



Budapest University of Technology and Economics

Faculty of Transportation Engineering and Vehicle Engineering



TDK

Formula Student versenyautó aerodinamikai elemeinek tervezése és gyártása

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Budapest, 2014.



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Preface

Magyar

A 2013-as szezonban csapatunk, a BME Formula Racing Team először alkalmazott aerodinamikai csomagot, amely ellátta a feladatát, amire tervezték: a minél nagyobb leszorítóerő elérését. Azonban ez a konstrukció nehéz volt, és a nem optimált geometria miatt rengeteg járulékos közegellenállással járt, ami a tesztek során az akkumulátor idő előtti lemerülésében jelentkezett. Ezt a szélcsatorna analízisek is megerősítették, az aerodinamikai csomagot nem volt alkalmas egy elektromos autó kiszolgálni. Ennek következtében a következő szezont teljesen új alapokra helyeztük

A 2014-es szezonban azt a célt tűztük ki, hogy egy elektromos autónak megfelelő, hatékony, kis tömegű aerodinamikai csomagot tervezzünk. Ehhez első lépésben járműdinamikai szimulációk segítségével megállapítottuk az optimális leszorítóerő-légellenállás arányt. A követelményeknek megfelelő, alacsony Reynolds-számú szárnyprofilok kutatása során kiválasztottuk a számunkra megfelelőeket, amelyek végső elrendezését érzékenységvizsgálatok és számos szimuláció során optimalizáltuk 2D-ben. A szárnyprofil összeállításokon további finomításokat hajtottunk végre 3D-ben, valamint különböző szárnyvéglap geometriák vizsgálatával meghatároztunk egy végleges formát.

A szárnyak anyagaként a nagy szilárdsága és merevése ellenére kis sűrűségű szénszálerősítésű kompozitot választottuk. Sajátos gyártástechnológiája miatt sok geometriai tervezési szempontot figyelembe kellett vennünk. A költséghatékonyság érdekében olyan szerszámokat terveztünk, amelyeket a szárnyfelek legyártása után készülékként is használhattunk a ragasztások végrehajtásához, a pontos végső geometria elérése érdekében.

A rétegrend tervezésénél törekedtünk arra, hogy csak olyan irányokban legyenek erősítő szálak, amelyekben szükséges, így csökkent a nem teherviselő anyag az alkatrészekben, ami tömegcsökkenést eredményezett. A végelelemes analízis során az irányfüggő viselkedés miatt ortotróp anyagmodellt alkalmaztunk. Az analízishez szükséges minden anyagtulajdonságot az általunk gyártott próbatestek szabványos vizsgálataival határoztunk meg a BME Polimertechnika Laboratóriumának szakítógépein. A végelelemes modellt többlépcsős iterációs folyamattal validáltuk a mérések



segítségével, míg kielégítő pontosságot értünk el, majd elvégeztük az analíziseket valamint az optimalizációkat. Ezután a szerszámok marása, és a termékek vákuuminjektálással történő gyártása következett, amit a termék felek összeragasztása és az utómunkálatai követtek.

A tömeg és a közegellenállás csökkentésével, valamint az elért leszorítóerő növelésével elkészült a Formula Student 2014-es mezőnyének az egyik leghatékonyabb szárnya, amelynek a köridőkre gyakorolt jótékony hatását a tesztek során is megtapasztaltuk.

English

In the previous season our team, the BME Formula Racing Team applied an aerodynamic package on its car for the first time. It served its purpose to achieve the maximum possible downforce, but that concept was heavy, and because of the non-optimized geometry it generated a lot of drag. This was shown on wind-tunnel tests and also on real-life tests, where it caused early battery discharges. This package was not capable of serving an electric car well. Because of all these we developed an entirely new aero package on new bases.

In season 2014. our goal was to design wings which are efficient, light, thus fit to an electric car. To achieve this, the first step was to produce laptime-simulations to find the optimum in the downforce/drag ratio. During the research of the profiles with low Reynolds-numbers we chose which the best for our application was. The final concept was achieved after producing sensitivity-analysis and numerous simulations in 2D. Then we further refined the geometry in 3D and finalised the form after the investigation of different endplate-concepts.

Because of its high strength and stiffness and low density, we chose carbon-fibre reinforced composites as the material of the wings. We had to keep a lot of design aspects in mind concerning the geometry because of this material's unique manufacturing process. To be cost-efficient we designed moulds which can also be used as tools for the bonding process to achieve accurate final geometry.

During the design of the ply-sequence we strived to put the fibres only in the directions where it's needed. Thus the amount of non-structural material reduced, which caused weight-reduction. Because of the direction-dependency we applied orthotropic materials in the finite-element analysis. We produced standardized test on specimens



manufactured by us, to get all the material properties we needed for the analysis. The finite-element model was validated by measurements to achieve the satisfactory accuracy. Then the analysis and optimizations were produced. After that, the moulds were milled and the products were manufactured using vacuum assisted resin-transfer moulding. After that the bonding and the finishing of the parts were made.

By reducing the weight and the drag, and increasing the downforce, one of the most efficient wings of the Formula Student 2014. competitions was created. The aero package also proved its good effects on laptime during the tests.

1. Introduction

1.1. Formula Student



Figure 1: Teams in Formula Student Germany 2014 [1]

Formula Student is the most recognized automotive-related constructor contest in Europe, in which teams of university and academy students compete with each other in designing and building race cars. Several countries of the continent host such races, e.g. the United Kingdom in Silverstone, Germany in Hockenheim, Austria in Melk, Italy in Fiorano, Russia in Moscow, Spain on the Circuit de Catalunya and Hungary in the Győr-Gönyű Harbour. Behind these events stand key-significant companies and high-profile professionals such as Shell or Ross Brawn, team principal of MERCEDES AMG PETRONAS. The main goal of this competition is to inspire participants and train adventurous, innovative young engineers.

On a race weekend, 40% of the maximum possible score can be obtained in the so-called static events through presentations that involve the general and technological design, cost and sustainability of the car, as well as the team's business model. If the car meets the mechanical and safety requirements specified by Formula SAE, the teams can showcase their strengths on the track against each other by/during the dynamic events.



1.2. BME Formula Racing Team

Our team, the BME Formula Racing Team was founded at the Budapest University of Technology and Economics in 2007 with the purpose of taking part in the Formula Student competition and making a tradition in Hungary. **In its six years of existence, the team has already built 9 race cars.** Over this span of time more than 350 students have participated in designing, procurement, manufacturing, assembly and other important areas such as logistics, management and economical administration. As of now, the team operates with 65 active members, most of them are mechanical-, electrical-, transportation engineering and economics students.

In 2011 the team presented its first car with an electrical drivetrain. In 2012, taking over key design elements of the combustion car, a new model was built which was 44% lighter in weight than the previous one. Other approaches in the last couple years the BME Formula Racing Team started to develop race cars in two years periods. Last year in 2013 - after a generation shift and setting electric car development as main goal of the team - we created a brand new car: electric drivetrain, hybrid chassis (with carbon composite monocoque which is considered unique in Hungary), CAD-designed wire harness, etc. The 2014 season was the second year of the period. This was the year when we evaluated the results of the previous year, redesigned many components while we kept those, that performed perfectly. We also remanufactured most the components. The connection between the last year's FREC-003 and the new FREC-004 is undeniable but the successor is a much more reliable, mature and well tested construction.

Our aim was the development of the car with an emphasis on aerodynamics and electronics.

We find it important to integrate the team's activity in our studies at the university, form a tighter bond with crucial departments and industrial companies, gain recognition of teachers and representatives of professions, and also popularize our organization amongst other students and a bigger audience. Based on the design processes of our cars more than 25 individual semester projects, 3 FISITA Student presentations, 44 SSA projects and 30 theses were made. These projects in themselves represent a high professional level, but also emphasize the team's general know-how.



Figure 2: Formula Student Hungary Awards Ceremony, Győr, August 2013

1.3. *The role of wings*

Racing has a simple rule: go around the track faster than the others. To achieve this you must move quicker, have more acceleration and less mass to work with. With this philosophy you must have more power and as minimal weight as possible, but you can't do anything with more power if you don't have enough grip and can't get the power work on the track through the tyres. You can achieve more grip if you increase the load on the tyres, for this the team has two ways: increase the weight or have some other way to generate force acting downwards. The first one obviously a foolish solution, because the heavier car surely won't go faster than the lighter, this can be analysed through many vehicle dynamical point of view, but this isn't the topic of the essay. The subject of this essay is in fact the other solution, having more grip on the tyres through aerodynamic downforce.

The role of the aerodynamic package on a race car may sound simple: generate downforce. This might be a good theory but soon it becomes very clear that this can't be achieved easily, downforce goes hand in hand with drag. A much more complex criteria system must be set for the different parts of the aerodynamic package. The detailed criteria for the different aerodynamic elements can be seen in the following.

1. Front wing

- a. Don't have a negative effect on the rear wing.

- b. Provide sufficient airflow to the radiators, brake coolers and the diffuser.
- c. Generate sufficient downforce with the least possible drag for better vehicle, while decreasing the total drag of the vehicle.

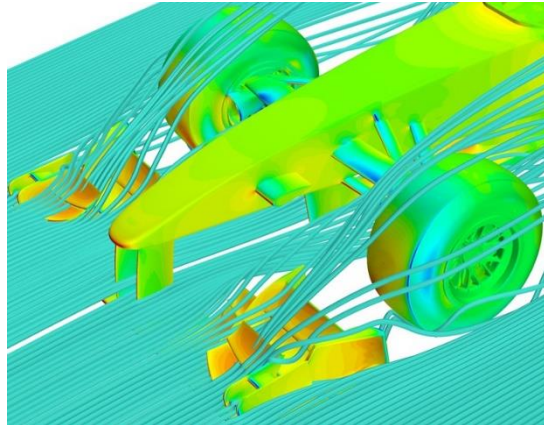


Figure 3: Airflow around a Formula 1 car's front wing [2]

2. Bodywork

- a. Have an aerodynamic shape that has minimal drag.
- b. Provide sufficient airflow for different parts as radiators, exhaust system.

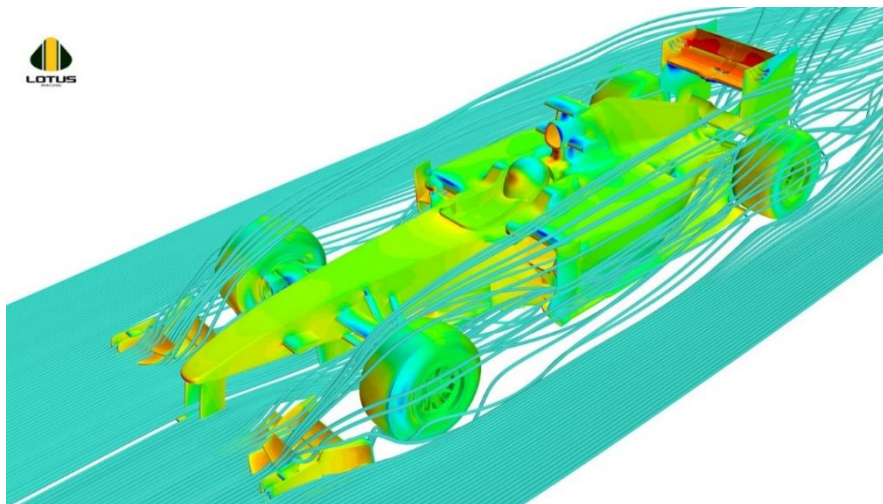


Figure 4: Airflow around Lotus R31 [2]

3. Diffuser

- a. Reduce the total drag of the car.
- b. Generate a sufficient amount of downforce with minimal drag.

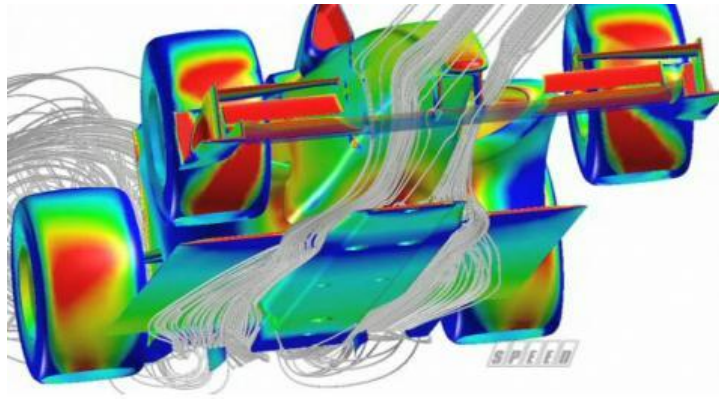


Figure 5: Diffuser of an F1 race car [3]

4. Rear wing

- a. Generate sufficient downforce with minimal drag.

With these in mind a racing team can begin the designing process of the aerodynamic package for a race car. This process is detailed in the next chapter.

1.4. Project Plan

For the BME Formula Racing Team's mechanical engineering section it was the greatest challenge in 2014 to create the aerodynamic package. For such a complicated task, we had to create a well-planned schedule and assign responsible people to all critical roles, and also declare responsibilities precisely

We assigned every different role to the group members depending on their skills. Aerodynamic calculations and track tests were done by Tamás Henczi, and he was also responsible for the development of the geometry. Structural design and FEM calculations were assigned to Ákos Bolyky. The material properties and validation of calculations were done at the Department of Polymer Engineering, the tests lead by Benjámin Bruncsics. Machining of the CNC milled moulds was assigned to Roland Tarcsai and part production was led by Benjamin Bruncsics and Roland Tarcsai.

Overseeing the whole project was the responsibility of Ákos Bolyky.

For the project, we set up a critical path method model and also made a project plan, these can be seen on the images below (**Figure 6**); along with the allocation of separate tasks. For this process we used Smartsheet which's functionality is focused on the ability to organize, share, and update tasks and files.



			Task Name	Durat	Start	Finish	Prez	% Comp	Assigned To	Status
1079			2014	233	2013.09.30.	2014.08.1		69%		Complete
1080			FREC-004	216	2013.09.30.	2014.07.28.		79%		Complete
1081			Electronics	181	2013.09.30.	2014.06.09.		57%	Czikó Ádám	In Progress
1781			Mechanics	215	2013.10.01.	2014.07.28.		98%	Nagy Alex	Complete
1782			Milestones	133	2013.10.01.	2014.04.03.		100%	Nagy Alex	
1787			Aero	106	2013.11.01.	2014.03.28.		100%	Bolyky Ákos	Complete
1788			Milestones	51	2013.11.01.	2014.01.10.		100%		
1789			Skeleton freez	1	2013.11.01.	2013.11.01.		100%	Tamás Henczi	
1790			Design dreez	1	2014.01.10.	2014.01.10.		100%	Tamás Henczi	
1791			Modelling and simulation	46	2013.11.01.	2014.01.03.		100%	Bolyky Ákos	
1792			Front wing	16	2013.11.01.	2013.11.22.		100%	Bolyky Ákos	
1793			Rear wing	16	2013.11.22.	2013.12.13.		100%	Bolyky Ákos	
1794			Undertray	16	2013.12.13.	2014.01.03.		100%	Bolyky Ákos	
1795			Car balance settings	6	2014.01.03.	2014.01.10.		100%	Tamás Henczi	
1796			Manufacturing	38	2014.01.30.	2014.03.24.		100%	Benjamin Brun	
1797			Első szárny felfogatás	37	2014.01.30.	2014.03.21.		100%	Roland Tarcsa	
1801			Hátsó szárny felfogatá	36	2014.01.30.	2014.03.20.		100%	Roland Tarcsa	

Figure 6: The project in Smartsheet

With constant consultation between the composites and aerodynamic crew we managed to complete this project. The finished project is presented in this thesis.



2. Aerodynamics

2.1. Restrictions from the rules

In this chapter I'm going to discuss the restrictions set by the 2014 Formula SAE Rules. These restriction can be found in "Article 2: General Requirements" and in "Article 9: Aerodynamic Devices".

Rules affecting the aerodynamic package are:

1. The top 180 degrees of the wheels/tires must be unobstructed when viewed 68.6mm above the plane formed by the tops of the front and rear tires.
2. The wheels/tires must be unobstructed when viewed from the side.
3. No part of the vehicle may enter a keep-out-zone defined as a circle 68.6mm larger radially than the outside diameter of the tire with the tires steered straight ahead with a 77kg driver seated in the normal driving position. The inner sidewall of the tire (vehicle side) is not included in this assessment.
4. In plain view, no part of any aerodynamic device, wing, under tray or splitter can be:
 - a. Further forward than 762 mm forward of the fronts of the front tires
 - b. No further rearward than 305 mm rearward of the rear of the rear tires.
 - c. No wider than the outside of the front tires or rear tires measured at the height of the hubs, whichever is wider.
5. All wing edges including wings, end plates, Gurney flaps, wicker bills and undertrays that could contact a pedestrian must have a minimum radius of 1.5 mm.
6. No power device may be used to move or remove air from under the vehicle except fans designed exclusively for cooling. Power ground effects are prohibited.
7. Egress from the vehicle within the time set in Rule T4.8 "Driver Egress," must not require any movement of the wing or wings or their mountings.
8. The wing or wings must be mounted in such positions, and sturdily enough, that any accident is unlikely to deform the wings or their mountings in such a way to block the driver's egress.

9. The Tractive-System-Active Light (red light on top of the main hoop continuously flashing with a frequency between 2Hz and 5Hz) must be clearly visible from every horizontal direction, except small angles which are covered by the main hoop, even in very bright sunlight. The TSAL must be visible by a person standing up to 3m away from the TSAL. The person's minimum eye height is 1.6m.

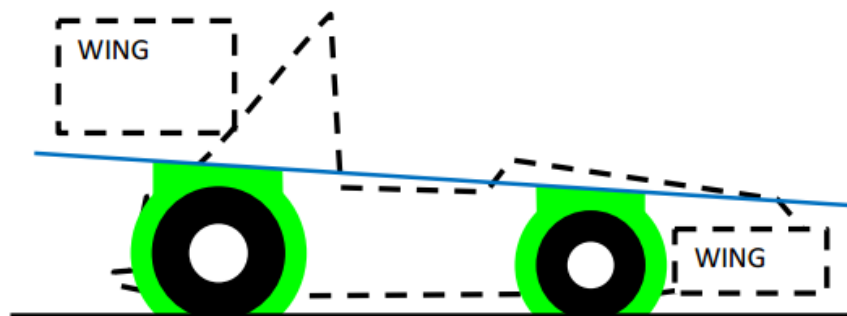


Figure 7: Representation of the restrictions set by the rules [4]

2.2. Analysing the FREC-003 base car

To be able to design wings that improve a car you first have to understand the still wingless car's properties. For this I had to analyse the wingless car to get the drag and downforce coefficients. The steps for the CFD analysis are: creating the model, generating the mesh, setting the numerical parameters for the simulations, and finally examining the results.

The parameters of the car can be seen on the picture and the table below:

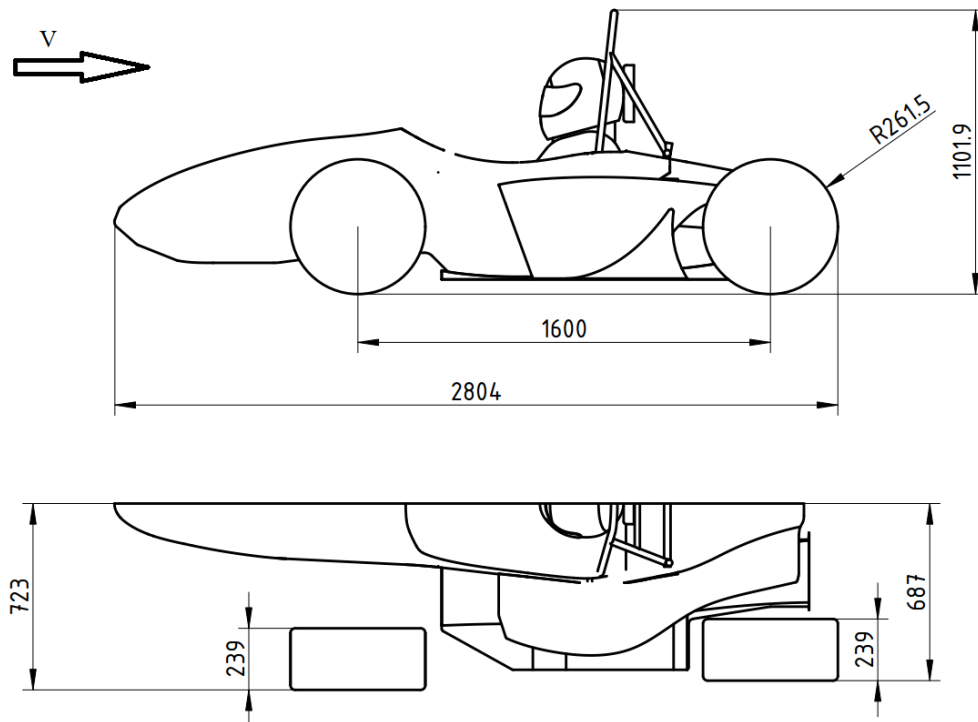


Figure 8: The base car's parameters

Property	Size [mm]
Length	2804
Wheelbase	1600
Height	1101,9
Wheel diameter	523
Wheel width	239
Front track	1207
Rear track	1135

Figure 9: The base car's properties

Property and notation	Size
Speed: V	20 [m/s]

Reference drag area: A_{ref}	0,555 [m ²]
Air density: ρ	1,225 [kg/m ³]
Dynamic viscosity: μ	15,329 [Ns/m ²]
Reference length: L	2,804 [m]
Reynolds-number	3660000 [-]

Figure 10: The reference values

2.2.1. *Creating the model*

As mentioned above the first step is creating the model for the analysis. The model from which I created the model for the analysis is the final CAD model of the FREC-003, the team's race-car of the season 2013. I thank here to Béla Székely for delivering me the model of the vehicle.

Analysing this model would be too complex, because the car consists of many parts with different sizes and curvatures. Further difficulty is that there are aerodynamic parts - like the chassis - , and many non-aerodynamic, so called blunt parts - like the tubular space-frame, suspension parts, and the pilot himself - , in the model at the same time.

Because a model containing even the last screw is way ahead of my computational capacities (PC-wise), I needed to simplify the car's model. For this I used the Creo Parametric 2.0 CAD program.

I used the following simplifications:

1. I replaced the pilot with a simple chest and helmet model.
2. I closed the cockpit opening, erased the dashboard buttons and the steering wheel.
3. I cut the car's model in half.
4. I erased the complex parts from the model: drivetrain, suspension.
5. I simplified the wheel: instead of the carbon-aluminium composite wheel and the rubber tyre, I used a cylinder.

6. Further simplifications on the rear of the car: I substituted the tubular space-frame and the motors, accumulator, electronics, etc. in it with a one-piece solid model.

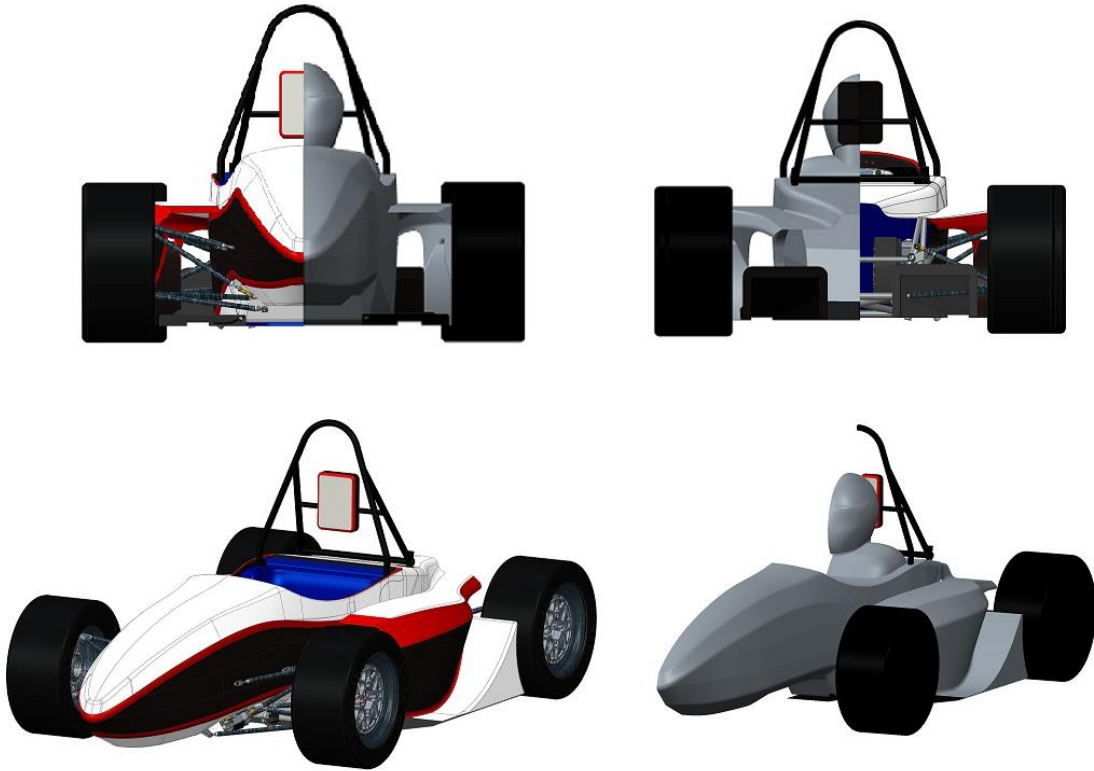


Figure 11: The original and the simplified CAD model

7. After this I imported the geometry in the Ansys Workbench 14.0 Design Modeler to further simplify the model. With the Merge, Repair Edge and Repair Face functions I reduced the number of small surfaces and edges.
8. I defined the computational volume for the car, and created the negative of the car with the proper tyre contact patches.

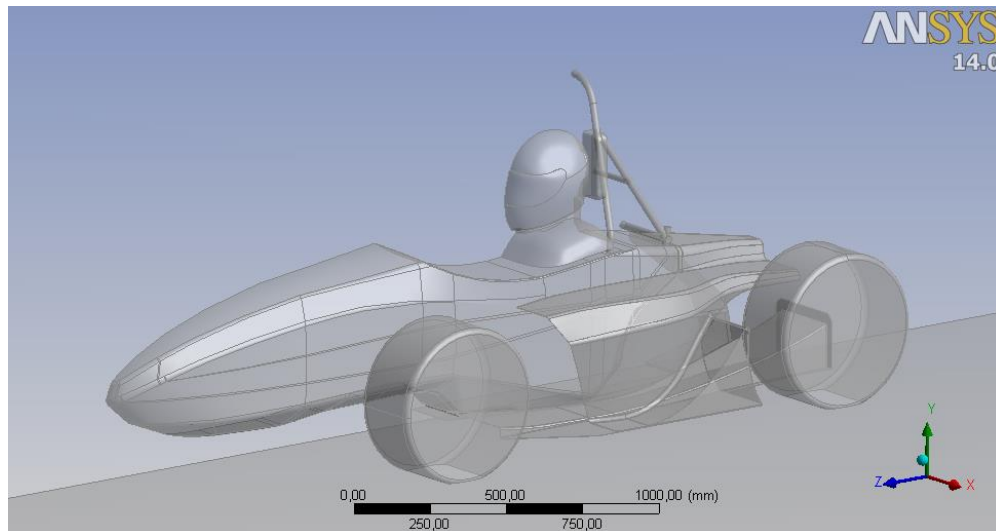


Figure 12: The negative of the simplified geometry

2.2.2. Generating the mesh

To reach the correct accuracy during the simulations I had to generate a proper mesh of good quality and density. Considering my computational capacity I had to try many different setting to find the optimum in mesh size and quality.

