. Completed HPF024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