The mesh finally generated consisted of 3.7 million tetrahedral element from which I generated a polyhedral mesh with 840 thousand elements. The meshes can be seen below:

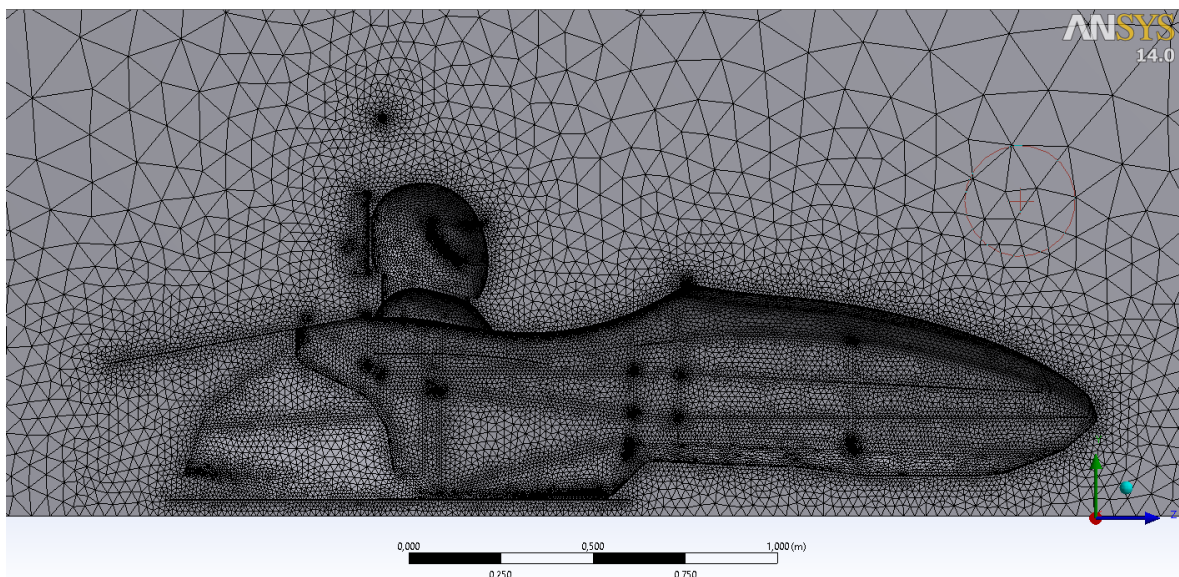


Figure 13: The original tetrahedral mesh generated for the model

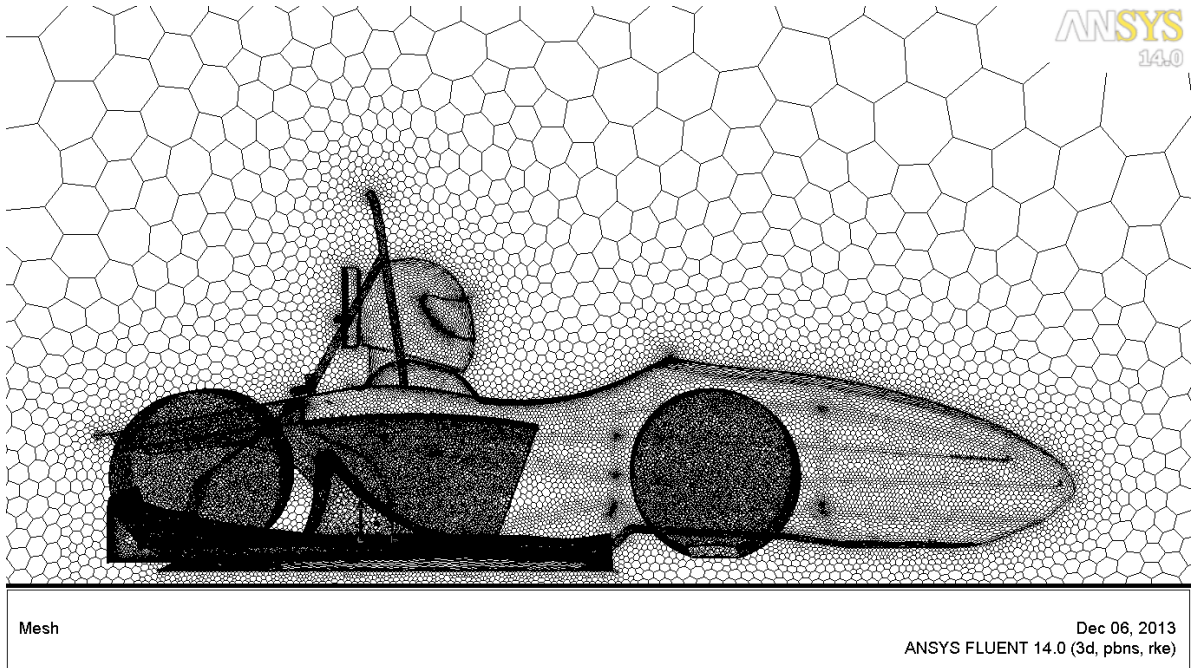


Figure 14: The polyhedral mesh

2.2.3. Numerical settings

I used the following settings for the simulations:

- Steady state analysis for 200 iterations, then Transient calculations with timesteps of 0.0005, maximum number of iterations were 25 per timestep.
- Turbulence model: Realisable k-epsilon with Enhanced Wall Treatment.
- Material: constant density air.
- No energy equations included in the calculations.
- Boundary conditions:
 - “symmetry” on both sides and on the top of the model
 - “velocity inlet” on the inlet side to set the vehicle’s speed.
 - “stationary wall” on the ground to match the parameters of the windtunnel experiment.
 - “outflow” on the back of the model.

2.2.4. Result of the CFD analysis

The residuals of the simulation showed good convergence. The results of the simulations are:

- Drag coefficient: $c_d=0.51$ [-]
- Downforce coefficient: $c_l=-0.215$ [-] (the car generates lift)

In the following I show some pictures of the completed calculations and describe them.

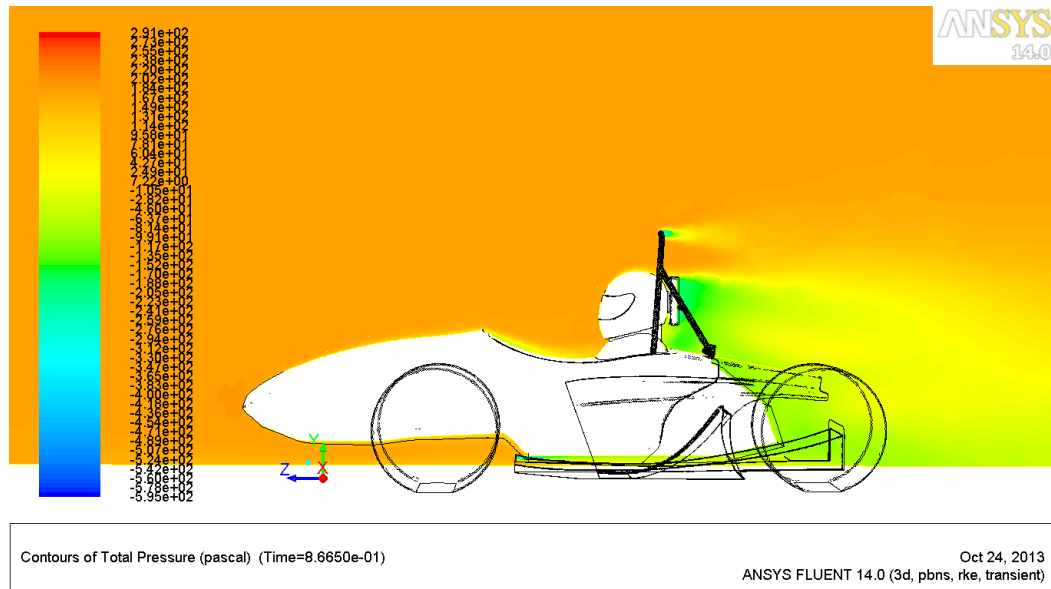


Figure 15: The total pressure visualised on the symmetry plane

On the picture above and below you can see the separations on the FREC-003, these turbulent areas add much to the vehicle's drag coefficient. The areas on the symmetry plane show the possible improvements: aerodynamic head restraint a more aerodynamic rear part of the car could decrease the car's drag significantly.

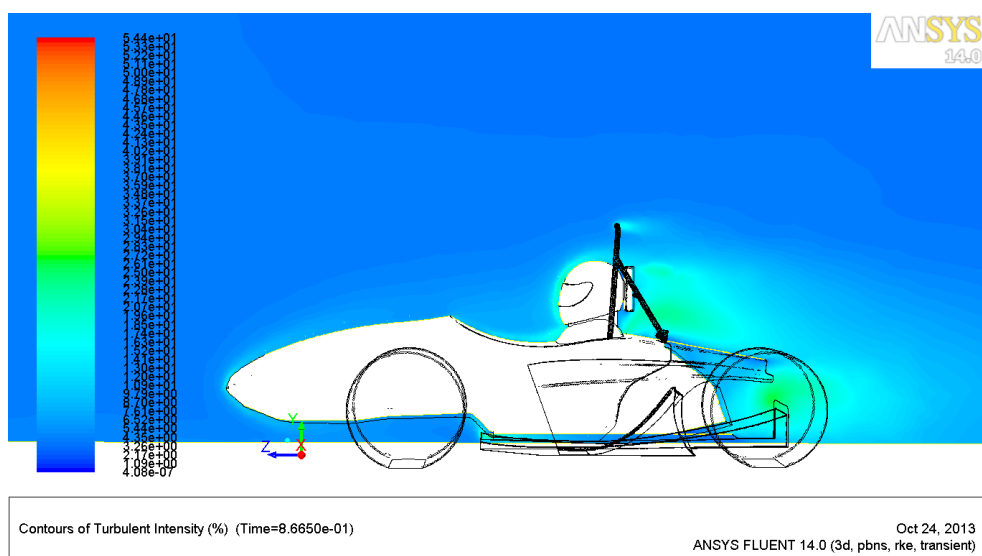


Figure 16: The turbulent density visualised on the symmetry plane

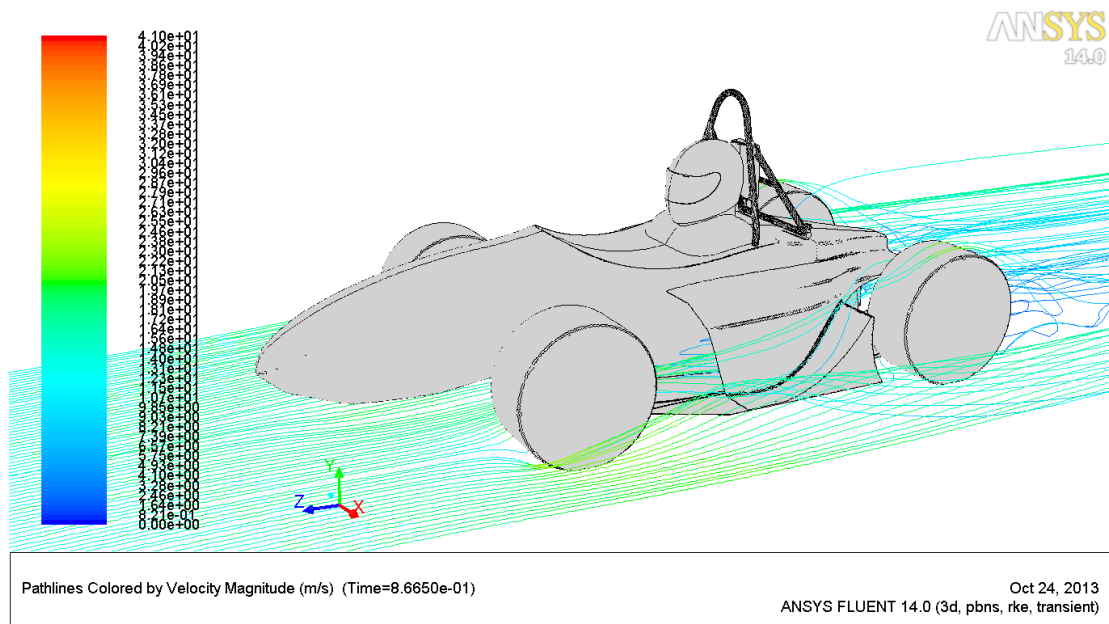


Figure 17: Airflow around the base car (1)

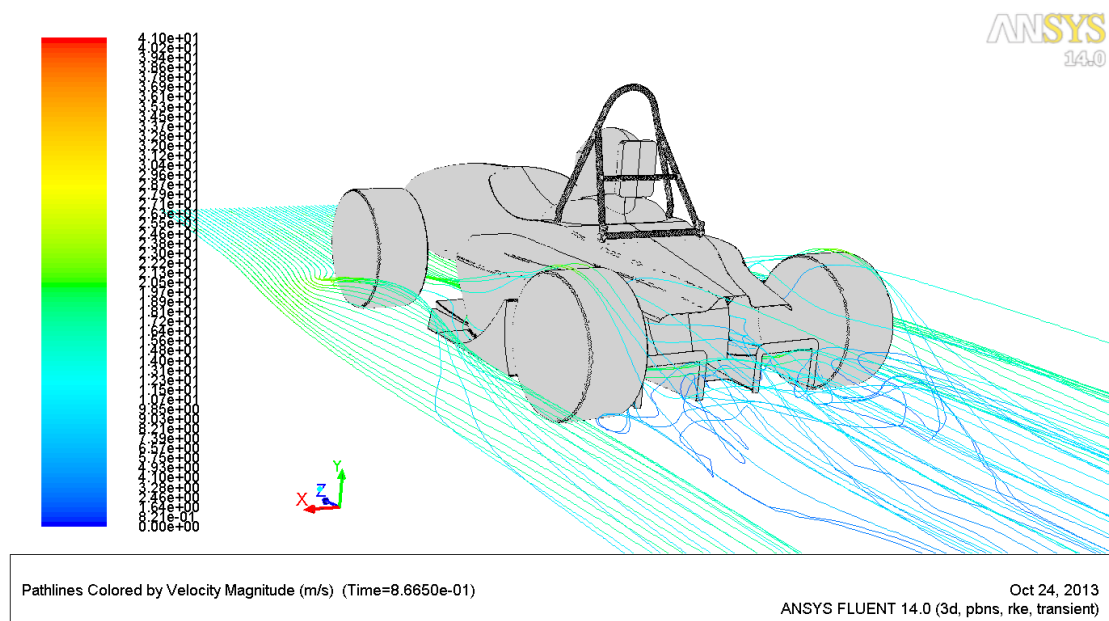


Figure 18: Airflow around the base car (2)

On the pictures above showing the streamline show that the side-pod completes its function properly, because it deflects the air off of the rear wheels, thus decreasing the drag. The streamlines also show, that the front wheels generate a vortex on the outer side which adds to the vehicle's drag significantly. This effect could be neutralized with the use of a front wing.

2.2.5. *Windtunnel experiments*

The BME Formula Racing Team performed a windtunnel experiment on the 27th of September in 2013. The purpose of this experiment was to validate the car's calculated drag coefficient from the CFD analysis. The team tested several configurations and setups of the car, but I'm only showing the relevant values needed for the validation of the CFD analysis.

As mentioned in the previous chapter the drag coefficient of the base car was 0.51 [-]. Through the windtunnel experiment we determined a drag coefficient of 0.636 [-]. The calculated drag is 19.8% smaller than the one determined with the experiment, this difference can be explained:

- The simplifications of the CFD model decrease the calculated drag.
- The accuracy of the measured drag was not known.
- The configuration measurement can have a great effect on the measured data.
- The cross section area of the car was too large compared to the windtunnel's, the ratio was more than 20%.

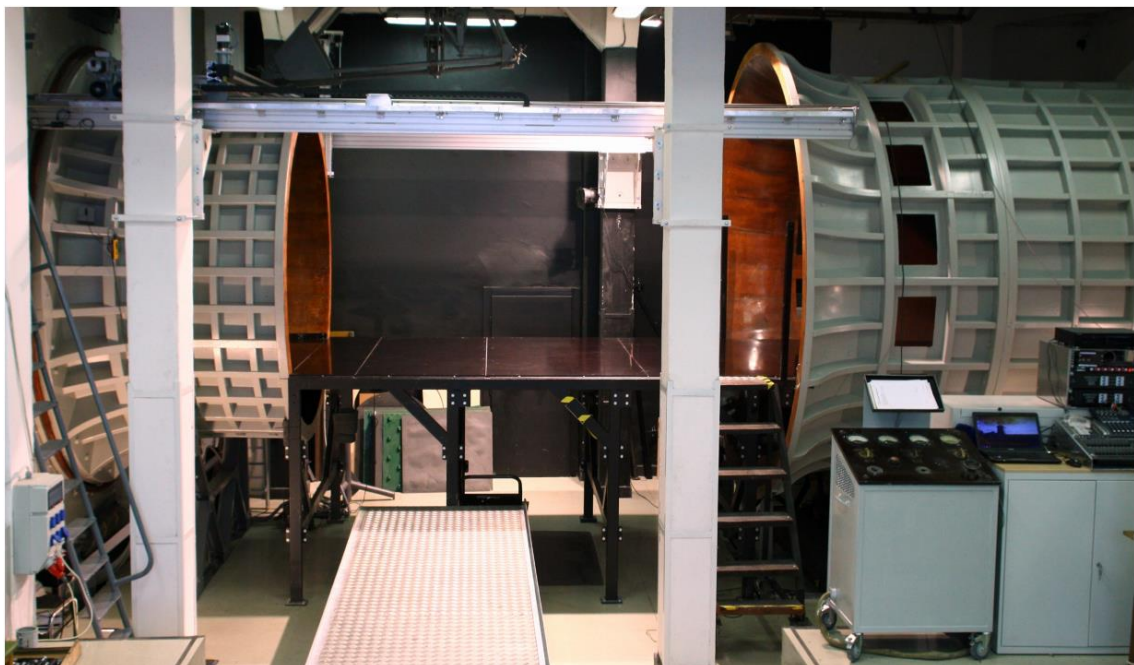


Figure 19: The Kármán Tódor windtunnel

2.3. Competitor analysis

In this chapter I'm going to show the concepts used by other teams. I'm only going to show the electric cars' aerodynamic packages because the wings used on the combustion engine cars generate too much drag to be used on an electric car. The pictures below represent this difference between KA-Racing's KIT 14e electric and KIT14c combustion engine cars.

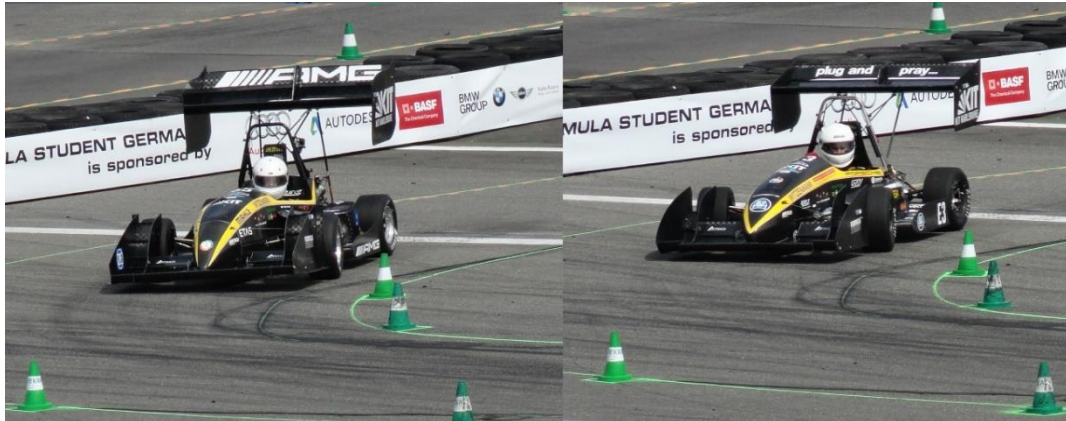


Figure 20: The difference between KA-Racing's combustion engine and electric car (1)

The rear wing of the combustion car consist of 3 elements with great angle of attack with large camber and chord length, while the front wing consists of 4 elements. Through this design they manage to get high downforce values but they also generate a lot of drag possibly. The aerodynamic package design of the electric car show completely other aspects: 2 element rear wing with low angle of attack and low camber, and also the front wing has only 3 elements.

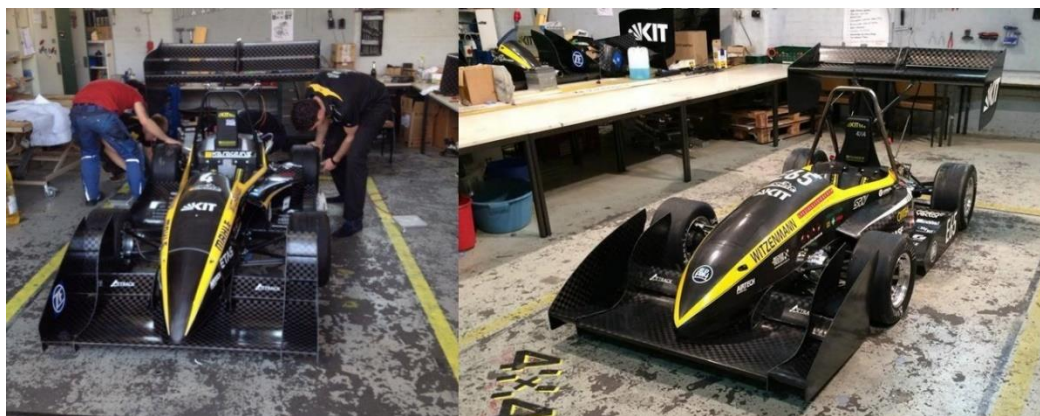


Figure 21: The difference between KA-Racing's combustion engine and electric car (2)

In the following I'm going to introduce the most complex and most minimalist electric cars of the Formula Student Germany 2014 competition. On the next image you can see "grimsel", the 8th car of the Academic Motorsports Club Zurich (AMZ). The team uses a 3 element front wing with a main element and 2 flap elements. On the rear wing they also use 3 elements, but instead of the "main+2 flaps" concept they use a slat, a main and a flap element. With this solution they can have a big combined chamber on the wing with low angle of attack, thus large amount of downforce with relatively low drag ratio. Another feature of the car are the rear tire wings on the side-pods which reduce the drag of the car. Their diffuser is also more advanced than most of the teams, they use a 3-channel diffuser with 1-1 channels below each side-pod and 1 below the car going straight to the back of the car.



Figure 22: AMZ's 4 wheel drive electric car

The car seen on the next picture is DUT Racing Team's "DUT14". The car is around 155kgs, the aerodynamic package represents this light-weight design of the car: the wings are small, have small chord length, camber and also low angle of attack rates. The diffuser is also really simple with 3 trays, 1-1 at each sides (I can't write side-pods, because aren't any), and 1 below the car. The whole aerodynamic package generates minimal drag with the just right amount of downforce. Simple and light-weight.



Figure 23: DUT Racing Team's electric car

2.4. Designing the aerodynamic package

In this chapter I'm going to show the design process of the aerodynamic package for the BME Formula Racing Team's 2014 season car, the FREC-004. The process consists of three major steps: setting the requirements for the aerodynamic package, designing the front wing and designing the rear wing.

2.4.1. Setting the requirements

To design the aerodynamic package best suited for the car we made multiple lap-time analyses to determine the best downforce-drag ratio for the car, which was simple: as high as possible. Because we can't get a ratio of infinite we needed to get a goal to focus on. This goal was set to 2.5, because that's the average downforce-drag ratio of a Formula 1 car. This might sound impossible, but we thought this to be achievable because an F1 car has to live up to even more rules than a Formula Student car, we have the freedom to utilize our creativity. With this goal, the 2.5 downforce to drag ratio we had our designing target.

Another aspect of designing an aerodynamic package is the balance of the car. One part of this balance is the weight balance which determines the center of gravity of the car. The other half of the balance is the aerodynamic balance which is also very important to think of while designing a car, it determines the pressure center of the car. The following picture shows the aerodynamic force distributions on an F1 car.

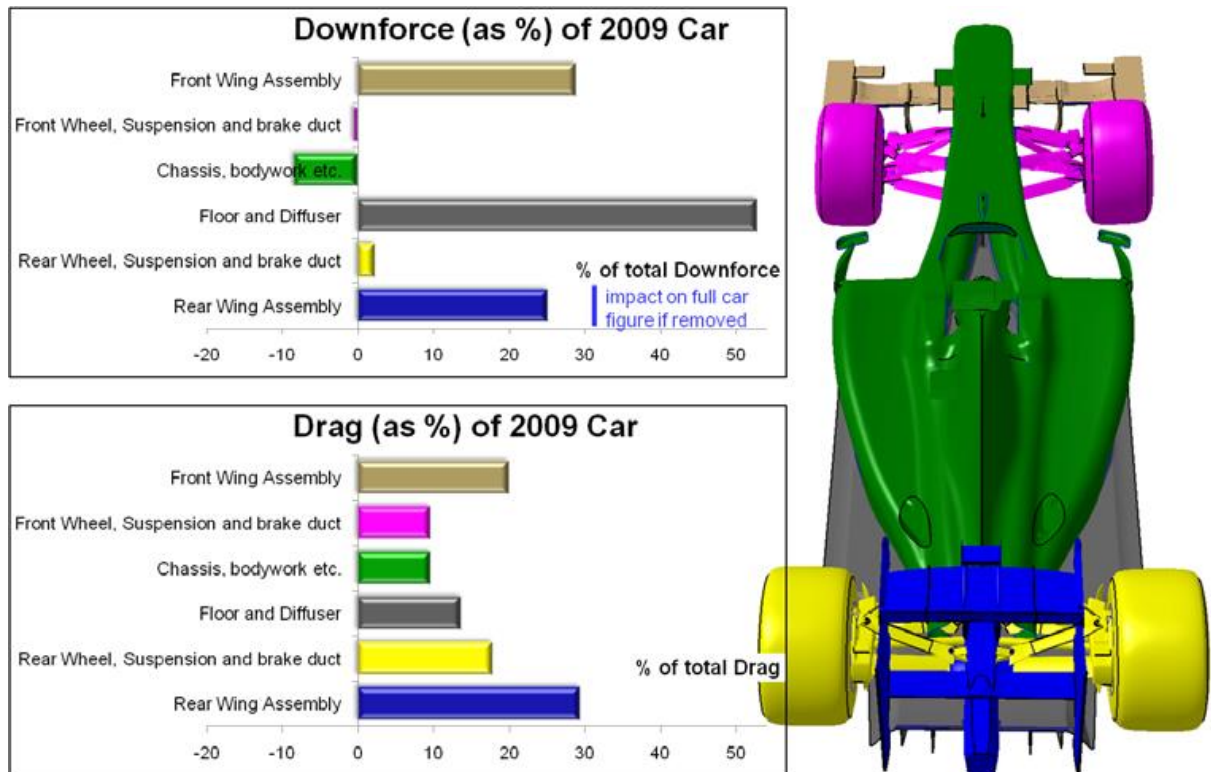


Figure 24: The downforce and drag distribution on an F1 race car [5]

Comparing the front and rear wing we can see that the front wing has a higher downforce to drag ratio than the rear wing. This is because of the aerodynamic balance which has the following components to consider:

1. If the car has too high downforce on the front wing compared to the rear wing the car becomes over-steered, while if the car has too high downforce on the rear wing compared to the front wing the car becomes under-steered.
2. If the car has too much drag on the rear wing it also influences the aerodynamic balance because it tries to raise the car's nose, it becomes under-steered. If the car has too high drag on the front wing it tries to raise the rear of the car, it becomes over-steered.

Note: The diffuser has a very high downforce to drag ratio so it doesn't influence the car's balance significantly because the high downforce gets balanced out with the drag of the floor.

Conclusion: a good aerodynamic balance must be kept. This doesn't mean that a front wing with better downforce-drag ratio must be designed, it means that we must balance out the forces of the wings to keep the car's steering uninfluenced.

2.4.2. *Front wing*

In this chapter I'm going to show the development of the front wing. The designing process consisted of 2 major steps: finding an optimal 2D airfoil assembly and creating an optimal 3D wing geometry.

For an optimal 2D airfoil assembly I had to analyse several multi-element wing design. At first I analysed 2-element wing assemblies consisting of a main and a flap element. In the first case I used NACA4415 main element with 4415, 7415 and 9415 flap element and I observed the effect of the flap element's angle of attack and relative position to the main element. On the following tables I show the results of these simulations.

Version	Position (X;Y) [mm]	Angle of Attack [°]	cd	cl	cl/cd
v1.1	320; 120	10	0,0576	1,1646	20,2160
v1.2	340; 120	15	0,0778	1,4803	19,0279
v1.2.5	340; 115	15	0,0903	1,7072	18,9131
v1.3	360; 120	17.5	0,1038	1,8187	17,5212
v1.3.5	360; 115	17.5	0,1336	2,0366	15,2410
v1.4	370; 120	20	0,0760	1,4021	18,4548
v1.4.5	370; 112.5	20	0,0877	1,6265	18,5468
v1.5	380; 120	25	0,0973	1,7169	17,6490
v1.5.5	380; 110	25	0,1227	1,8698	15,2416

Figure 25: 4415 main element with 4415 flaps



Version	Position (X;Y) [mm]	Angle of Attack [°]	cd	cl	cl/cd
v1.1	320; 120	10	0,0622	1,2017	19,3134
v1.2	340; 120	15	0,0871	1,5734	18,0575
v1.2.5	340; 115	15	0,0998	1,7881	17,9094
v1.3	360; 120	17.5	0,1134	1,9463	17,1694
v1.3.5	360; 115	17.5	0,1451	2,1714	14,9648
v1.4	370; 120	20	0,0780	1,4317	18,3458
v1.4.5	370; 112.5	20	0,0925	1,6910	18,2727
v1.5	380; 120	25	0,1019	1,7835	17,4978
v1.5.5	380; 110	25	0,1292	1,9813	15,3315

Figure 26: 4415 main element with 7415 flaps

Verzió	Pozíció (X;Y) [mm]	Angle of Attack [°]	cd	cl	cl/cd
v1.1	320; 125	10	0,0716	1,3400	18,7156
v1.2	340; 125	15	0,0978	1,6766	17,1406
v1.2.5	340; 120	15	0,0902	1,57447	17,4616



v1.3	360; 125	17.5	0,1114	1,9144	17,1823
v1.3.5	360; 120	17.5	0,1059	1,8342	17,3244
v1.4	370; 125	20	0,1258	2,0941	16,6521
v1.4.5	370; 117.5	20	0,1175	1,9654	16,7254
v1.5	380; 120	25	0,1545	2,2895	14,8210
v1.5.5	380; 115	25	0,1481	2,1712	14,6650

Figure 27: 4415 main element with 9415 flaps

There are two conclusions to be stated: with equally well angled and placed flap element the element with more camber generates more downforce and naturally more drag. Because of the very high downforce-drag ratios I can say that the NACA9415 should be used as flap element.

As the next step I'm going to choose the best main element for the 9415 flap element. For this I examined three main elements: NACA 2415, 3415 and 4415. Other, higher cambered element weren't examined because of the early flow separation.

The results of the main element simulations can be seen below.

	cd	cl	cl/cd
v1.1	0,0716	1,3400	18,7156
v1.2	0,0978	1,6766	17,1406
v1.2.5	0,0902	1,5745	17,4616
v1.3	0,1114	1,9144	17,1823
v1.3.5	0,1059	1,8342	17,3244
v1.4	0,1258	2,0941	16,6521
v1.4.5	0,1175	1,9654	16,7254



v1.5	0,1545	2,2895	14,8210
v1.5.5	0,1481	2,1712	14,6650

Figure 28: 4415 main element with 9415 flaps

	cd	cl	cl/cd
v1.1	0,0726	1,4675	20,2075
v1.2	0,0952	1,8006	18,9189
v1.2.5	0,0928	1,7298	18,6344
v1.3	0,1079	2,0419	18,9276
v1.3.5	0,1064	1,9514	18,3414
v1.4	0,1204	2,2270	18,4957
v1.4.5	0,1186	2,0980	17,6881
v1.5	0,1502	2,3648	15,7494
v1.5.5	0,1481	2,3071	15,5747

Figure 29: 3415 main element with 9415 flaps

	cd	cl	cl/cd
v1.1	0,0693	1,5176	21,8842
v1.2	0,0895	1,8591	20,7611
v1.2.5	0,0896	1,8329	20,4597
v1.3	0,1008	2,1325	21,1652
v1.3.5	0,1021	2,0417	19,9987
v1.4	0,1116	2,2855	20,4733

v1.4.5	0,1139	2,2137	19,4416
v1.5	0,1396	2,5514	18,2749
v1.5.5	0,1424	2,4501	17,2020

Figure 30: 2415 main element with 9415 flaps

Conclusion: the 1.5 version of the NACA2415 main element with a 9415 flap element is the best suited for our purposes because it still has very high downforce to drag ratio and it has the best downforce coefficient.

Main element	Chord length	0,4 m
	Distance from ground	50 mm
Flap element	Chord length	0,2 m
	Position	x=380 mm; y=120 mm
	Angle of Attack	25°
Simulation results	Downforce coefficient	2,55136
	Drag coefficient	0,13961
	Downforce-drag ratio	18,27491

Figure 31: The properties of the best 2-element wing assembly

The best 2-element 2D airfoil assembly.

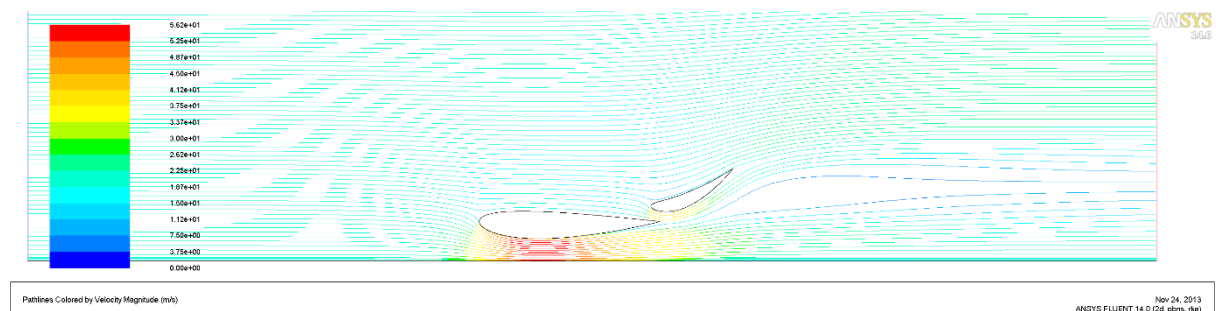


Figure 32: Airflow around the best 2-element wing assembly

I'm going to use this as the base of the 3-element wing assembly analyses. As the second flap element I chose the NACA9415 also. I examined element's effect on the downforce and drag with the different positions and angle of attack values. The following table shows the positions and angle of attacks for the second flap.

Version	X position [mm]	Y position [mm]	Angle of Attack [°]
v2.1	470	200	35
v2.2	480	200	35
v2.3	485	205	35
v2.4	485	205	40
v2.5	500	205	45
v2.6	510	210	50

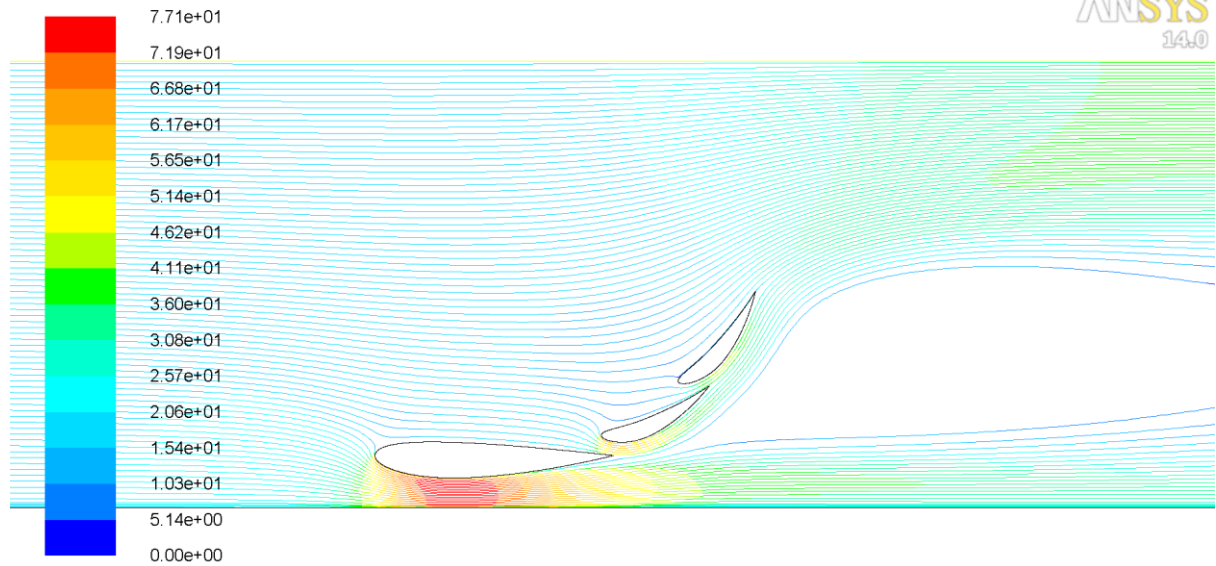
Figure 33: The 3rd flap's positions relative to the main wing's leading edge

The results of the simulations are shown below.

	cd	cl	cl/cd
v2.1	0,5894	3,4048	5,7765
v2.2	0,4696	4,4326	9,4397
v2.3	0,4856	4,5228	9,3138
v2.4	0,5654	4,9430	8,7430
v2.5	0,6801	5,3464	7,8606
v2.6	0,8053	5,8384	7,2500

Figure 34: Simulation results for the different 3-element wing assemblies

The streamlines around the final 2D airfoil assembly can be seen on the picture below.



Pathlines Colored by Velocity Magnitude (m/s)

Nov 24, 2013
ANSYS FLUENT 14.0 (2d, pbns, rke)

Figure 35: The final 3-element front wing assembly with 2415 main and 9415 flap elements

The mesh generated for the best configuration was a 186 thousand element mesh with triangle elements and 2 inflation sets: one on the ground for better ground effect and one on the wing elements for better simulation results.

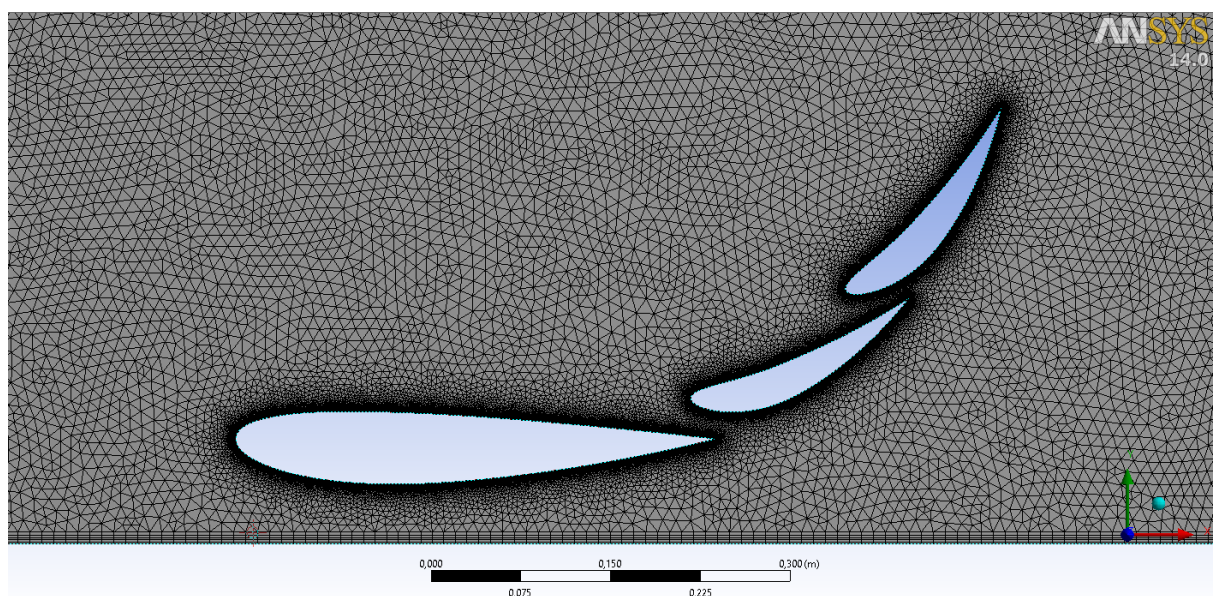


Figure 36: The mesh generated for the wing assembly

With the final 2D airfoil assembly the team could start designing the 3D geometry. The first question was: what sweeping should be used for the leading edges to define the final 3D form?

To answer this question many parameters had to be checked. As first step we checked the effect of forward bent wings. The next picture shows the difference between a normally “extruded” wing design and a forward bent shape.

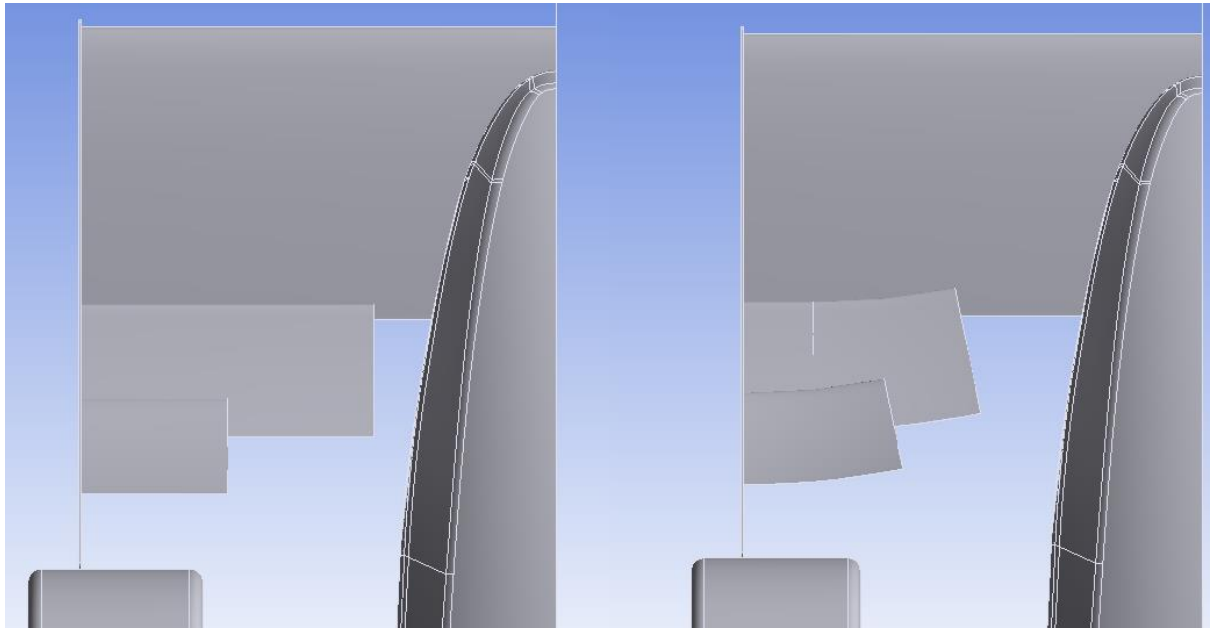


Figure 37: Different 3D front wing designs

After many iterations of the 3D form the simulations showed no improvement in downforce nor in drag. Because of this feature not having any major effect, we decided not to use it to improve the manufacturability of the flap elements.

The next question was the shape of the front wing seen from the front. As it can be seen on this early design the base shape was very simple, it was an assembly from extruding the airfoils.

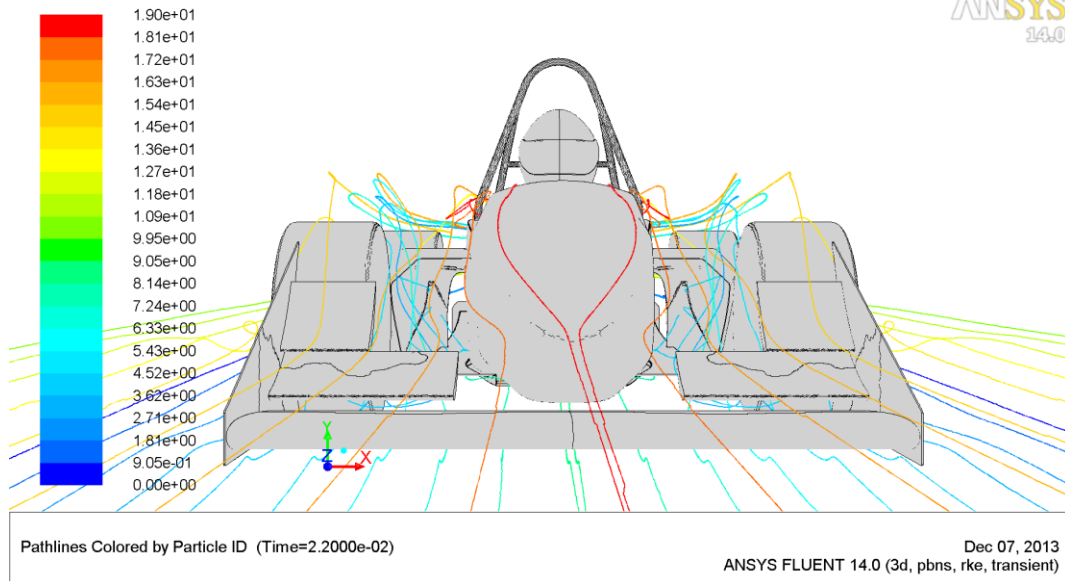


Figure 38: Airflow around a preliminary front wing design

Through hard designing work and many iterations we were able to determine a more optimal geometry for the first wing, which can be seen on the next pictures.

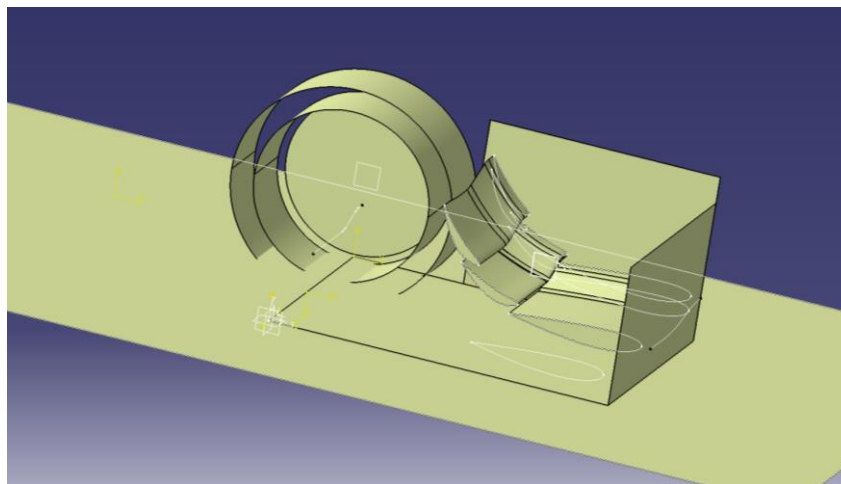


Figure 39: The final front wing design without the endplate (1)

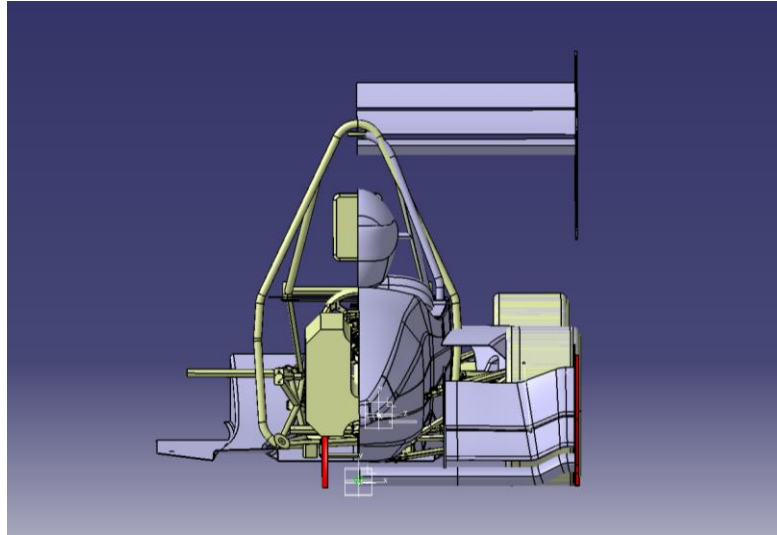


Figure 40: The final front wing design without the endplate (2)

The base idea behind this concept was to bring the airfoil assembly closer to the ground and still have a useful size on the suction side of the endplate. To achieve this we brought the whole assembly down and bent it upwards while maintaining the optimal gaps between the airfoils and thus keeping the endplate in place and shape.

The endplate also plays a great role in the wing design because it determines the main vortexes generated on the wing, thus having a major role in the efficiency. As the next picture shows we examined to major design concepts and many different variations for each version.

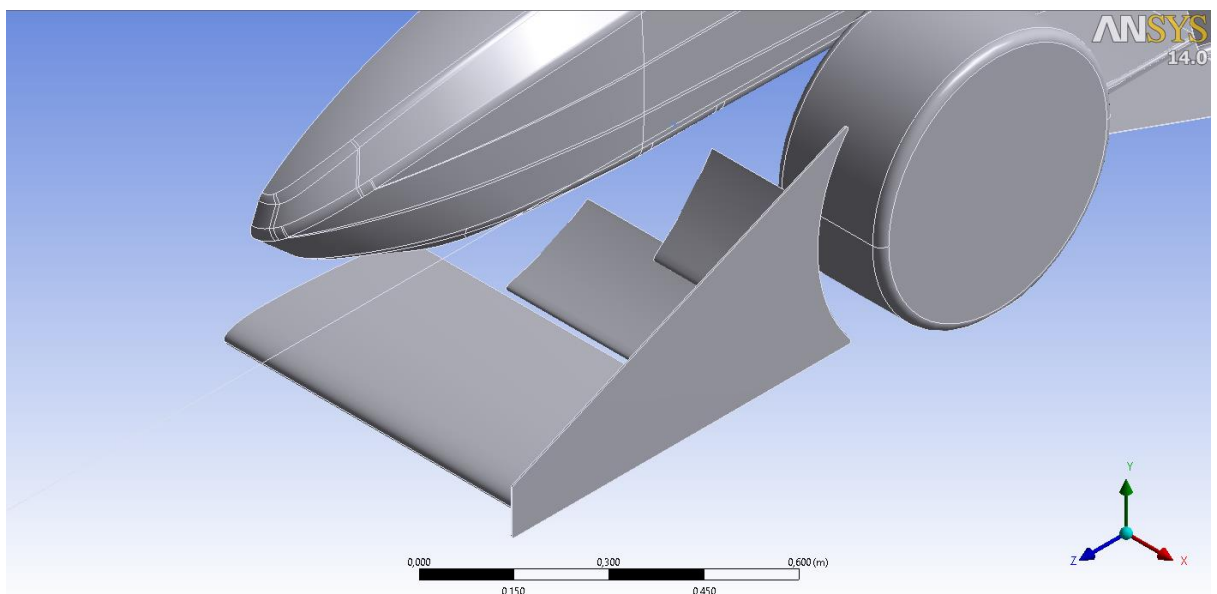


Figure 41: Preliminary front wing endplate design (1)

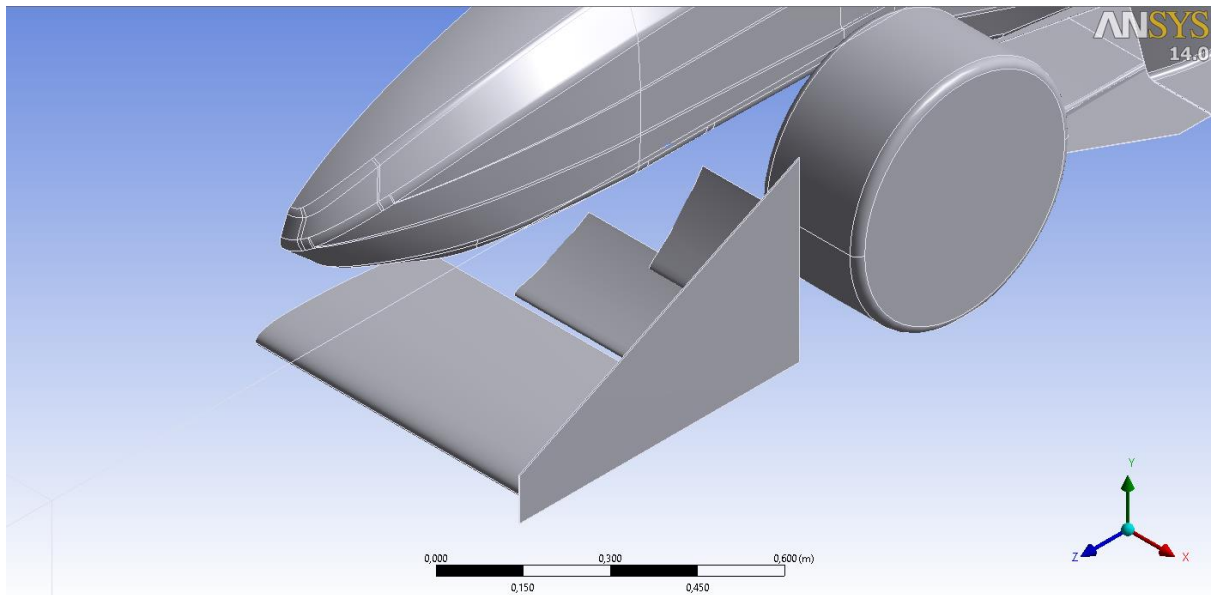


Figure 42: Preliminary front wing endplate design (2)

Through many simulations we managed to get a quasi-optimal endplate shape with which the front wing had minimal drag and maximum downforce. The final endplate can be seen on the next pictures, as well as the final front wing shape.

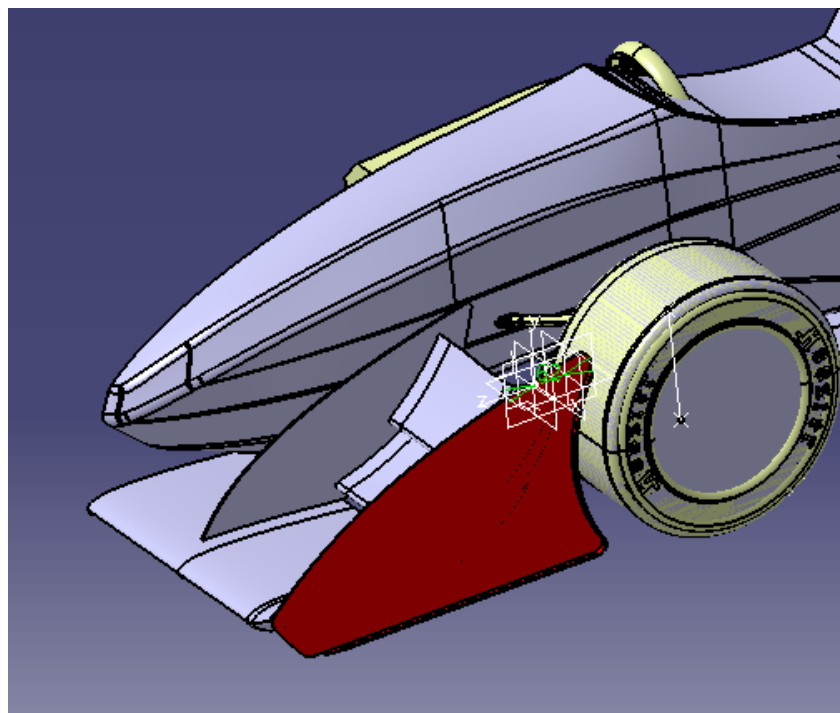


Figure 43: The final front wing design (1)

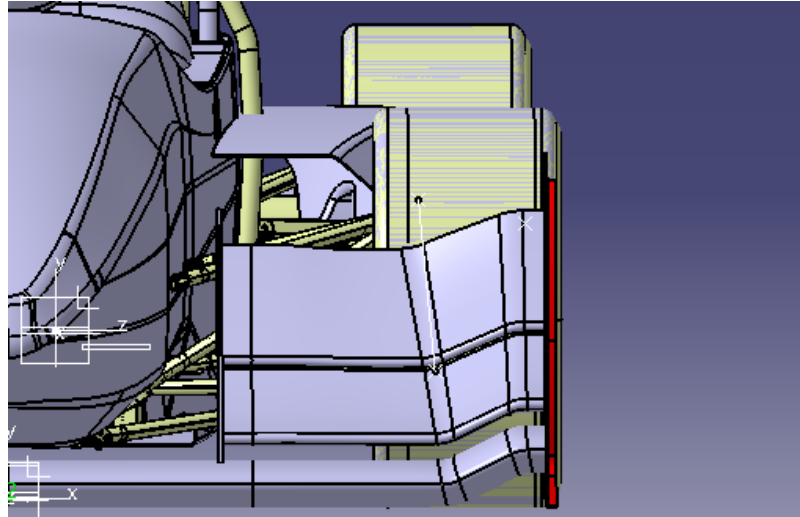


Figure 44: The final front wing design (2)

2.4.3. *Rear wing*

For the 2D optimization of the rear wing the team used another technique, we used the Design Exploration Toolbox of Ansys. For this we determined the following input parameters for the flap element of the rear wing: x and y position relative to main element (trs1x, trs1y, trs2x, trs2y), angle of attack (rot1, rot2). The next picture shows the geometry of the rear wing.

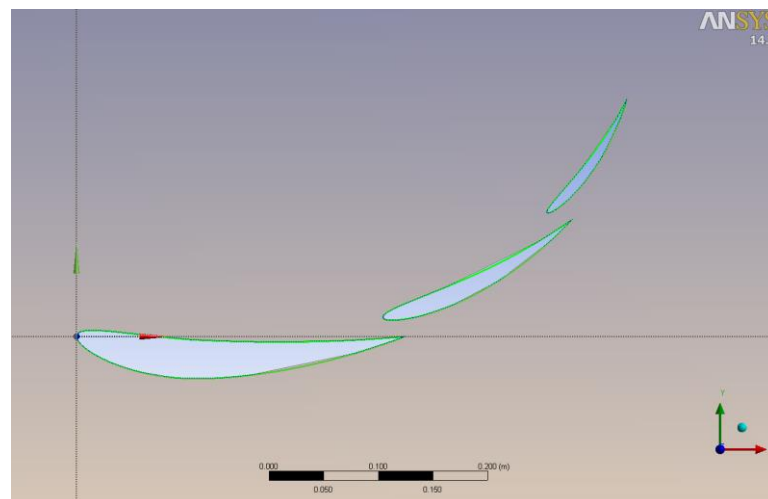


Figure 45: The rear wing's 2D base geometry

For optimization processes we used a mesh consisting of around 42.000 elements depending on the proximity of the flaps to each other. The mesh was built up from triangle elements and 2 inflation sets: one on the ground for better ground effect and one on the wing elements for better simulation results.

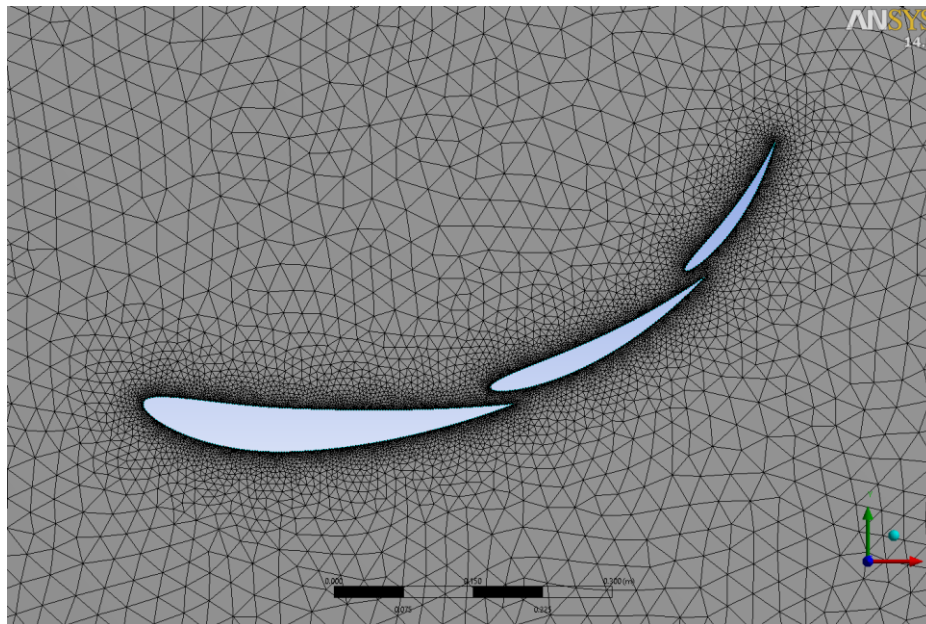


Figure 46: The mesh generated for the 2D rear wing geometry

Through the calculations we were able to create Sensitivity analyses between the input and output parameters. The summary of the Sensitivity analyses is shown on the picture below.

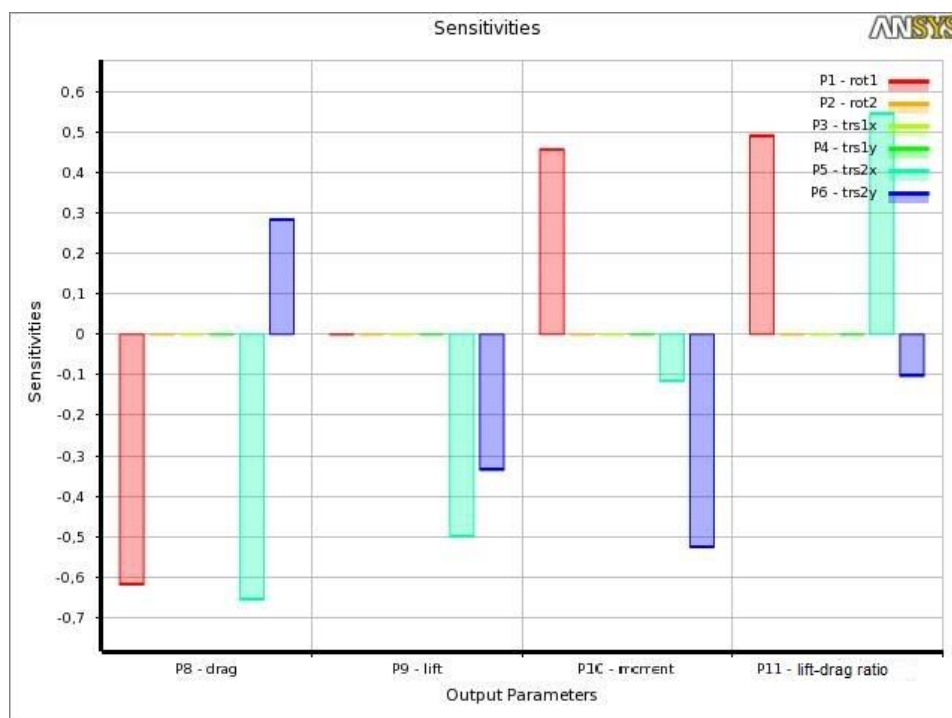


Figure 47: The sensitivity analysis of the rear wing

The picture shows, that for example if the first flap's angle of attack is increased then the drag of the rear wing assembly increases. Another example of the diagram is that if the y position of the second flap is increased then the (negative) lift to drag ratio of the rear wing is decreased. The same sensitivity between the input and output parameters can be seen on the following picture of the Linear Correlation Matrix.

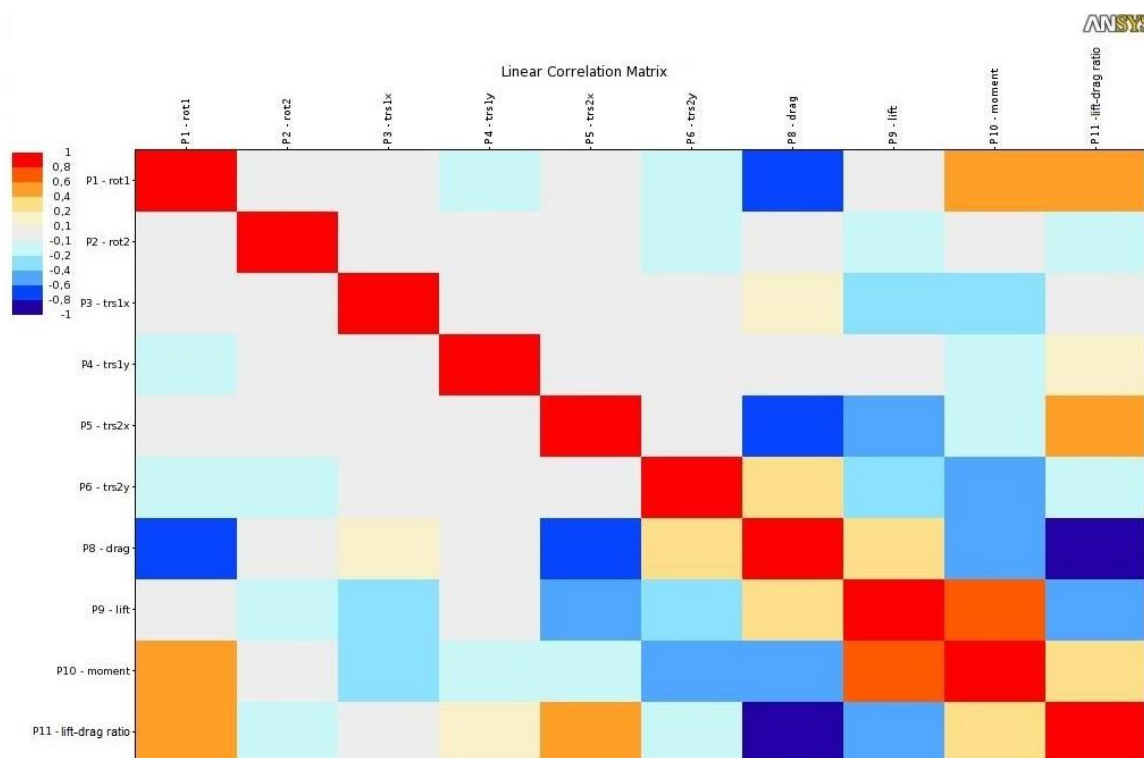


Figure 48: The linear correlation matrix of the rear wing

An example input parameter matrix is shown below with the result of the calculations as well. I marked the results with the highest downforce, the lowest drag and the highest downforce-drag ratio. (In this case the negative value of the lift represents the downforce)

	rot1	rot2	x1	y1	x2	y2	lift	drag	lift-drag ratio
Current	27.500	55.000	0.280	0.017	0.430	0.113	-646.408	40.262	16.055
DP 1	20.000	47.500	0.280	0.017	0.441	0.093	-398.989	23.579	16.922
DP 2	22.500	50.000	0.280	0.017	0.438	0.100	-414.061	25.442	16.274
DP 3	25.000	52.500	0.280	0.017	0.434	0.106	-427.750	27.390	15.617



DP 4	30.000	57.500	0.280	0.017	0.426	0.119	-439.981	31.817	13.828
DP 5	32.500	60.000	0.280	0.017	0.421	0.126	-371.691	38.760	9.589
DP 6	35.000	62.500	0.280	0.017	0.416	0.132	-342.602	52.616	6.511
DP 7	25.000	60.000	0.280	0.017	0.434	0.106	-404.878	29.309	13.814
...									
DP 39	22.500	36.000	0.280	0.017	0.438	0.100	-397.250	20.833	19.068
DP 40	22.500	35.000	0.280	0.017	0.438	0.100	-393.083	20.439	19.232
DP 41	20.000	48.500	0.280	0.017	0.441	0.093	-392.798	23.925	16.418
DP 42	20.000	46.500	0.280	0.017	0.441	0.093	-401.688	23.263	17.268
DP 43	20.000	41.500	0.280	0.017	0.441	0.093	-404.317	21.836	18.516
DP 44	20.000	36.500	0.280	0.017	0.441	0.093	-390.826	20.001	19.540
DP 45	20.000	31.500	0.280	0.017	0.441	0.093	-368.811	18.111	20.364
DP 46	20.000	26.500	0.280	0.017	0.441	0.093	-340.815	16.108	21.158
DP 47	20.000	21.500	0.280	0.017	0.441	0.093	-310.132	14.374	21.575

Figure 49: The results of the 2D optimization process

As with the front wing, the next question was the 3 dimensional geometry of the rear wing. A simple solution was chosen: straight, “extruded” elements. This was chosen because it makes composite designing and manufacturing easier. For better aerodynamic properties a high pressure side console was designed for the rear wing as seen on the picture below.

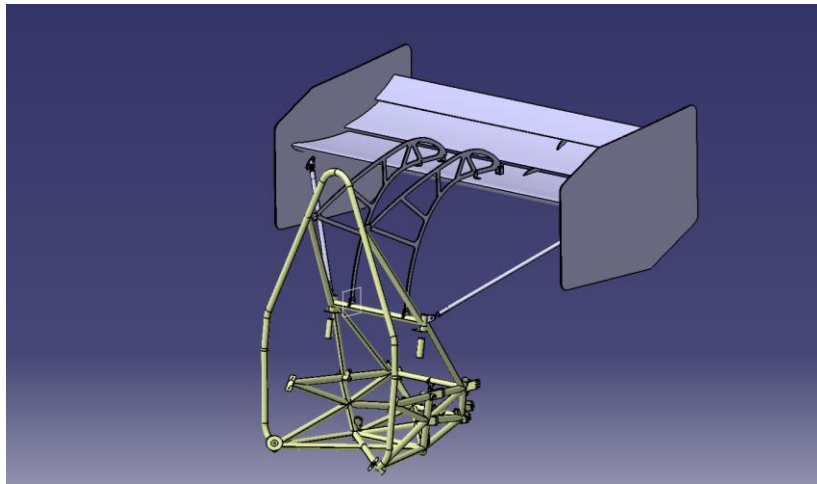


Figure 50: Preliminary 3D design for the rear wing

For the rear wing's endplate design many shapes were tested through CFD. The requirement of the final geometry was to reduce the drag of the rear wing as much as possible while maintaining the aerodynamic balance of the car. The final geometry with the best endplate design can be seen on the following pictures.

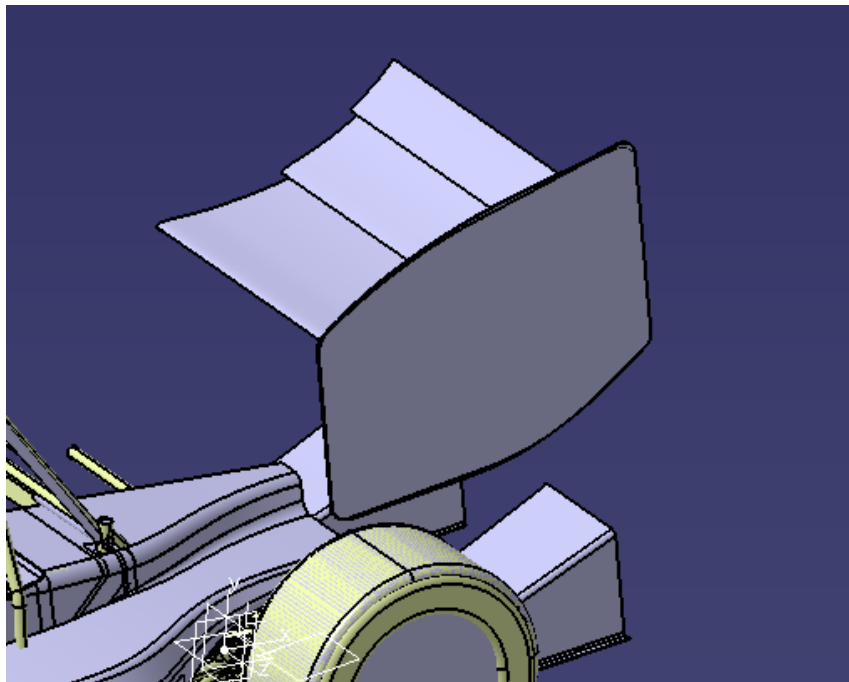


Figure 51: The final 3D rear wing design (1)

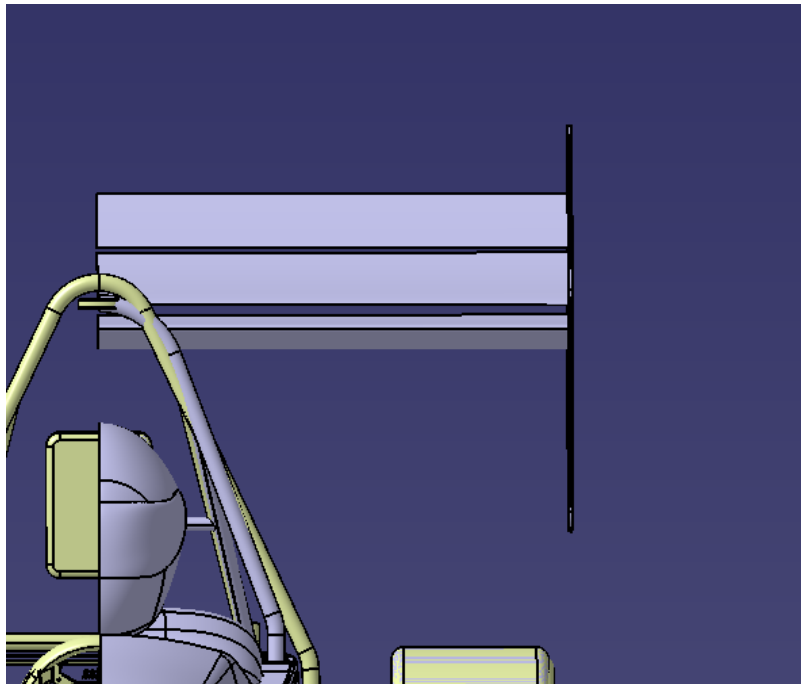


Figure 52: The final 3D rear wing design (2)

2.4.4. Summary

In the following I'm going to show some pictures from the final geometry's simulation. On the first picture below the streamlines and the pressure distribution are shown, while on the second picture the turbulence's kinetic energy is represented.

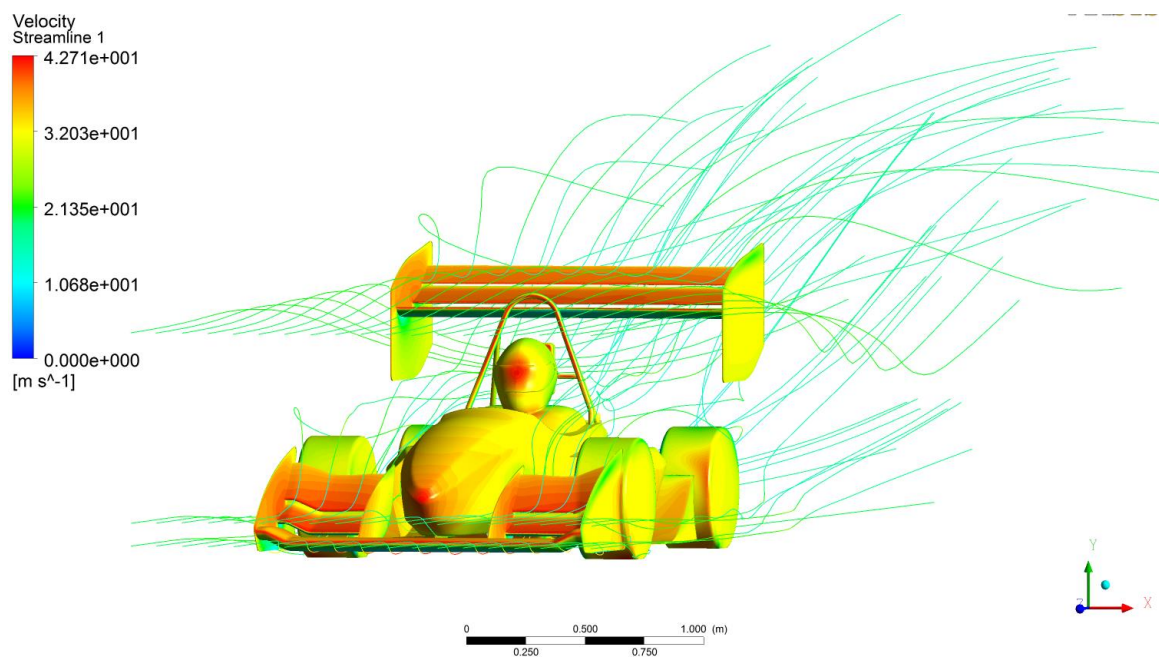


Figure 53: Airflow around the final aerodynamic package (1)

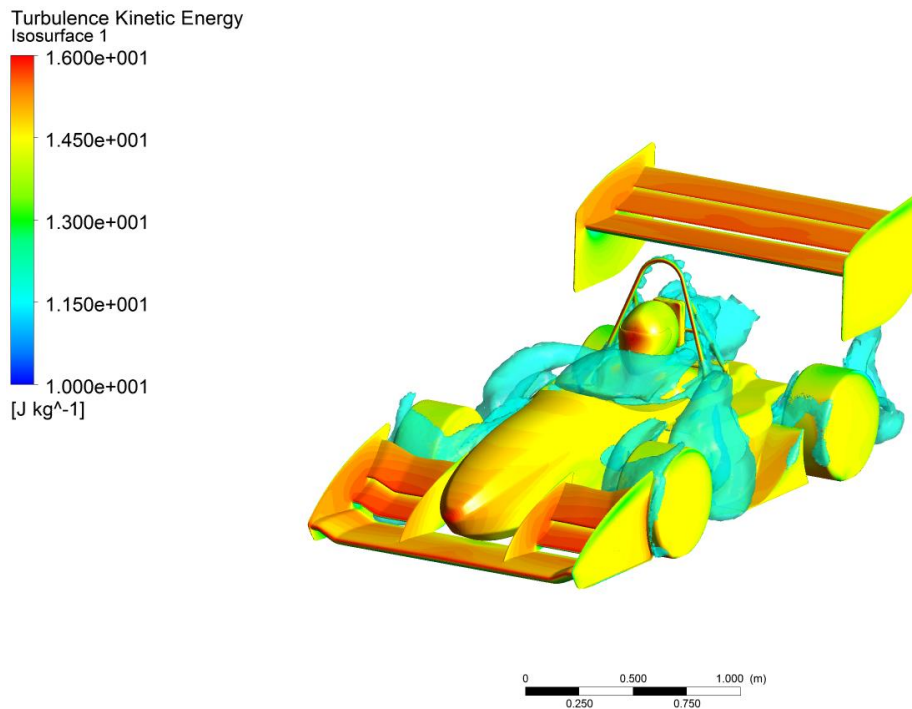


Figure 54: Airflow around the final aerodynamic package (2)

The pictures above show that the wheels generate much turbulence which increases the car's drag significantly. The wings don't contribute to the turbulence generation notably thus generating only minimal drag.

The pressure levels around the car and the wings also show that the wings work properly, generating downforce through the pressure difference on the top (high pressure side) and bottom side (suction side) of the wings.



Figure 55: The pressure distribution on the symmetry plane

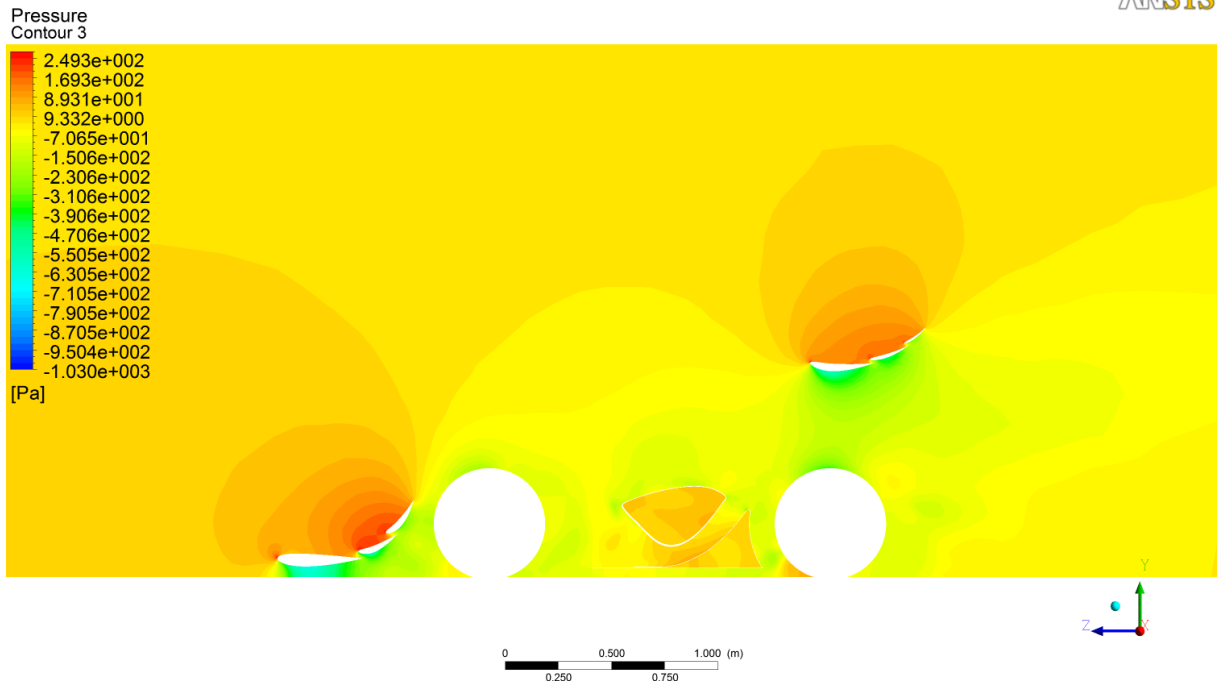


Figure 56: The pressure distribution around the wheels

Through many working hours and simulations, the aerodynamic group of the team was able to design one of the most efficient aerodynamic package of the 2014 Formula Student season. The calculated downforce and drag coefficients, and the downforce to drag ratio can be seen in the next table.

	Car with Aerodynamic package	Base Car
Cl	3.086	-0.215
Cd	1.002	0.510
Cl/Cd	3.079	-0.422

Figure 57: Comparing of the aerodynamic coefficients

Conclusions:

- Downforce: As we could see the base car generates lift, which spoils the vehicle dynamic properties of the car. With the aerodynamic package the car generates downforce which improves our car's behaviour on the race track.



- Drag: The car with the aerodynamic package generates more drag than the base car, this is due to the induced drag of the downforce generating wings. This isn't critical, because the advantages of the major downforce improvement outweigh the disadvantage of this minor drag increment.
- Downforce-Drag Ratio: As ours design target was a ratio of 2.5, we can say that we've completed the design requirements.

3. Mechanical design

3.1. Material selection

As we are designing a race car, weight is a very important aspect during the design of all the vehicle's components. As we see it, the two main tools of weight reduction are good choice of materials and finite element optimizations. Because of its excellent mechanical properties, we are trying to use composite materials wherever it is possible on our race car.

Composite materials originally came from military and the aerospace industry, and nowadays they are used in more and more applications where low weight is required. The main mechanical properties of composites compared to other common materials are shown on **Figure 58**.

	ρ [g/cm ³]	E [GPa]	σ_b [MPa]	(E/ ρ)/steel	(σ/ρ)/steel
Steel	7,8	210	600	1	1
Aluminium	2,8	70	100	0,9	0,5
Titanium	4,5	114	1000	0,9	2,9
Carbon/Epoxy	1,6	210	2000	4,9	16,3
Glass/Polyester	2	50	1200	0,9	7,8

Figure 58: Comparison of different materials [10]

Of course there are several variations of each material types with a wide range of properties, **Figure 58** shows only general data for comparison. As you can see the carbon fibre reinforced epoxy is far the best concerning the stiffness/weight and strength/weight ratios. However, these properties are only true for tensile load in fibre directions in the case of composites, their compressive strength is lower, but with thoughtful ply-sequence design high-strength and low-weight parts can be created using this material.

Besides the mechanical properties, composites also have the advantage of formability. Some important design aspects must be kept in mind, but they give a relatively big freedom in the shape design. This solution is also good for the team from the financial point of view, because the Hungarian carbon manufacturer company, Zoltek Zrt supports us with their unidirectional carbon fibre, and milling the moulds for the

composite parts out of foam or fibreboard is much simpler and cheaper than milling any metal parts.

3.2. *Structural design*

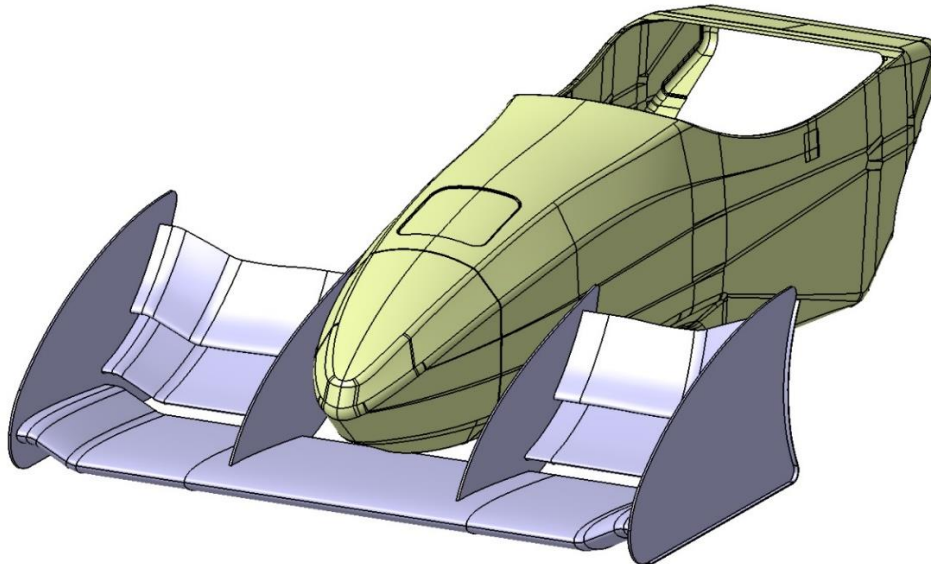


Figure 59: Front wing geometry as received from the aero team

The aero team have provided me an aerodynamically optimal shape without any consideration of manufacturability or the structural layout. My task was to create the structural design of the aero package.

3.2.1. *Design aspects of composite parts*

To be able to design and manufacture a race car in less than 10 months it is very important to consider every component's manufacturability during the beginning of the design phase, thus avoid time loss due to conflicts between the designers and the manufacturers. Every technology has its own requirements concerning the geometry. I laid down the ones for the wings according to the literature and the experience of our composites manufacturing team:

- Sharp edges must be avoided on the product. With our vacuum assisted resin transfer moulding (VARTM) technology a minimum of 3mm inner radius must be applied on every blend. Otherwise the quasi-homogeneous fibre-content cannot be provided, air bubbles can appear in the part, leading to decreasing in strength.

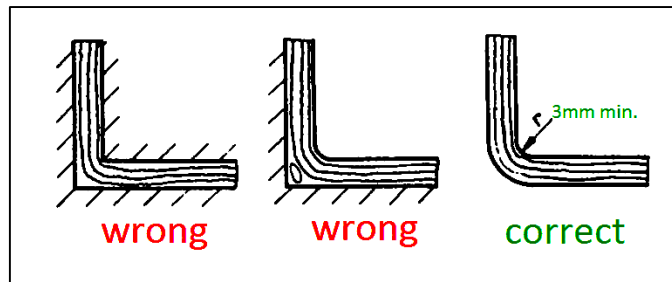


Figure 60: min. radius [11]

- A minimum of 3° draft angle must be applied and undercuts must be avoided to make sure that the product can be removed from the tool without damaging either.

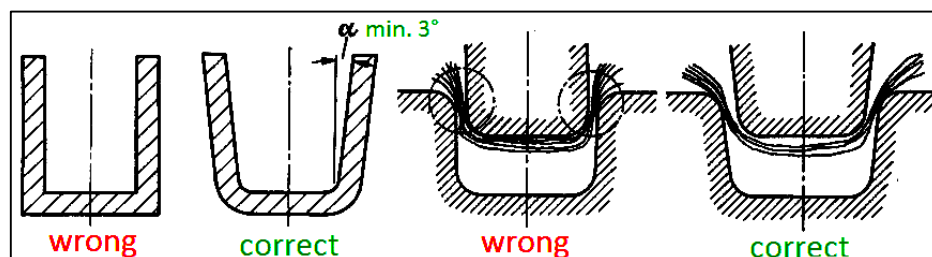


Figure 61: draft angle [11]

- Each component must be modelled as one coherent surface, thickened according to the numbers of plies. “Bumps” that can cause local increase of resin-content and air bubbles must be avoided.

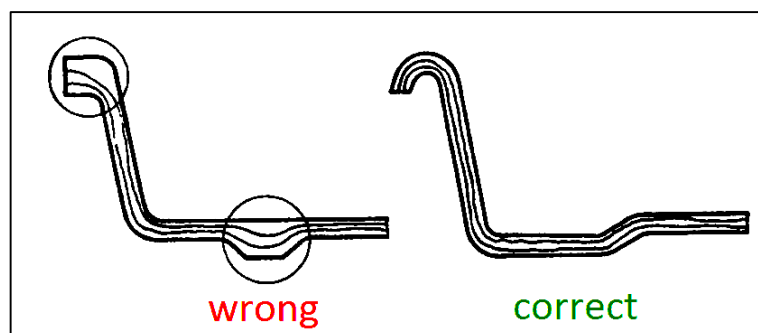


Figure 62: constant thickness [11]

- High surface stress must be avoided. Large washers must be used under bolt heads to dissipate the load.
- Where sandwich structure is applied, solid laminate must be used under bolt heads to avoid core failure. There must be a smooth transition zone in the core around the hole to avoid sharp steps.

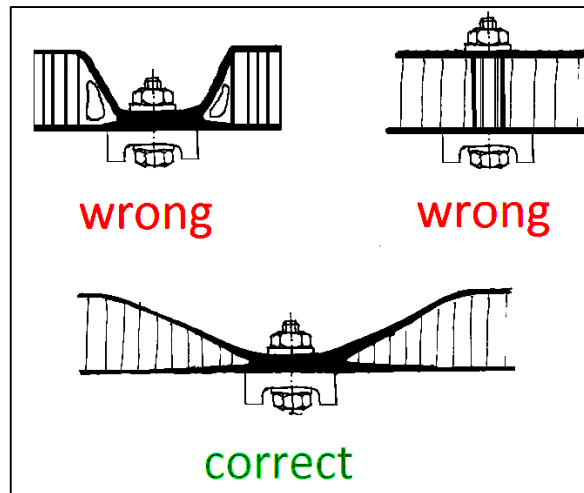


Figure 63: bolted connections on sandwich structures [11]

3.2.2. Leading edges

First I examined the curvature of the wings. The leading edges are critical regarding the minimum radius criteria. I chose to have a minimum of R5 on the outer surface of it, because probably the thickness will be less than 2mm. I ran curvature analysis in the CAD system on each of the elements. I set up the scale to show any surface that has less than R5 mm in red. As you can see on **Figure 64** the main element meets this requirement, it does not need to be modified.

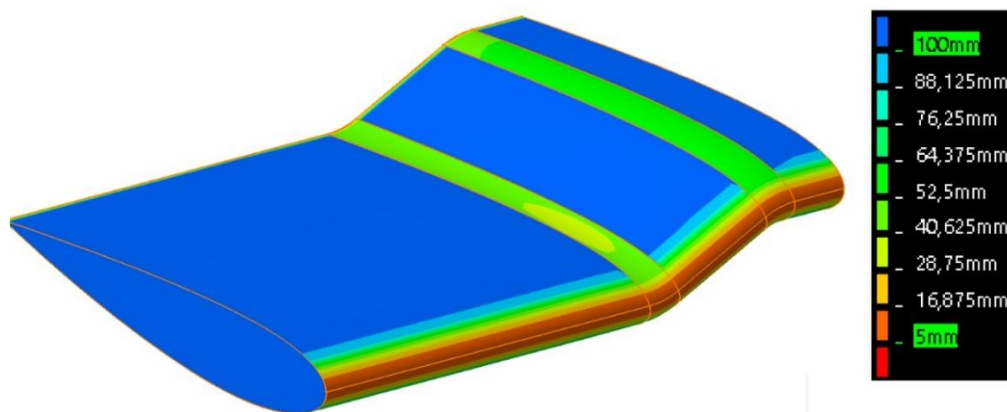


Figure 64: Curvature analysis - front wing main

Figure 65 shows the result of the analysis on the front wing flap. The cross section of the two flaps are the same, so it is enough to examine only one of them. The analysis shows that the radius of the leading edge is smaller than 5mm, so I have to make modifications on the flap.

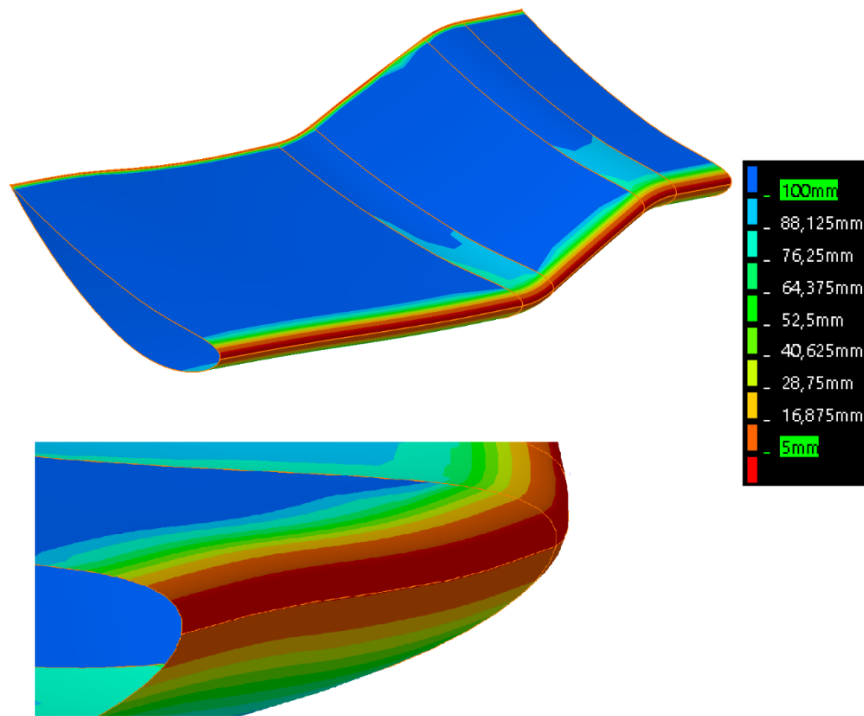


Figure 65: Curvature analysis - front wing flap

The correction must be done carefully, the changes of the shape must influence the airflow as little as possible. After various steps of iteration I modified the leading edge to have a minimum radius of exactly 5mm.

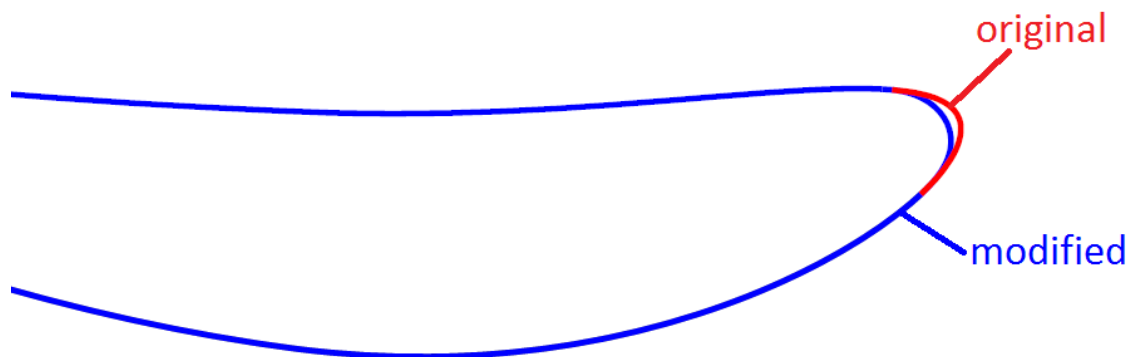


Figure 66: The modified profile compared to the original

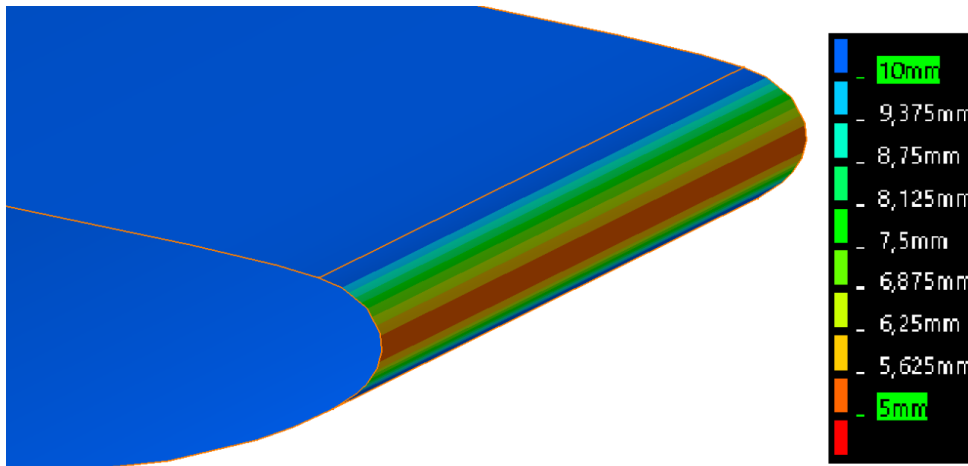


Figure 67: Curvature analysis of the modified flap

3.2.3. *Trailing edges*

The original model had sharp trailing edges (**Figure 68**), which cannot be manufactured accurately. The bonding of the upper and lower shell must be placed at the trailing edges. I investigated several options to find the best compromise between manufacturability, strength, weight and aerodynamic properties:

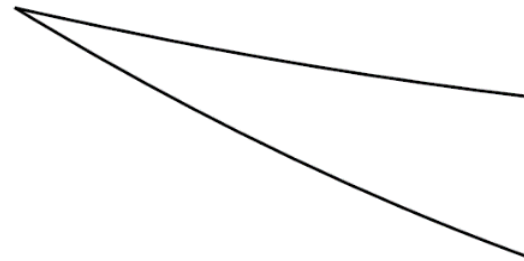


Figure 68: Original, Sharp trailing edge

- a) One solution is to trim both the upper and lower shell along a common line and fill the gaps with adhesive. This is a simple solution, there is no extra weight and extra need for manufacturing in it, but it is uncertain that the two edges can be trimmed to make contact along the whole width of the wing. It also ruins the trailing airflow.

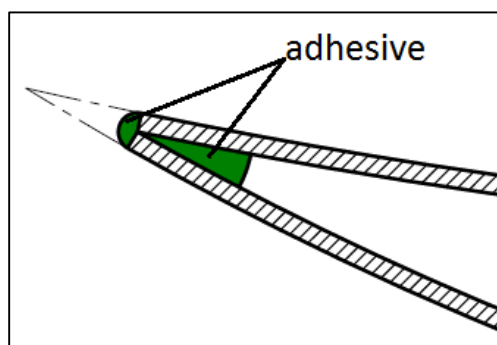


Figure 69: Trailing edge a)

- b) For aerodynamic reasons the best option is to manufacture an aluminium insert that has the exact same geometry as the original model, make bonding surfaces on it, and bond it in the edge. Exact geometry and high strength bonding can also be produced this way, but the weight of the insert would be too high and because of the spatiality of the geometry, expensive and complicated 5-axis CNC milling of the insert would be required.

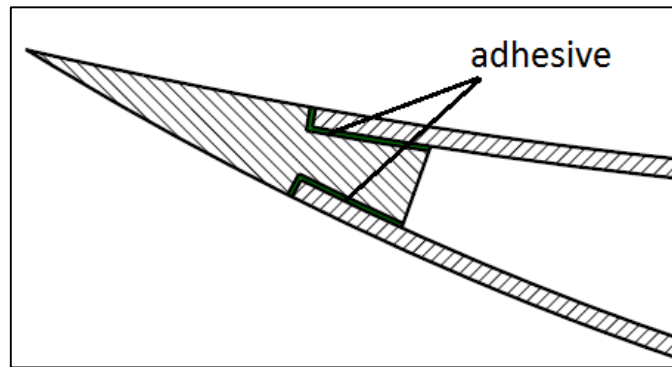


Figure 70: Trailing edge b)

- c) The solution for the problems of *option b)* would be to use a carbon-composite element on the edge. High strength bonding could also be produced this way, and its weight would be less than the aluminium insert. But an edge fillet of R3 mm should be applied which would ruin the geometry. This method would change the original shape most, airflow separation would occur and the properties of the wing would be ruined. Milling an MDF tool for the additional carbon part would be easier than the aluminium milling, but it is still too expensive and complex.

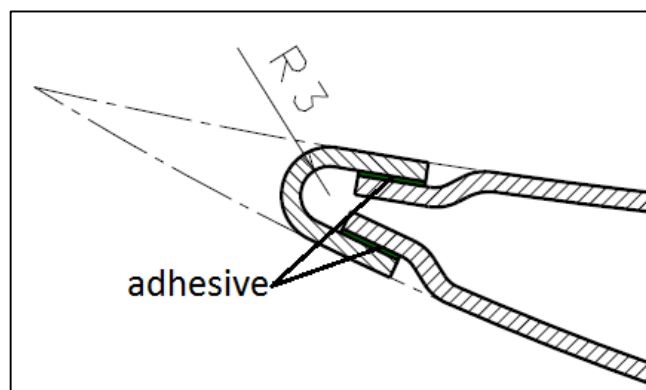


Figure 71: Trailing edge c)

- d) As an evolution of *option a)* the aero properties and the uncertainty of the connection can be fixed if one shell is trimmed when its inner surface reaches

the other side of the original geometry, and the other shell is trimmed where it reaches the first shell's inner surface. In this solution the lower shell should be longer because the airflow is more critical on that side, separation can occur more easily there. With this method the change of the original geometry is minimal. The strength of the bonding can be better than with *option a)*, but still not as good as the other solutions, there is still some uncertainty in the bonding.

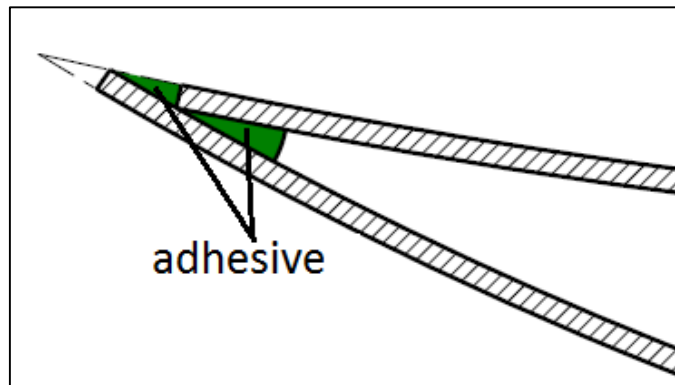


Figure 72: Trailing edge d)

- e) The strength and accuracy of the bonding can be increased by changing the curve of one of the shells at the back to align to the other one and create a bonding surface. This method is easy to manufacture, provides strong bonding and the increasing of the weight is negligible. But from the aero point of view it is worse than option d), it changes the direction of the trailing flow too much, the relative position of the 3 wing elements should be re-optimised.

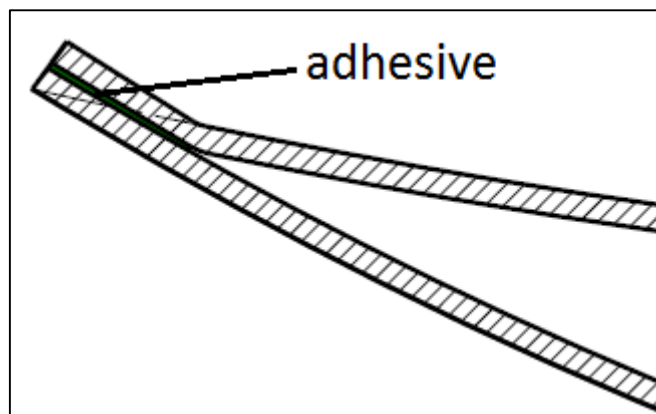


Figure 73: Trailing edge e)

None of the above described solutions are perfect, every one of them have advantages and disadvantages. In order to be able to find the best choice, I created a decision matrix

with all the possibilities and the design aspects. In the matrix the higher number from 1 to 10 means the better solution.

Aspects	Weighting factor	Method				
		a)	b)	c)	d)	e)
Weight	1,0	10	2	5	9	9
Bonding strength	0,7	5	10	10	7	9
Effects on downforce	1,0	7	10	3	8	7
Effects on drag	1,0	8	10	3	9	7
Manufacturability	0,7	8	3	4	9	10
Cost	0,9	10	1	3	10	10
Additional time	1,0	10	4	4	10	9
Summary		53,1	36,0	27,5	<u>56,2</u>	54,3

Figure 74: Decision matrix of trailing edge concepts

As shown on **Figure 74**, *solution d)* has the highest score slightly ahead of *solution e)* and *a)*, so I chose this method to be realised.

3.2.4. Parting lines

As the wing elements will consist of two parts bonded together, the parting lines must be defined. The main aspect here that I must keep in mind is the draft angle, and besides that, the aerodynamic properties are also very important.

First I evaluated the solution of the wings from the season before. As you can see on **Figure 75** overlap between the upper- and lower shells were created on the leading edge, and this overlap was used as bonding surface. This solution was simple to produce, but it had several issues. First of all, there was a big step in the profile at the leading edge. It had catastrophic effect on the airflow, which ruined the efficiency of the wings. The other problem was that the two shells could not be fit together correctly, because there was no exact mating surface defined. Therefore we could not guarantee, that the profile of the final part after the bonding will be the same as which the simulations were ran on. This had bad effects on the aero properties, but also on the feasibility, because the final geometry was so different from the model that we could not bond the inserts in the profile.



Figure 75: Leading edge of last year's wing

After all this experience I aimed to make a bigger effort on the accuracy of the final parts. To achieve that, I have to put the bonding surface somewhere else. I decided to create the overlap on the upper side of the profiles, near the leading edge. The reason for that is there is enough place, the curvature of the profile is much lower there, so it was easy to create the step in the lower shell there, and the gap which is generated by the 3mm radius rule could be minimized. Also it is better to put this gap on the top, because, as I mentioned before, the airflow at the lower side is more critical and more sensitive than it is at the upper side. The gap can be filled with adhesive, therefore the geometry of the product can be even closer to the simulated one. As shown on **Figure 76**, smooth and accurate leading edge geometry can be achieved with this concept, which would make the new wings better than its ancestors.

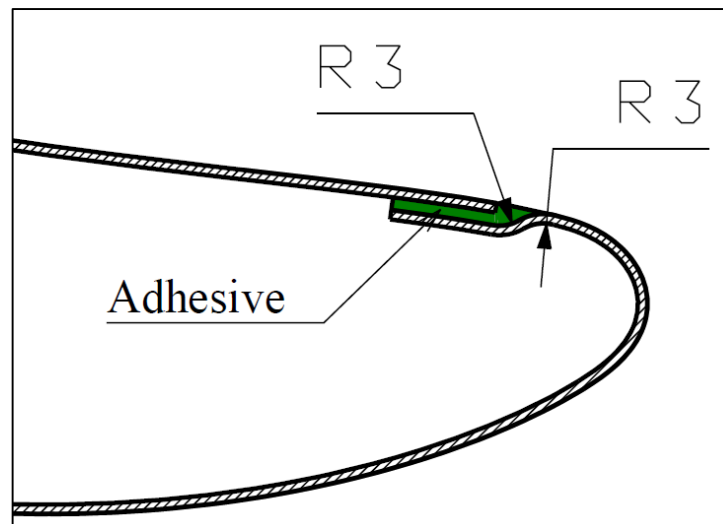


Figure 76: Final leading edge concept

However there is a difficulty in this layout: The lower shell cannot be manufactured in one mould because of the undercut in it, so a two-part mould must be designed. After I defined the parting line on the front edge of the profile, I ran draft analysis on the lower shell to make sure its manufacturability.

3.2.5. *Mounting points*

The mounting concept of the front wing is shown on **Figure 77** below. Because of the rules, a 4mm thick aluminium plate, called ‘anti-intrusion plate’, must be mounted to the front of the monocoque. I decided to put the connection points of the front wing on this plate, because it required minimal modifications on last year’s construction, only 4 aluminium flaps had to be welded on the anti-intrusion plate. As shown below, two consoles are connected to these flaps which hold the main element. These consoles are manufactured with water-jet cutting from the same sheet of aluminium as the anti-intrusion plate and the flaps welded on it, to make the process cheaper and simpler.

The wing is fully constrained by two carbon-composite rods with ball-joints bolted in their ends. The angle of the wing can be set by changing the length of these rods. It can easily be done even in assembled condition, because one of the ball joints’ thread is left handed, the other’s is right handed. Therefore the length can be changed by loosening the locking nuts and rotating the rod.

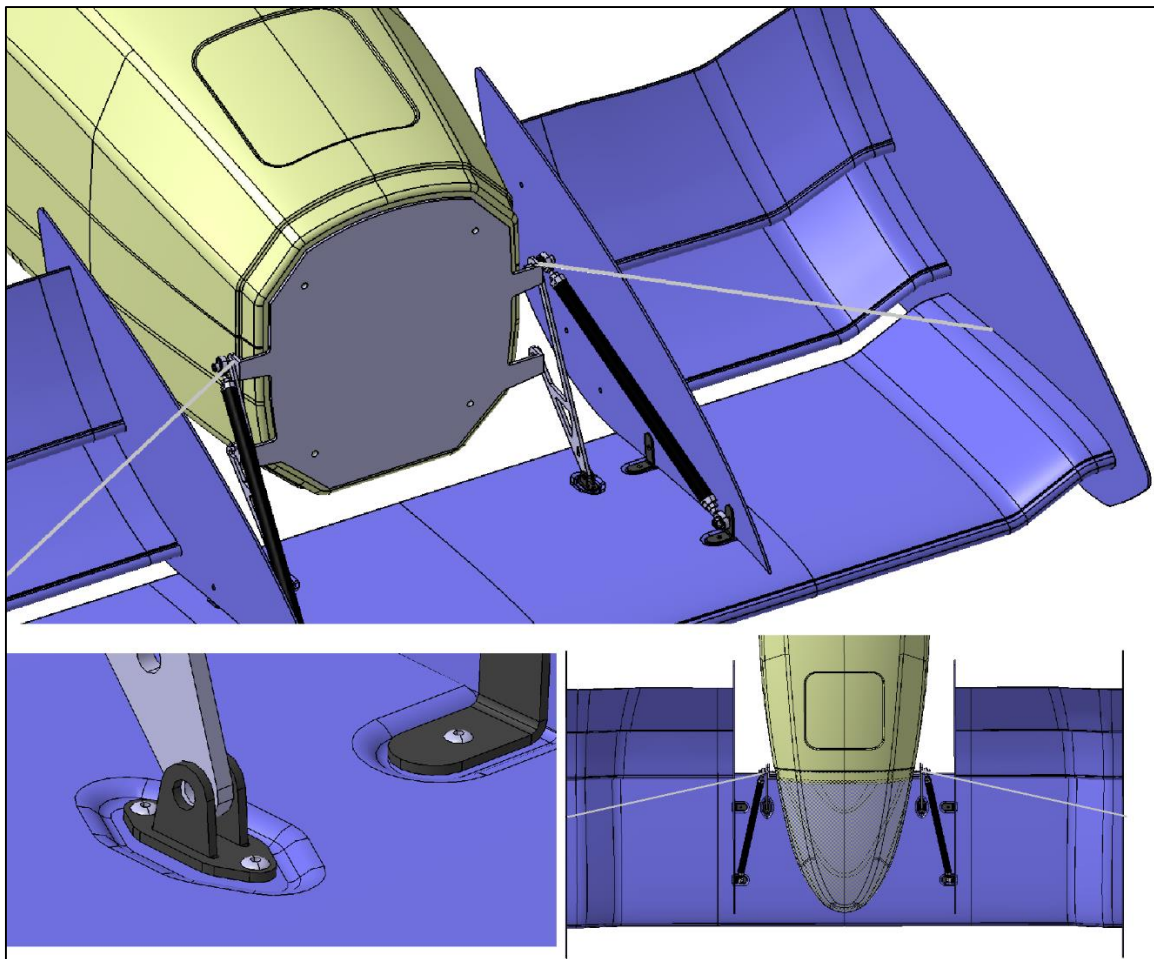


Figure 77: Front wing mounting concept

The forces are mainly generated by the flap elements, therefore I was striving to put the mounting points on the wing as wide as possible, but still, the main element must be very stiff, thus heavy to avoid big deflections at the side ends with this concept. As shown above on the figure, I solved this problem by using two additional steel wires which hold the ends of the wing and prevent deflection.

The overall weight can be reduced by reducing the number of bolts and other fasteners. That is why I tried to combine the connection points, and put the ends of the console, the carbon rod, and the wire together to the upper flaps of the anti-intrusion plate, and the other side of the rod to the L-profile steel that holds the inner endplate.

As shown on **Figure 78**, aluminium inserts are water-jet cut from the same 4mm thick sheet, and bonded in the end of each profiles. The wing elements are bolted to the endplates by the two threaded holes on these end-inserts, and that is how the endplates hold the elements together.

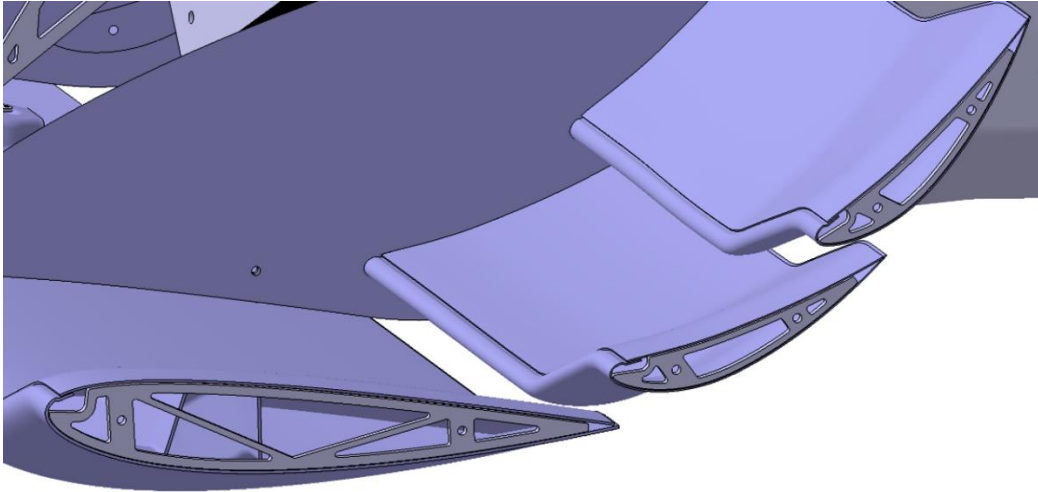


Figure 78: Al inserts in the end of the profiles

According to my experience in structural analysis, the high stresses are usually generated near the mounting points. Therefore my idea was to design an inner stiffening (the omega) inside the main element which connects the mounting points, and reaches to the side ends. This element would carry most of the load, therefore the upper- and lower shells could be very light. This element would also provide bonding surfaces between the two shells which increases the safety of the bonding. I designed it to be in the part where the wing profile is the thickest to achieve maximum second moment of inertia. The structure is shown on **Figure 79** below.

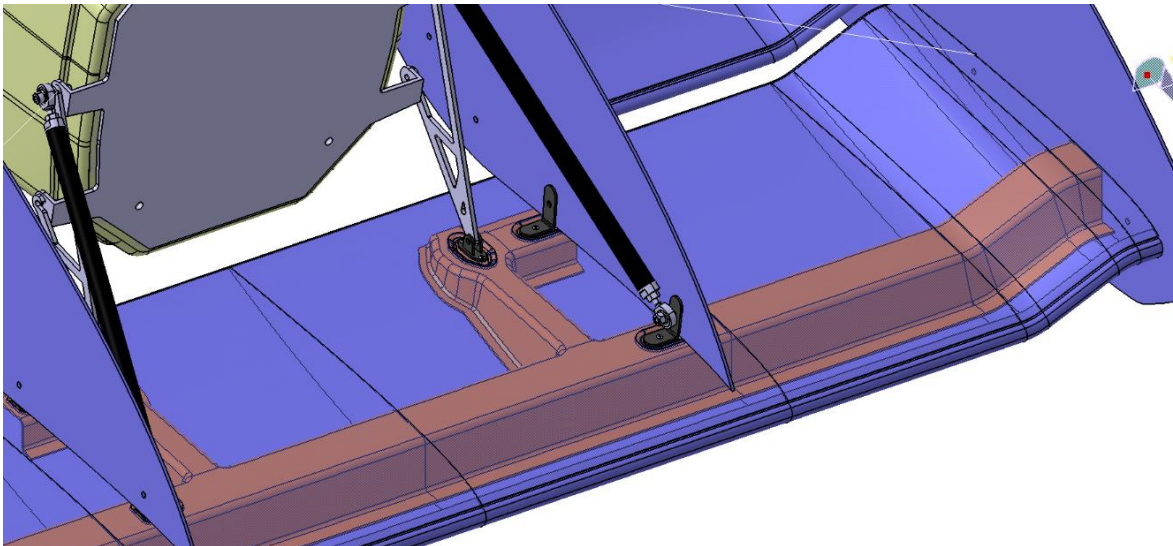


Figure 79: Inner stiffening of the front wing (omega)

The construction of the mounting point on the wing is shown on **Figure 80**. I designed a flat mating surface on the upper shell under every joining elements, which provide good bonding strength. However these elements are bonded together, tensile stress would be

generated in the adhesive which is not optimal, so the bonding is supported by rivets. Rivets are much lighter than bolts, and they can be applied from the outer side after the elements are bonded together. To avoid high surface pressure, the composite layers are flanked by two steel plates. The mating surface is lowered to provide that it has the smallest possible effect on the airflow.

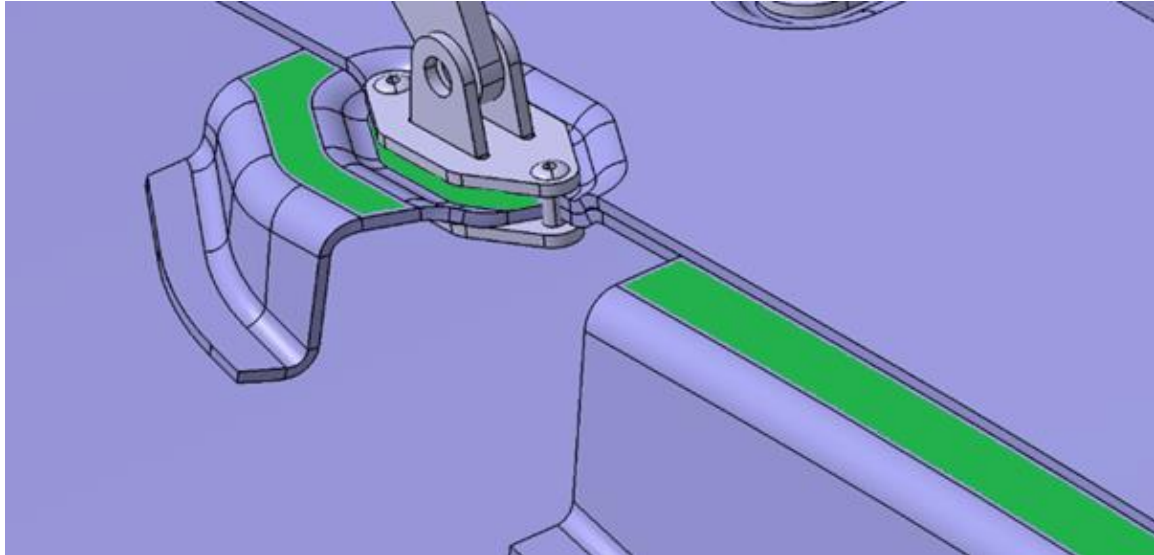


Figure 80: Construction of mounting points

4. Finite element analysis

4.1. Defining the material-model

4.1.1. *Mechanical properties of fibre-reinforced composites*

The definition of polymer-matrix composites: solid material that contains at least two different components. One of them is called the matrix, which has lower strength and density, the other one is the high-strength and/or –modulus reinforcing fibre material. The matrix surrounds the reinforcing material completely, and the adhesion between them is excellent, even under high-level deformations. [16]

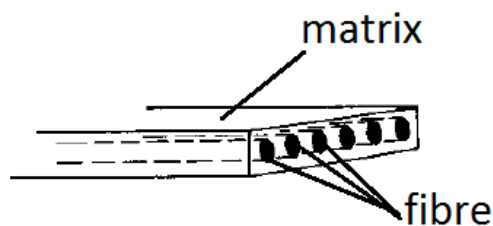


Figure 81: structure of composites [12]

In most mechanical structures the loads have a well-defined direction, where significantly higher stresses are generated than in others. With traditional materials strength cannot be increased in only one direction, this means additional useless weight. This is the reason why composites have been created. Their biggest advantage is that the mechanical properties of composite parts can be optimised in any directions by different ply-sequences. This advantage also makes it difficult to design components with these materials.

In reality, composites are inhomogeneous anisotropic materials, but it is a very good approximation to model them as homogeneous anisotropic, or as in our case, orthotropic. There is a big variety of available dry fibre layouts in the market, I will use two types: the 2D roving fabric and the unidirectional material. The philosophy I will use when creating the ply-sequence is to put as many UD layers in as necessary for reinforcement, and one layer of fabric on the outside surface for decoration and because of its better impact-handling. The strength of these types in the different directions are shown on **Figure 82**.

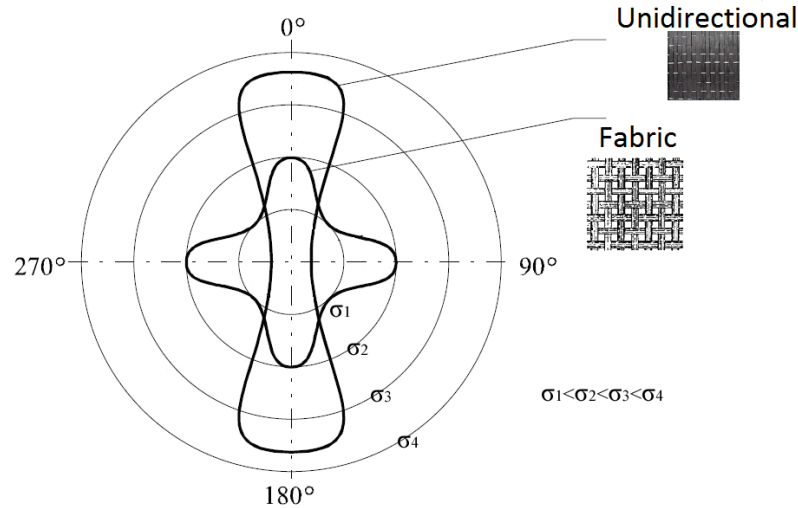


Figure 82: Polar diagram of composites' strength [13]

As mentioned above, the used material model will be orthotropic 2D.

4.1.2. Failure criterion

Fibre-reinforced materials have several failure modes, for example fibre brittle, fibre pull-out, fibre-matrix debonding, or matrix cracking. It is impossible to predict all of these failures accurately, so it is much more difficult to design parts with this material than for example with metals. There are several failure models of composites, based on many different theories, and they are still being developed.

For the analysis of the wings I will use the **Tsai-Wu** composites failure criterion. It is the most commonly used model, because it is relatively easy to use, it takes more failure modes in consideration, and it is available in many FEA software. According to the theory, failure will not occur, if:

$$F_1\sigma_1 + F_2\sigma_2 + F_{11}\sigma_1^2 + F_{22}\sigma_2^2 + F_{66}\tau_{12}^2 + 2F_{12}\sigma_1\sigma_2 < 1 \quad [12]$$

$$F_{11} = \frac{1}{X_1^T X_1^C} \quad F_1 = \frac{1}{X_1^T} - \frac{1}{X_1^C} \quad F_{22} = \frac{1}{X_2^T X_2^C} \quad F_2 = \frac{1}{X_2^T} - \frac{1}{X_2^C} \quad F_{66} = \frac{1}{S^2}$$

Where:

- X_1^T, X_2^T : Tensile strength in fibre-, and perpendicular directions
- X_1^C, X_2^C : Compressive strength in fibre-, and perpendicular directions
- S : Shear strength

The software computes this value on every node, and simply, if it is higher than 1, the part is going to break.

4.1.3. *Determination of material characteristics*

To define the material model, the tensile strength, the compressive strength and the in-plane shear strength are required in both 0° and 90° fibre orientation. We used an individual fibre-matrix combination of which the manufacturer does not have a data sheet with the properties so it was necessary for us to determine these characteristics ourselves.

4.1.3.1. *Specimen preparation*

We could select the materials from the range of our sponsors. As a reinforcing material we used Zoltek Panex 35 (200gsm) unidirectional fabric, as a matrix material we chose Ipox Chemicals 1052-5 resin system.

We used the vacuum bag technology similar to the final production. As it is visible on **Figure 83** we used a flat surface because we had to produce flat panels. We could make all the specimens at once so the conditions were the same for all pieces.

Curing was carried out in a Heraeus UT20 drying oven at 80°C for 6 hours.



Figure 83: Preparations for the vacuum infusion

Two out of the three types of tests we had to use end tabs. It is necessary to use tabs because during the tests the gripping jaws would crush the carbon fibre composite and also the tabs provide larger cross section at the gripping so the specimen will probably fail within the gage section.

We made these tabs from glass fibre with polyester resin using hand lamination. Bonding was carried out with Sikadur 330 two component adhesive which has a cure time of 6 hours. Mixing ratio was 4:1 (A:B).



Figure 84: Specimen cutting

4.1.3.2. Mechanical tests

We made the tests in our University's Polymer Engineering Laboratory, on a universal materials testing machine (Zwick Z050). This is a computer controlled (Zwick TestXpert 10.11) machine, which is accredited according to ISO9001

Determination of tensile properties

We carried out the tensile tests according to the standard MSZ EN ISO 527-5.

The tensile specimens had two different layups for the 0° tension (Type A) we used 4 plies and for the 90° test (Type B) we used 8 plies of the unidirectional fabric. The used dimensions are shown on **Figure 85**.

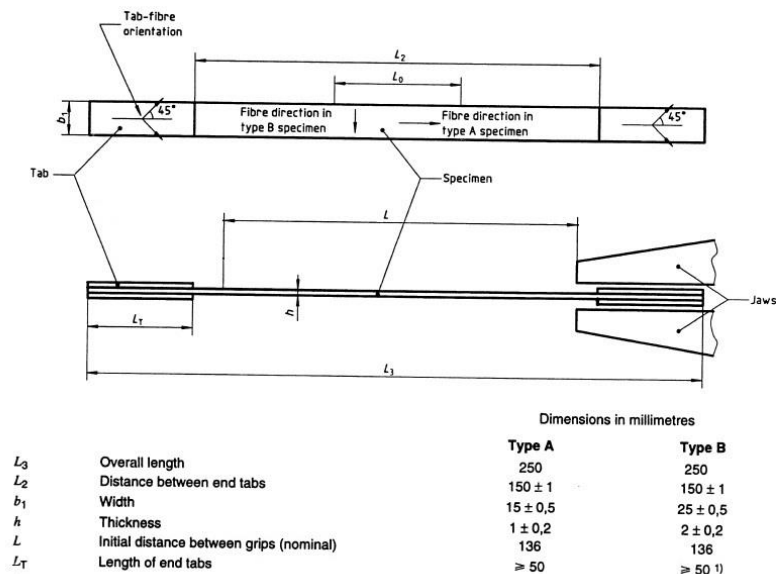


Figure 85: Dimensions of the specimens [7]

During this test the specimen is loaded along the longitudinal axis with a constant 2mm/min speed until failure. We recorded the load and displacement. We used a Messphysik video extensometer to measure longitudinal and transversal deformation because it is more precise than calculating from crosshead travel. The setup can be seen on **Figure 86**.

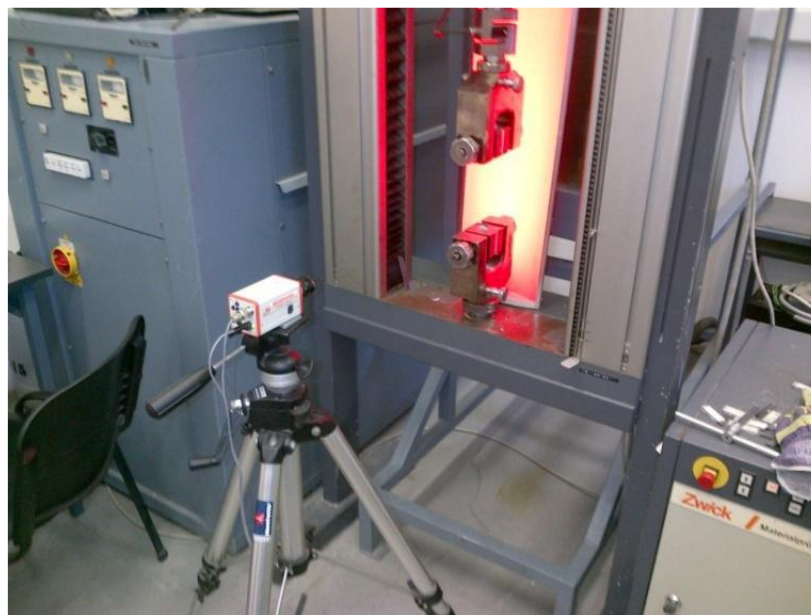


Figure 86: Video extensometer

Plane Shear Strength

We use the in-plane shear strength test to characterize fibre matrix interaction in our composite material. Here is a brief overview of this test method from the D 695 standard:

In-plane shear strength, as determined by this test method, is measured by applying a compressive load to a notched specimen of uniform width. The specimen is loaded edgewise in a supporting jig of the same description as that referenced in Test Method D 695 for testing thin specimens. A schematic of the specimen used for this test and the supporting jig is shown on **Figure 87**. Failure of the specimen occurs in shear between two centrally located notches machined halfway through its thickness and spaced a fixed distance apart on opposing faces. [8]

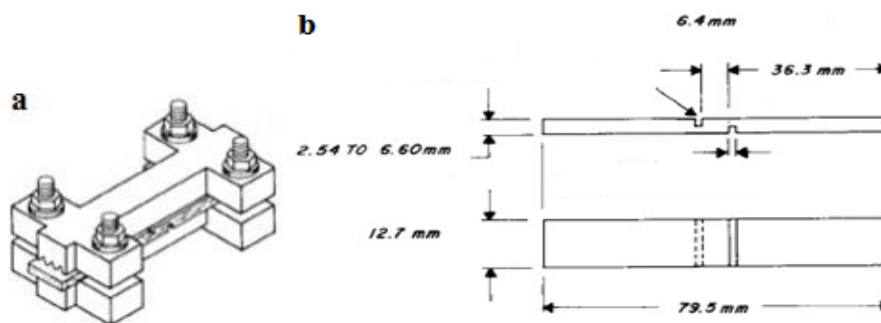


Figure 87: Specimen and Loading Jig for In-Plane Shear Test [8]

Significance and Use:

Shear tests of various kinds are widely used in the reinforced plastics industry to assess the strength of the reinforcement-to-resin bond in polyester-, vinyl ester-, and epoxy-resin composites. In addition to their importance for the generation of data for research and development, quality control, and specification purposes, such tests are of fundamental value to the fibrous reinforcement industry, since they can be used to assess the potential of new sizing systems for the surface treatment of glass fibres. This test method is useful for establishing the shear strength of laminates or other reinforced plastics having randomly dispersed fibre reinforcement. While the test also lends itself to parallel-fibre reinforced plastics, it has been designed to accommodate nonparallel-fibre reinforced materials that cannot be tested satisfactorily by the short beam procedure described in Test Method D 2344. [11]



Figure 88: Loading the specimen

We tested eight specimens in normal direction and (because the material is anisotropic) we tested eight more parallel with the principal axis of anisotropy. In the test machine we used the speed defined in the standard which is 1,5 mm/min.

Determination of compressive properties In the In-plane direction

For the compression of the fibre reinforced specimens we performed tests according to the MSZ EN ISO14126 which contains the procedures to determine mechanical properties. The standard geometry and schematics are shown on Figure 89.

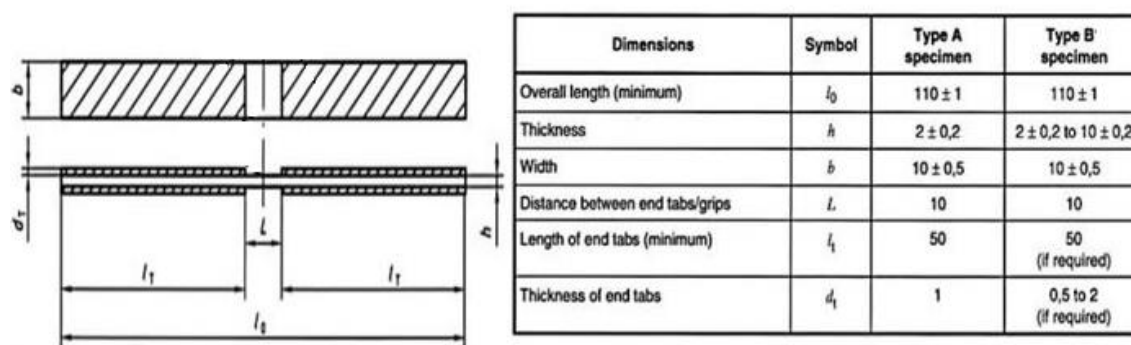


Figure 89: Compression specimen dimensions

4.1.3.3. Evaluation

During the actual test the machine registers displacement and load and writes it into row data files. Using these files we calculated strength and modulus according to the standards. After the evaluation of the data we calculated the mean strength and modulus from five individual values. Results are shown on **Figure 93**.

Tensile properties

According to the standard tensile strength is calculated with the following equation:

$$\sigma_t = \frac{F_{max}}{A}$$

where σ_t is strength in megapascals, F_{max} is the highest recorded force in newtons and A is the size of the specimen's cross section in square millimetres.

To determine the modulus we used the following formula:

$$E = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - \varepsilon_1}$$

where σ_2 , σ_1 , ε_2 , ε_1 are the coordinates for two points of the stress strain curve, where the material shows linear elastic properties. The modulus is the slope of this piece of the curve. See on **Figure 90** for details:

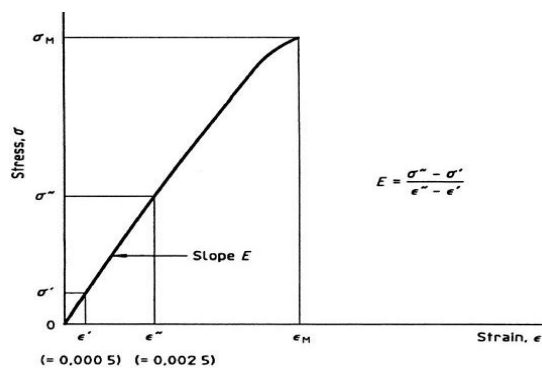


Figure 90: Stress-strain curve [7]

A typical stress strain curve can be seen on **Figure 91**.

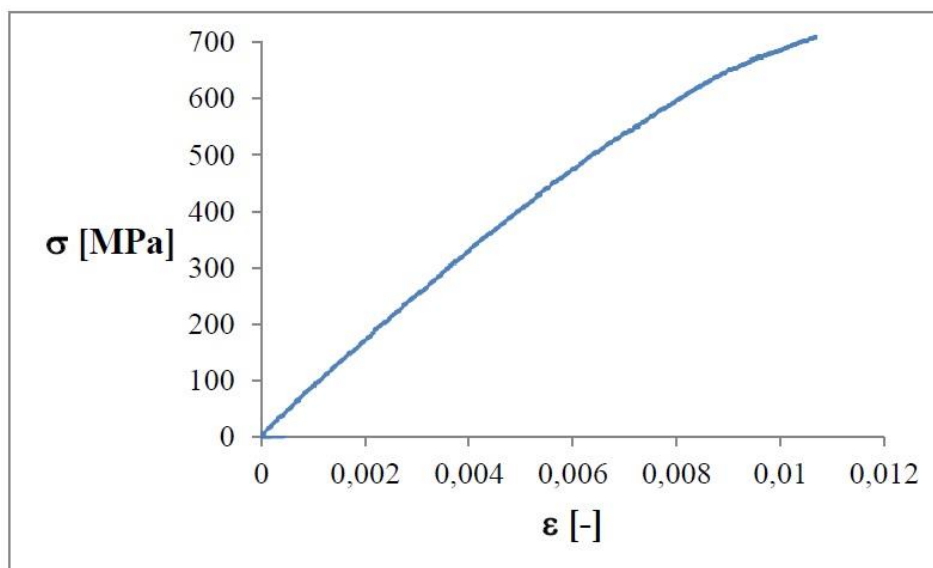


Figure 91: Tensile

In-plane Shear Strength properties

We calculated the in-plane shear strength by dividing the maximum shear load carried by the specimen during the test by the cross section of the specimen.

$$\tau_t = \frac{F_{max}}{A}$$

where τ_t is shear strength in megapascals, F_{max} is the highest recorded force in newtons and A is the size of the specimen's cross section in square millimetres. [8]

Compression properties

The evaluation was done using the same equations as for tension except that the load acts in the opposite direction (compression instead of tension). Nonetheless the machine output for load is still positive. [9]

A typical stress strain curve can be seen on **Figure 92**:

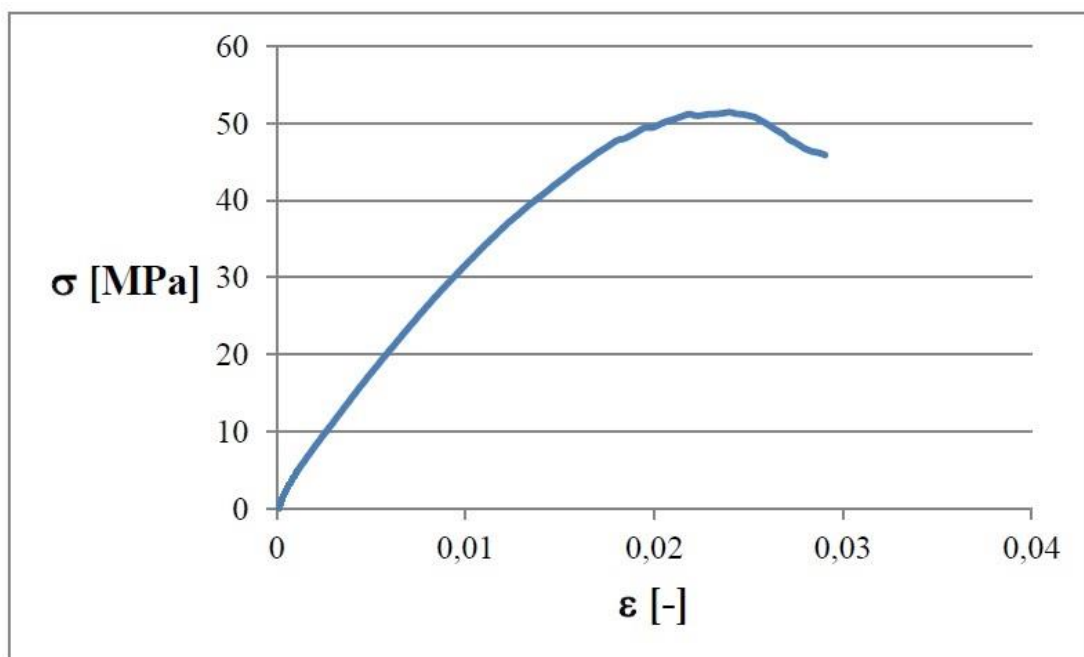


Figure 92: Compression

4.1.3.4. Summary of material properties

We see that for some results the scatter (deviation) is quite high. When composites are being tested usually larger deviations can be expected compared to metals. Nonetheless we have to improve specimen preparation techniques for more consistent results.

Zoltek200_ER1042EH2298					
Tension					
	σ			E	
0°	1245,63 ±	70,86	102,04 ±	22,4	
	σ			E	
90°	31,31145 ±	2,873063	5,479 ±	0,24	
Compression					
	σ			E	
0°	372,2266 ±	57,02705	6,287 ±	0,69	
	σ			E	
90°	72,24729 ±	6,426168	2,3 ±	0,16	
Shear					
	τ				
0°	31,12297 ±	5,191419			
	τ				
90°	4,510467 ±	0,703122			

Figure 93: Final results

4.2. Composite stacking

In the CAD/FEA software, composite stacking can be built on zero-thickness shells. So I modelled the mould-side surface of CFRP parts, than I modelled the border lines of the different zones on the shell. After that I had to define the stacking direction, than the laminate could be built ply-by-ply, defining each ply with its material, the zone, and its orientation, which is described as the angle between the fibres and the XZ-plane of the vehicle's basic coordinate-system. The origin of the basic coordinate system is situated on the ground, on the middle of the front suspension's track, the axis directions are shown on **Figure 94**.

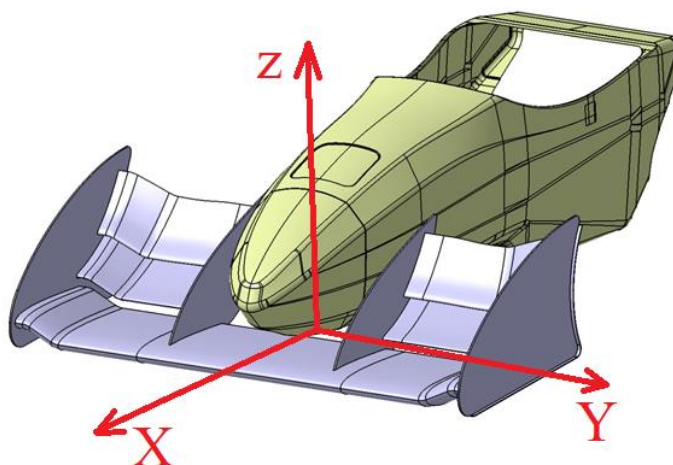


Figure 94: Basic coordinate-system of the car

To describe the ply-sequence I will use the conventional notation. For example: $[90^\circ f/0^\circ UD/45^\circ f]_T$ means that the ply-order starting from the mould-surface: 90° fabric, 0° unidirectional, 45° fabric, and the T-index means that this describes the total thickness of the part.

These stacking properties can be applied on 2D meshes, which is beneficial concerning the computational capacity needed.

4.3. Finite element mesh

A good quality mesh is an essential requirement of realistic results, therefore I laid great emphasis on creating them.

The most regularly used two-dimensional elements are the quadrilateral and the triangle elements. Basically the quad elements can provide higher accuracy, but they are more difficult to create on complex geometries, triangle elements can provide more accurate geometry in these cases. Therefore the practice is to use as many quad elements as possible, along with triangle elements where the shape requires it. I will create the two-dimensional mesh of the composite shells according to this theory. [14]

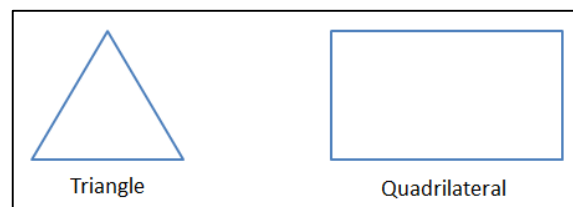


Figure 95: Commonly used 2D elements [14]

There is a slightly wider range of choices concerning the 3D elements. The most widely used 3D shapes are shown on **Figure 96**. The situation is similar to the 2-dimensional case, the hexahedron is the best choice concerning accuracy, but it is more difficult to create hexahedron mesh on complex geometry. Therefore usually automatic mesh generators create only tetrahedron elements. [14]

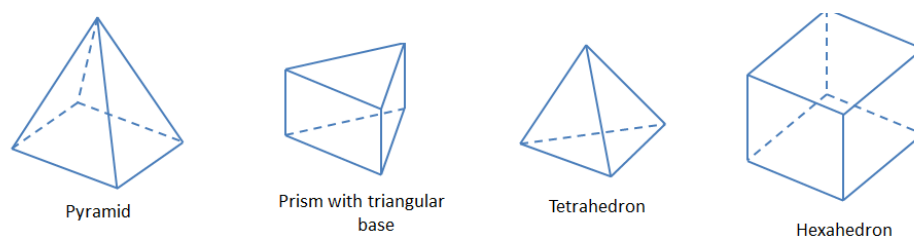


Figure 96: Basic 3D elements [14]

The nodes of all the above mentioned elements are connected with a straight line, which means that their approximation function is linear, therefore large number of elements are required to approximate a curved geometry well, and this increases the computational requirement. This is called the H-Method. [15]

By increasing the polynomial order of the element edges, the mesh can follow the curvature of the shape more accurately without increasing the number of elements. This is called the P-Method. As shown on the figures below, more accurate geometry can be achieved with less elements and the same computational requirement by using P-elements. [15]

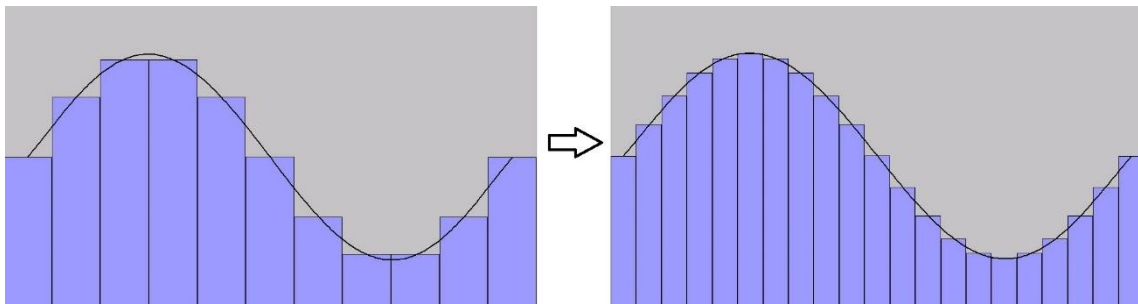


Figure 97: H-Method with Course Mesh (left) and Fine Mesh (right) [15]

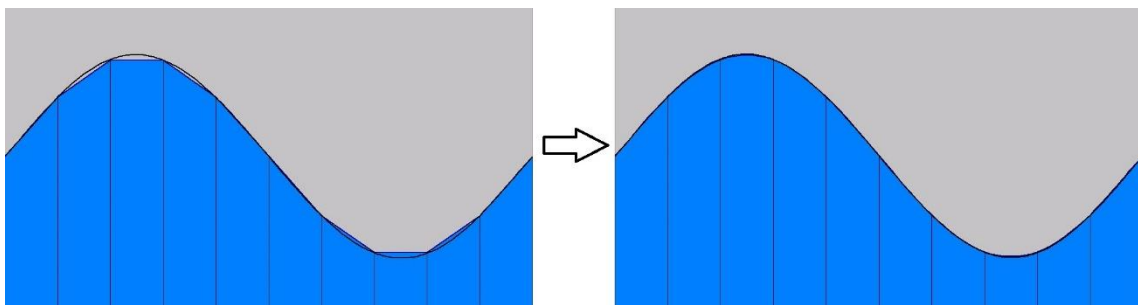


Figure 98: P-Method with 2nd (left) and 3rd (right) Order Polynomial [15]

Besides the type and size, the accuracy of the calculations is highly influenced by the shape of each elements. To avoid errors there are some rules that a good-quality mesh must meet. For example:

- The ratio of the length of an element's longest and shortest side must be as close to 1 as possible, otherwise it is distorted. This is called the Aspect Ratio.

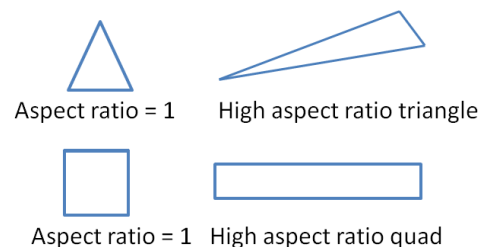


Figure 99 [14]

- The change in size should be smooth. There should not be sudden jumps in the size of the cell because this may cause erroneous results at nearby nodes.

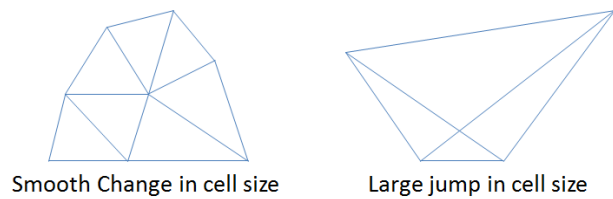


Figure 100 [14]

- The skewness of the elements should be minimal. This property is also in connection with the distortion.

In the 'Advanced Meshing Tools' module of Catia V5, there is an opportunity to evaluate the mesh according to the aspects above. The software can display each elements in green (error is unlikely), yellow (error is possible), or red (error is likely).

First I show the creation of the 2D meshes of composite shells on the example of the main element's upper shell. As shown on **Figure 101**, there are several parameters of a mesh. First I only set the Mesh Type to quadrilateral, the Element Type to Parabolic (P-method), the global size and the sag.

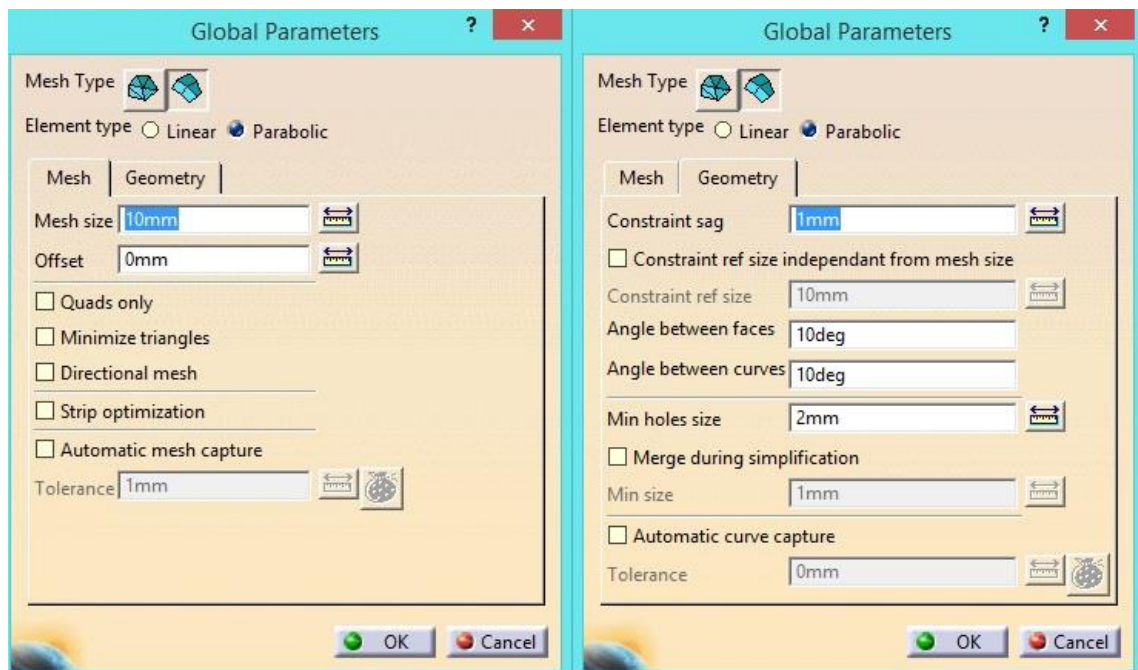


Figure 101: Global parameters of 2D mesh

After the mesh is generated, I set smaller local element size near the mounting points, because the highest stresses probably will be generated there. As shown on the figure below, some risky elements appeared which are highlighted with yellow and red colours.

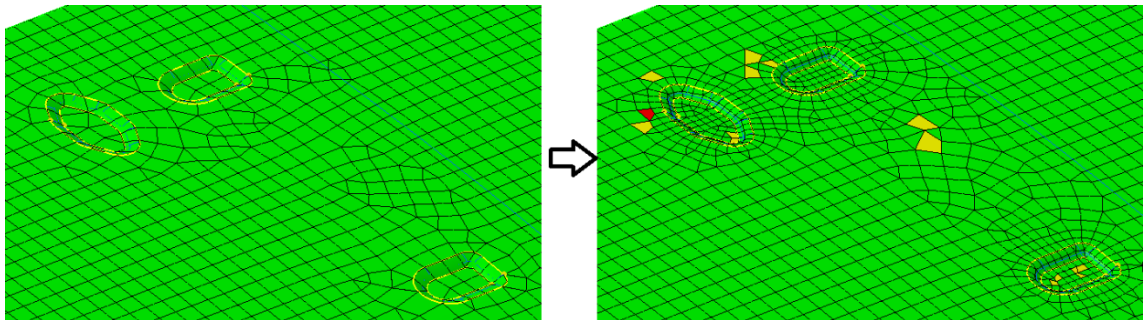


Figure 102: Locally refined mesh

Besides the automatic mesh regeneration, there are tools to modify each element manually. For example each nodes can be moved freely, and quad elements can be cut into two triangles along one of its diagonals, as illustrated below:

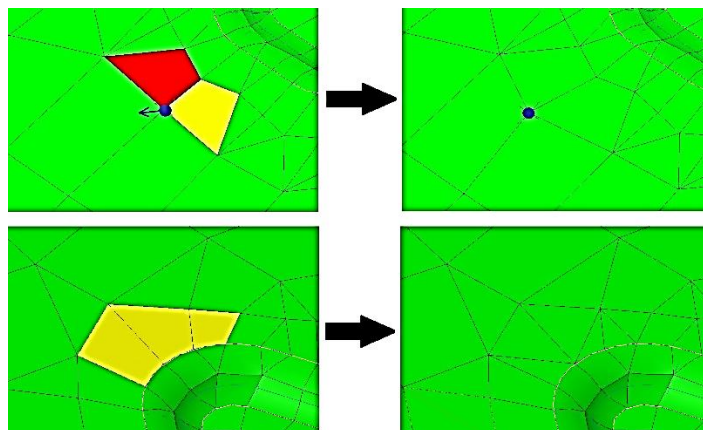


Figure 103: Manual corrections of the mesh

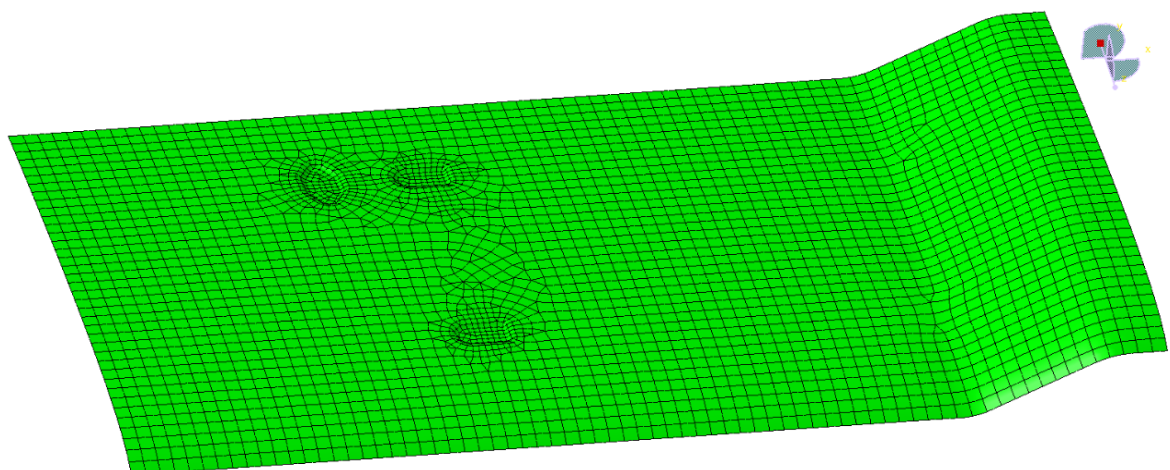


Figure 104: Final mesh of the upper shell

Before generating the 3D meshes, I simplified the geometry where it was possible, for example I removed unnecessary edge fillets. Only tetrahedron mesh can be generated automatically on solids in the software, therefore on the more complex solids, such as the adhesives I applied these elements, but in case of the inserts, which are sheetmetals, I created hexa-mesh manually. I applied local refinement near the critical areas.

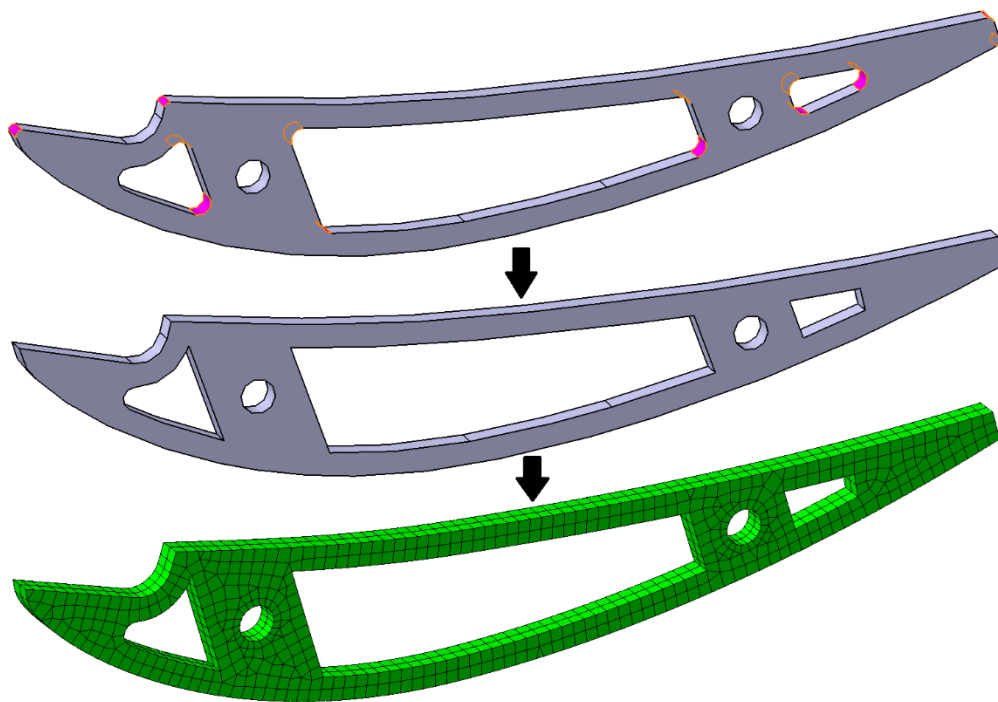


Figure 105: 3D mesh of front wing flap insert

4.3.1. *Convergence analysis*

After the first run of every analysis I investigated if further mesh refinement was needed, or the element size of each element is correct. For this I produced stress convergence analysis on the critical components. I explain it on the example of the trailing-edge bonding of the front wing flap.

First I set the element size to 6 mm, which was recommended by the software. Then I ran 6 analysis, reducing the size to 1mm in six steps, and captured the maximal stress and the number of finite elements. The value of the stress should have converged to a certain finite value. **Figure 106** shows the results of the analysis. It shows that by increasing the number of elements the stress does not change significantly until the element size reaches 1mm. After this value, there is a big jump, and the stress goes to

infinite by reducing the size. This means that singularity appears, and the result are not valid, so I did not take this point into account in the further investigations.

number of elemenzs	746	1549	2644	3998	6582	14738	39872
element size[mm] :	6	4	3	2,5	2	1,5	1
Von Mises stress [Mpa]:	1,36	2,26	2,4	2,42	2,56	2,49	4,82

Figure 106: Results of convergence analysis

Then I fitted an exponential function on the measurement points, using the method of least squares. The result:

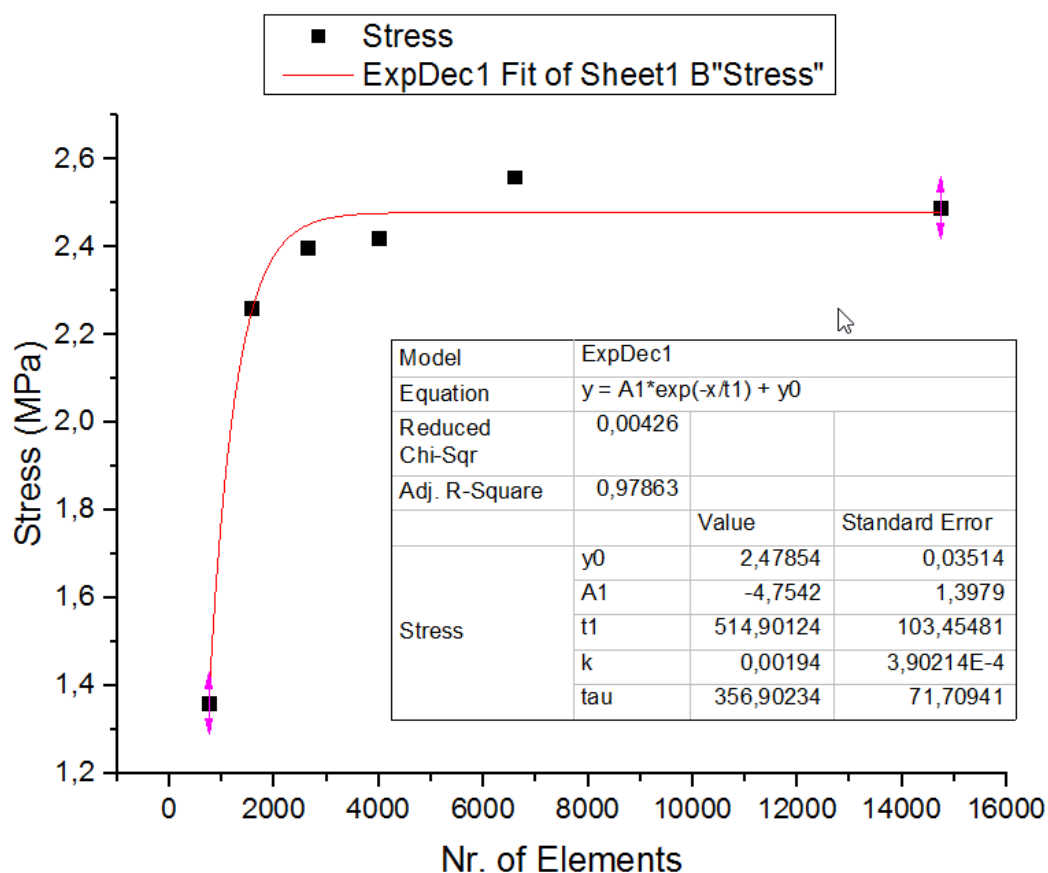


Figure 107: Stress vs number of elements

The limit of the function:

$$\lim_{x \rightarrow \infty} (-4,75 \cdot e^{\frac{-x}{514,9}} + 2,479) = 2,479$$

Concerning all, I choose the 2,5mm element size, because it approaches the 97,6% of the limit in infinite, and requires significantly less computational resources than the 2mm mesh.

4.4. Structural analysis

To make the finite element model as accurate as possible, all the front wing elements along with the holding consoles should be assembled and constrained together in one single model. With this method the influence of each components' deformations would be taken into account, which would increase the accuracy of the results. But the complexity of the model would also be increased, and because of the high number of elements and connection properties, it would take too much time to run the model, and the modifications would also be difficult. Therefore a model like this would not be useful for my application, because I will have to do a lot of iterations when creating the ply-sequences. A simple but useful model is much better for this kind of tasks. That is why I decided to make 3 different simulations: the endplates, the main, and the flap.

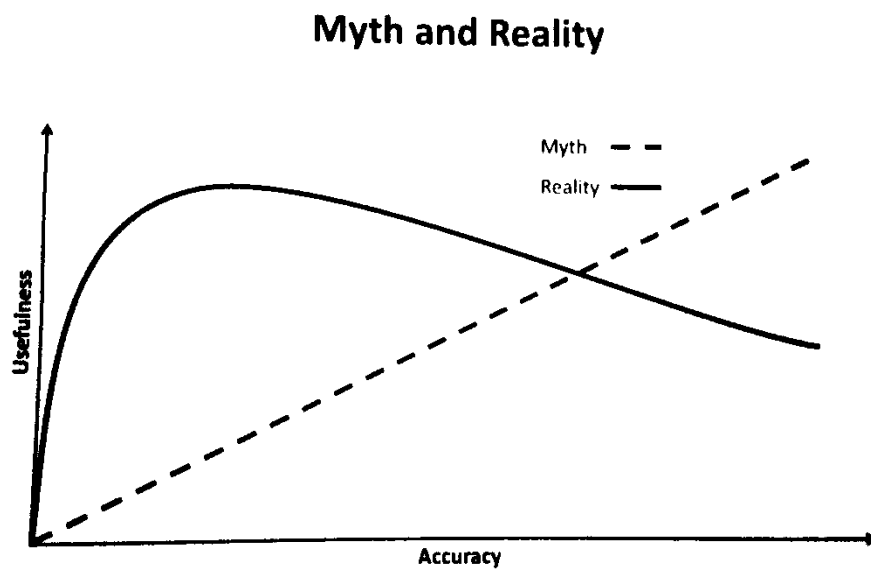


Figure 108: Usefulness vs accuracy of simulations [17]

4.4.1. Front wing flap

I started the analysis with the flap elements, because they are the ones that are influenced by the other components less. The two flaps have the same cross-section, thus almost the same geometry, so it is enough if I investigate the upper one, which has slightly higher loads, and use the same ply-sequence on the other one.

4.4.1.1. Loads and constraints

In this model there are 8 components: the upper shell, the lower shell, the two inserts, adhesive around both inserts, adhesive at the trailing edge, adhesive at the front. I

created the 3D model of the adhesives with the required thickness, and connected each part's bonding surfaces to the adhesive's surface with 'fastened connection'. The rigid mesh elements of these connections are the yellow ones on the figure below.

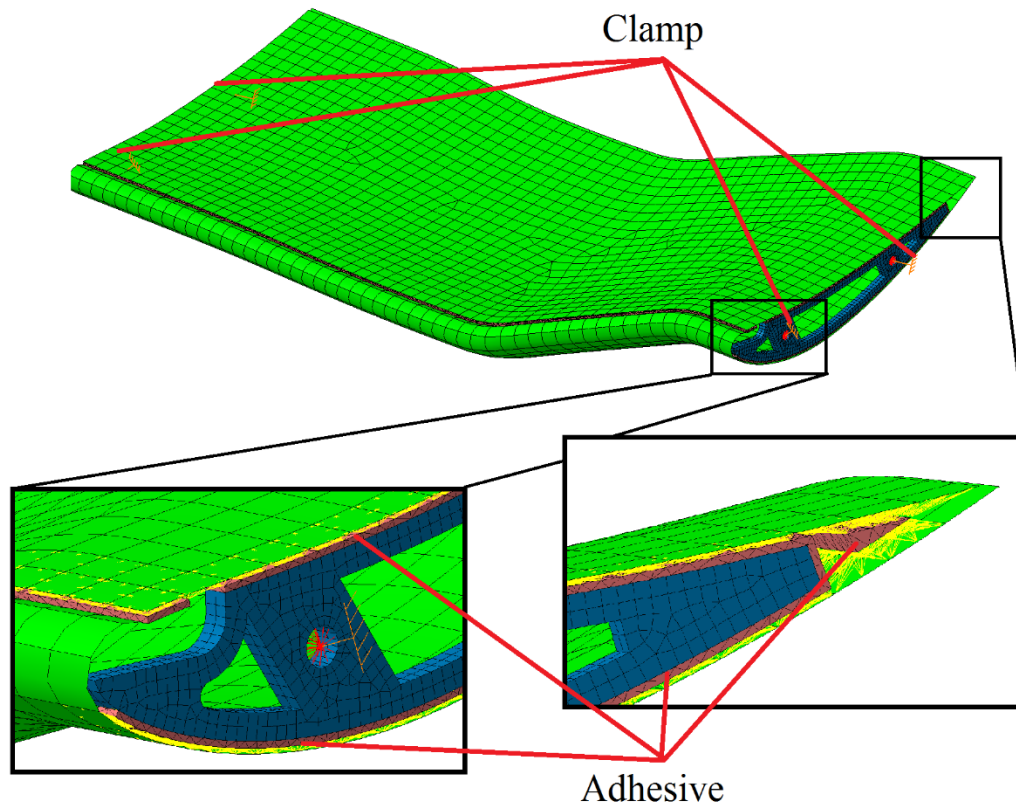


Figure 109: Constraints and connection of front wing flap

As shown on **Figure 109**, I created a finite element spider on the four threaded holes that are connected to the endplates, and made 'Clamp' restraints on them. Using these, of course, the deformation of the endplates are not taken into account, and this gives a little inaccuracy to the model. But the stresses will be higher this way, so the safety is increased, therefore it is not a problem.

The load on the flap is the air pressure when the vehicle travels its maximal speed, 130 km/h, which is calculated in CFD analysis on each elements of the mesh. There is a data mapping function in the FEA software which would make it possible to transfer the pressure of each point of the surface directly from the CFD software, but this means such a large dataset, that it increases the computational time to several hours with my hardware capabilities. I could not let that happen, so simplifications of the applied loads

must have been made. Therefore the aero team provided me simplified pressure data (**Figure 110**) which is of course slightly unrealistic, but also in the direction of safety.

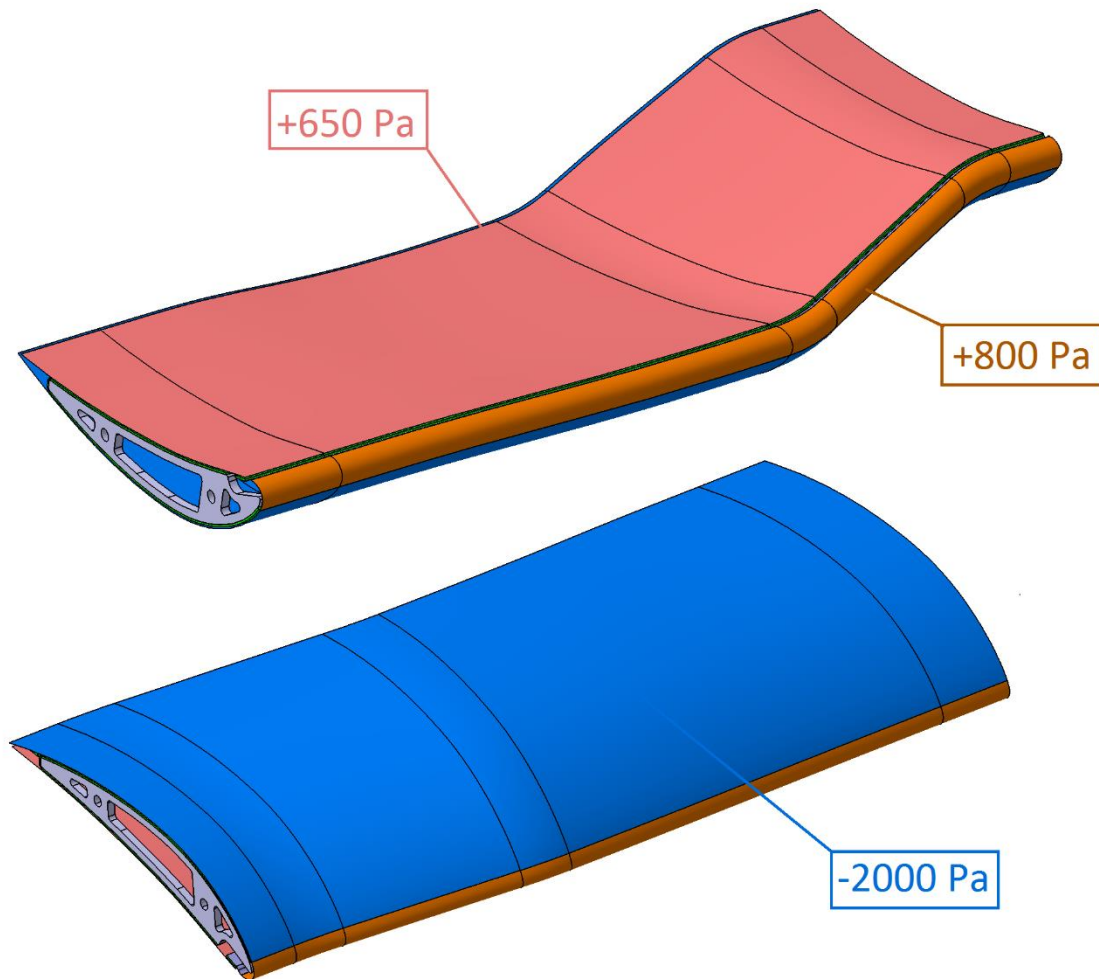


Figure 110: Applied loads

After I ran a few analysis it became clear that there are no high stresses on the composite shells, so I tried a minimal ply-sequence. It is highly recommended to use a symmetrical ply-sequence, especially in thin shells like this, otherwise deformation can occur, or inner stresses might be generated during the curing period of the resin. It is also recommended to add fabric ply to inner or outer layer, because it can absorb more impact damage than the unidirectional plies. Taking these into account, and that one 90° UD must be applied to handle the loads, the final ply-sequence of both the upper- and lower shells: $[\pm 45^\circ / 90^\circ \text{UD} / \pm 45^\circ]_T$.

4.4.1.2. Evaluation

After setting up the model I ran the analysis. In the post-processing phase I evaluated the Tsai-Wu index of the composite parts, the Von Mises stress of the aluminium inserts and the adhesive at the trailing-edge and the front. The principal load of the bonding around the inserts is shearing, so I examined shearing stresses there.

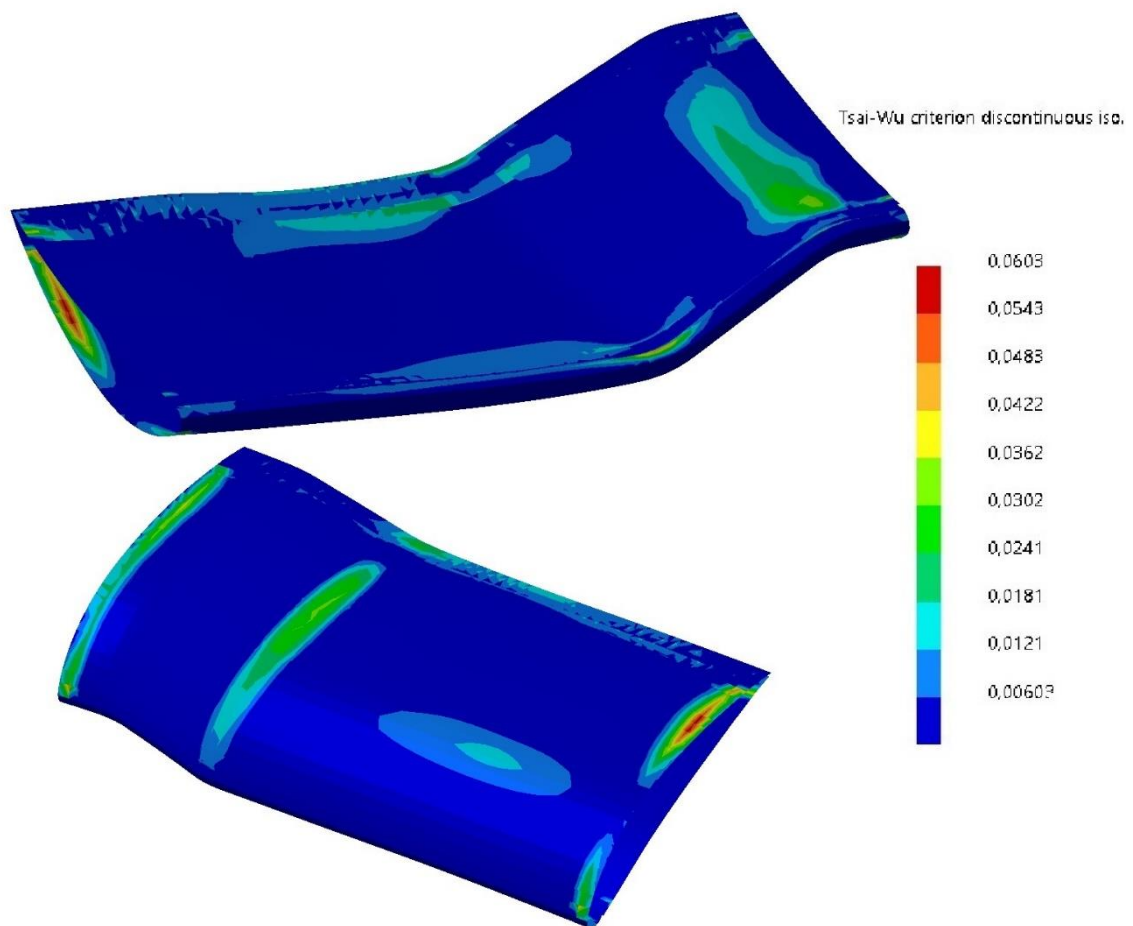


Figure 111: maximal Tsai-Wu index of composite shells

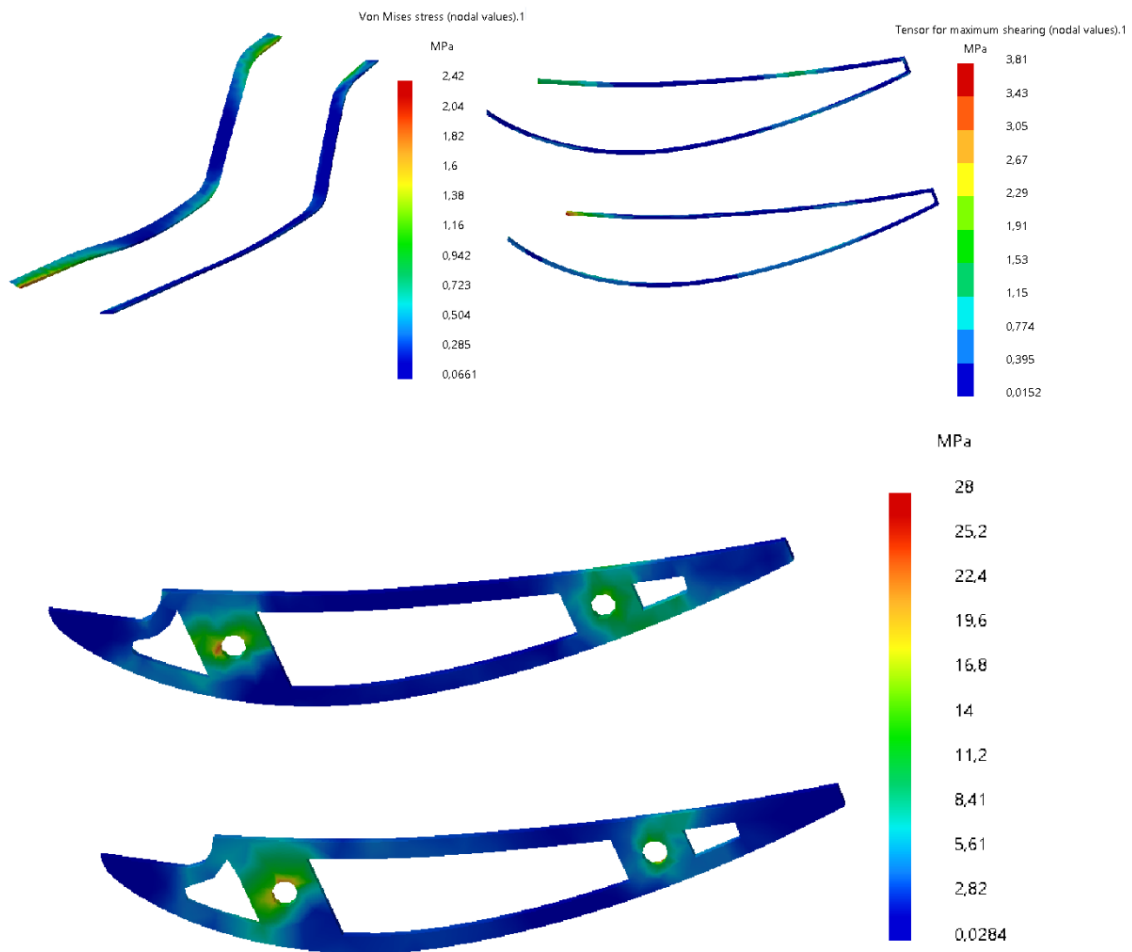


Figure 112: Stress of the inserts and the bonding

The final results of stress analysis:

Component	Material	Examined	Value	Limit	Safety factor
Upper shell	CFRP	Tsai-Wu	0,033	1	30,30
Lower shell	CFRP	Tsai-Wu	0,0603	1	16,58
Left insert	AlSi1MgMn - EN AW 6082 T6	Von Mises	28	250	8,93
Right insert	AlSi1MgMn - EN AW 6082 T6	Von Mises	23,8	250	10,50
sheared adhesive	Loctite 9466	Shearing stress	3,31	10	3,02
tensed adhesive	Loctite 9466	Von Mises	2,48	8	3,23

As shown above, there are no critical stresses in any of the components, so I investigated the stiffness. Deformations are shown on the figure below.

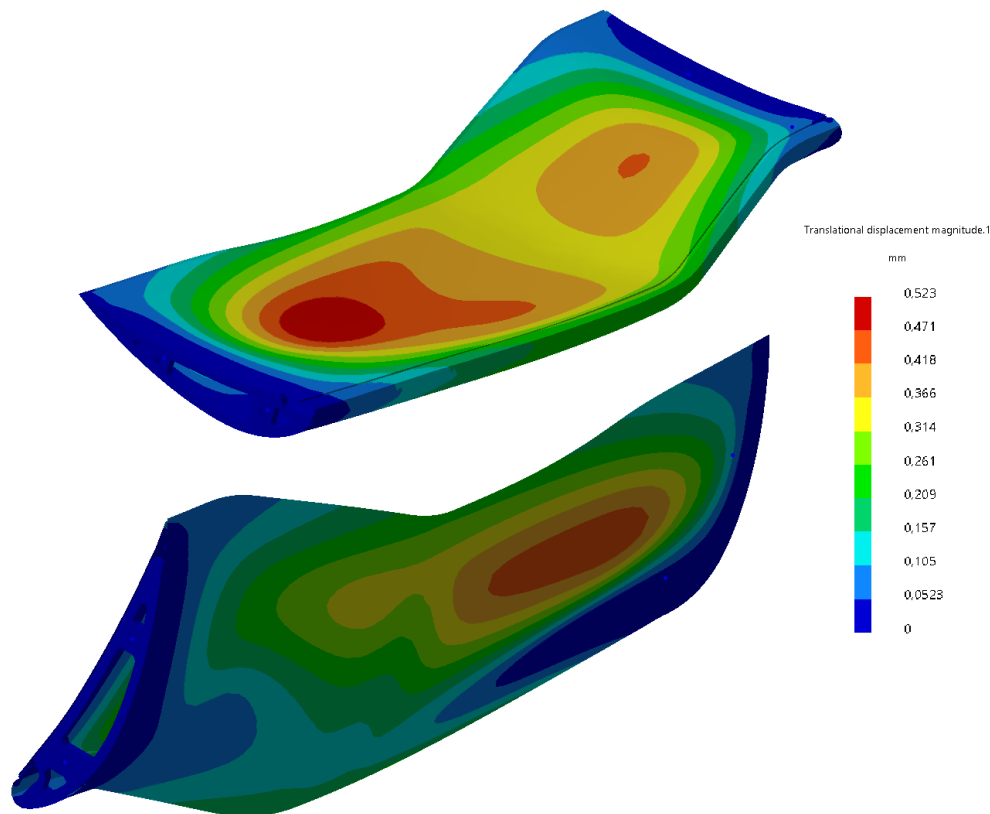


Figure 113: Displacement

The deformed mesh shows that the curved shape of the wing gives it an extra stiffness. The maximal deformation is on the upper shell, its deflection is 0,523 mm, which is acceptable.

4.4.2. *Endplates*

4.4.2.1. *Loads and constraints*

After the flap's ply-sequence is finalized, the endplates can be investigated. I analysed the endplate and the inner endplate in one model. As shown on **Figure 114**, I clamped the four drillings on the two endplates which are connected to the main element.

In the CFD software a force on one single point can be calculated which is equivalent to the pressure of each element. These equivalent points of the two flaps are 'F_2' and 'F_3'. I connected these points to the drillings with spider elements, and put the aero force of the flaps at 130 km/h on them. In the CAD system I calculated the flaps' centre of gravity (G_2 and G_3), and also connected these to the drillings with rigid spiders. Then I put the element's mass on the points, and created a lateral 2 g acceleration field to simulate cornering. This 2g includes a safety factor.

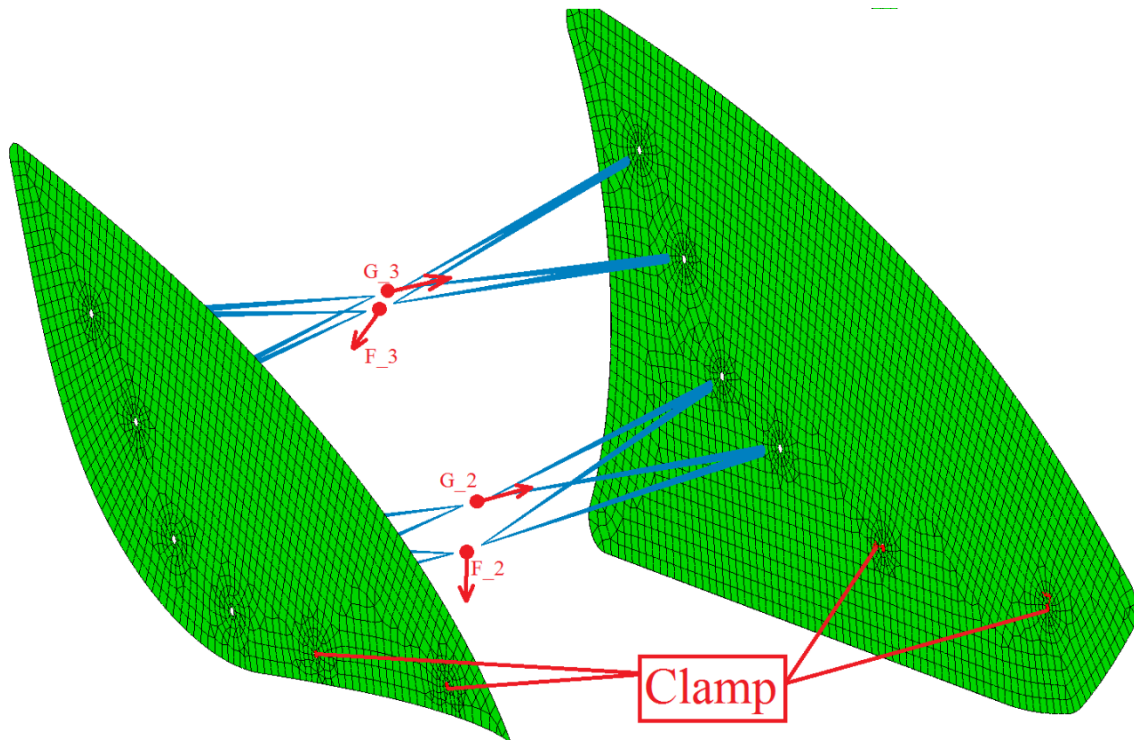


Figure 114: Loads and constraints of the endplates

The coordinates of the points and the values of the forces summarized:

Name	coordinates [mm]			Force [N]			Explanation
	x	y	z	x	y	z	
G_2	526,16	497,24	158,73	0,00	5,02	0,00	Lateral force of flap 1 during cornering
F_2	530,00	485,50	126,20	-52,00	13,74	-140,00	Resultant force of aero load on flap 1
G_3	416,04	496,69	284,46	0,00	5,02	0,00	Lateral force of flap 2 during cornering
F_3	415,00	489,50	274,00	-76,00	6,41	-63,00	Resultant force of aero load on flap 2

4.4.2.2. Ply sequence

It took several iteration steps to create the final stacking sequence of the endplates. In this work I will not present the whole process, only the final stage. As show on **Figure 115** and **Figure 116**, I used core material in the full surface of the endplates to increase stiffness, except in the red areas around the drillings to avoid core crack. Around the holes there are reinforcements and there are additional reinforcements which connect the mounting points of the flaps.

Zone	Ply-sequence
	$[0^\circ f / \text{Core} / 0^\circ f]_T$
	$[0^\circ f / 75^\circ \text{UD} / 75^\circ \text{UD} / \text{Core} / 75^\circ \text{UD} / 75^\circ \text{UD} / 0^\circ f]_T$
	$[0^\circ f / 75^\circ \text{UD} / 75^\circ \text{UD} / \pm 45^\circ f / 75^\circ \text{UD} / 75^\circ \text{UD} / 0^\circ f]_T$
	$[0^\circ f / 0^\circ \text{UD} / 0^\circ f]_T$

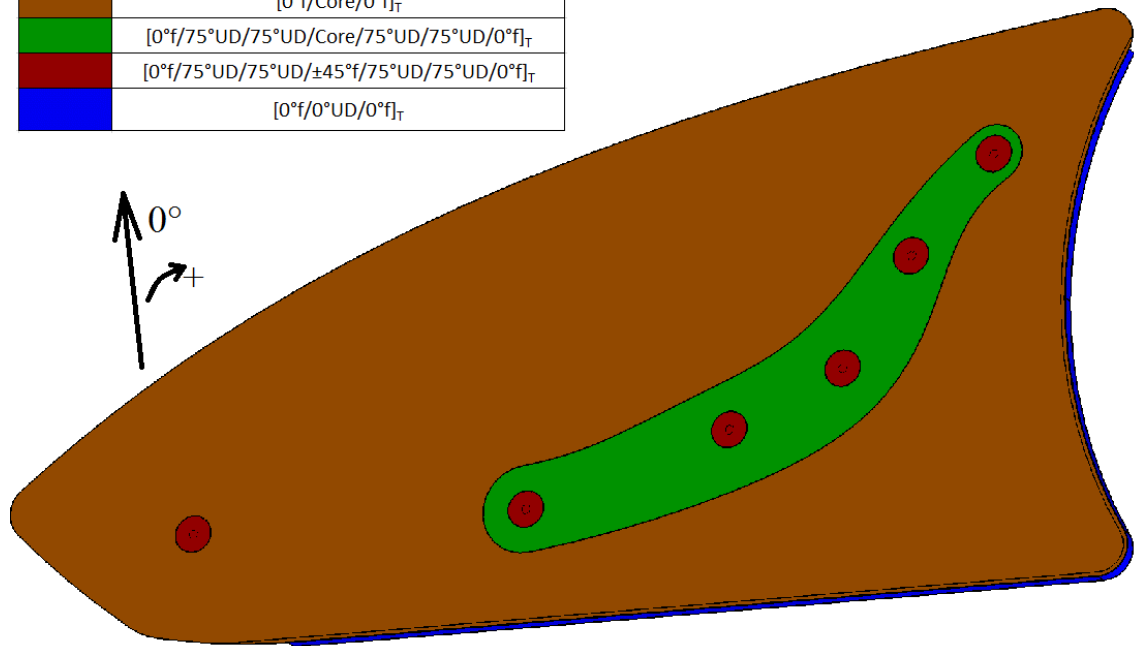


Figure 115: Ply-sequence of the endplate

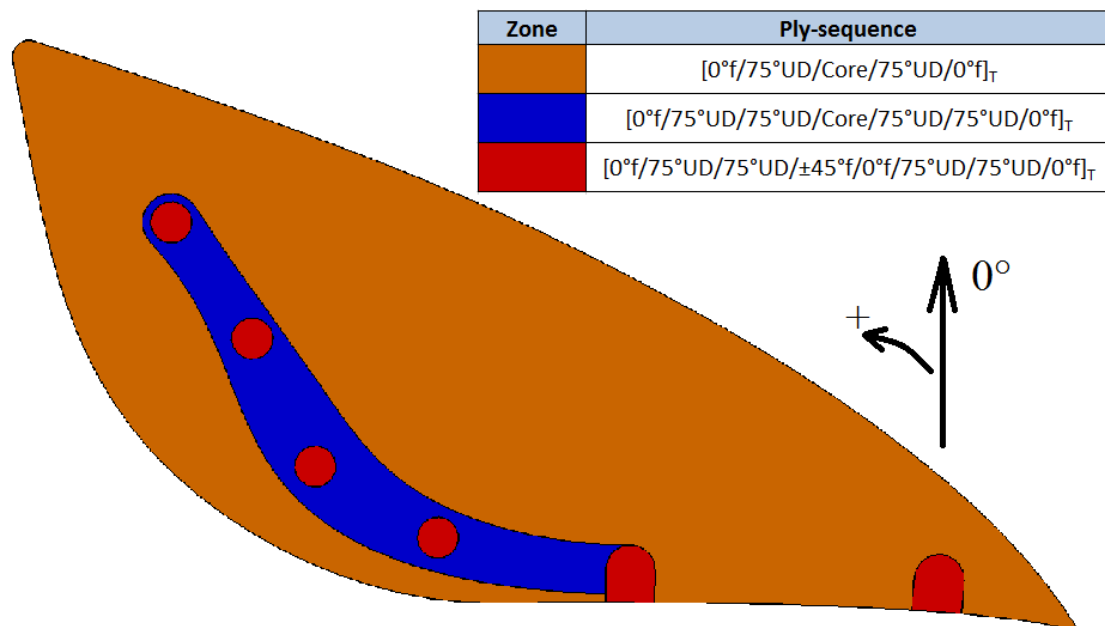


Figure 116: Ply-sequence of the inner endplate

4.4.2.3. Evaluation

As shown on **Figure 117**, The Tsai-Wu failure index is higher around the holes, that is why reinforcement is needed there. Just like in the case of the flap, the stress is not critical, the main design aspect was the stiffness.

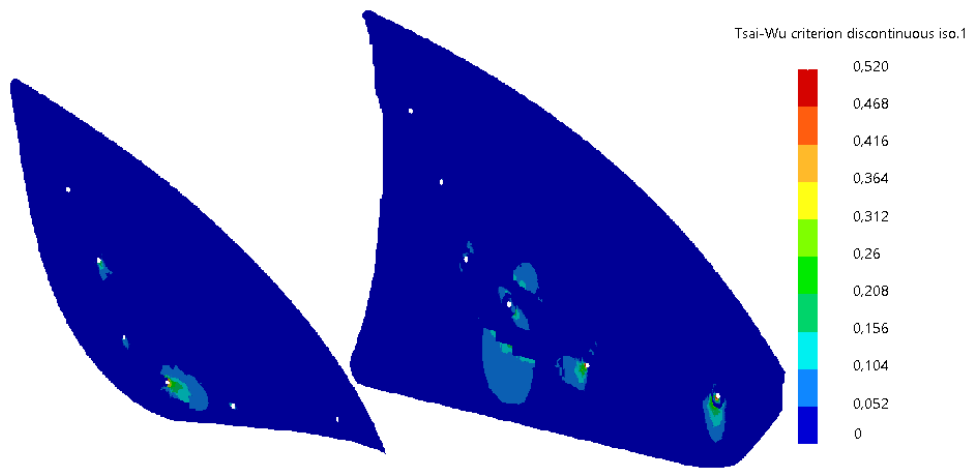


Figure 117: Tsai-Wu index

Summarization:

Component	Material	Examined	Value	Limit	Safety factor
Endplate	CFRP	Tsai-Wu	0,52	1	1,92
Inner endplate	CFRP	Tsai-Wu	0,41	1	2,44

Using our experiences and intuitions, we decided to define the stiffness as 1mm allowable deformation under these loads. Therefore I made the iterations on the ply-sequence until I reached 0,955mm with minimum weight.

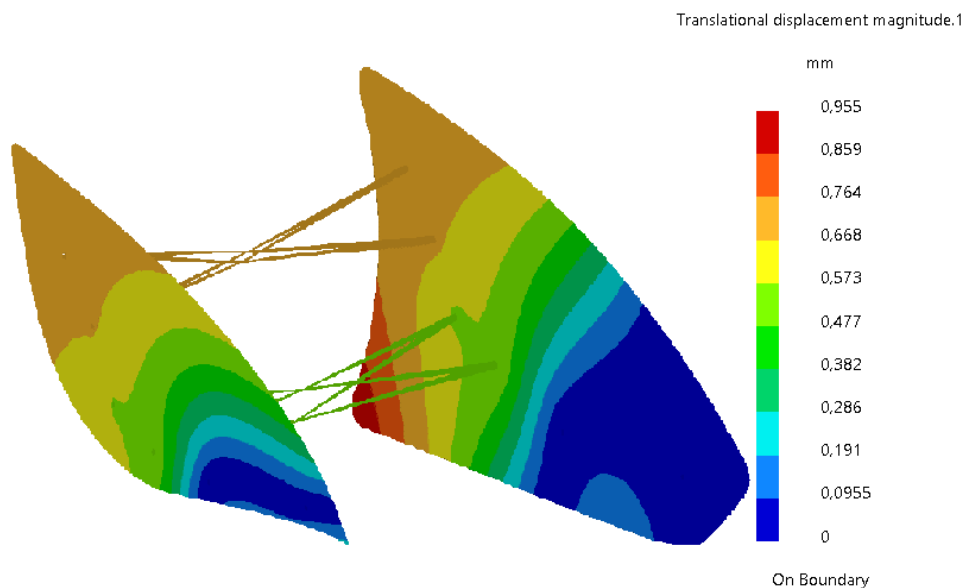


Figure 118: Deformation

4.4.3. Front wing main

4.4.3.1. Constraints

In the case of the front wing main, both the geometry and the loads are symmetrical to the XY-plane, therefore I only built a half-model, and applied a symmetry constraint to

decrease computational time. Similarly to the flap, the components of the main element are also connected together via 'Fastened Connection'. Also in order to reduce computational time, I did not build the connecting parts, for example the composite rods in the model, but I tried to replace them in the most realistic way. I created two 1D meshes to simulate the steel wire and the carbon rod. I created points in the centre of the ball-bearing and the fastening elements, and connected them to the mating surfaces via rigid spiders to simulate the L-profiles and the mounting flaps.

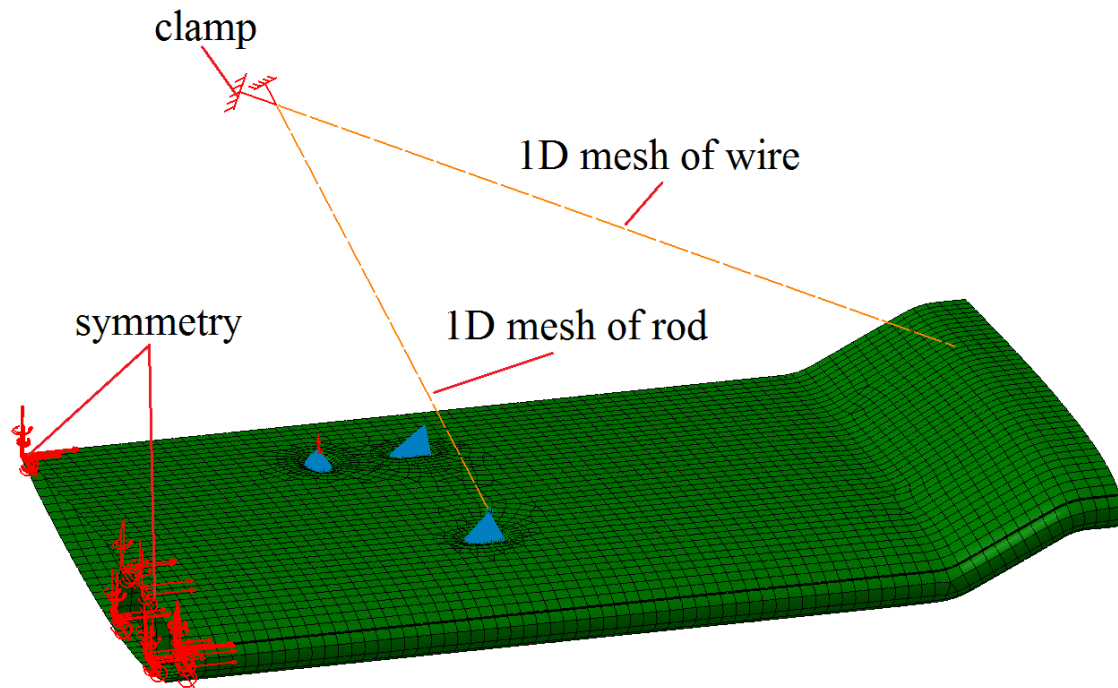


Figure 119: Constraints

4.4.3.2. Loads

Just like previously, I also received a simplified pressure distribution data from the aero team for the main element (**Figure 120**). Besides the forces generated by the main itself, the load of the two other elements are also transferred to it via the endplates. To define these forces as accurate as possible, I created 'reaction sensors' on the clamps of the endplates. The opposite of these reaction forces are the forces that effect the main element (**Figure 121**).

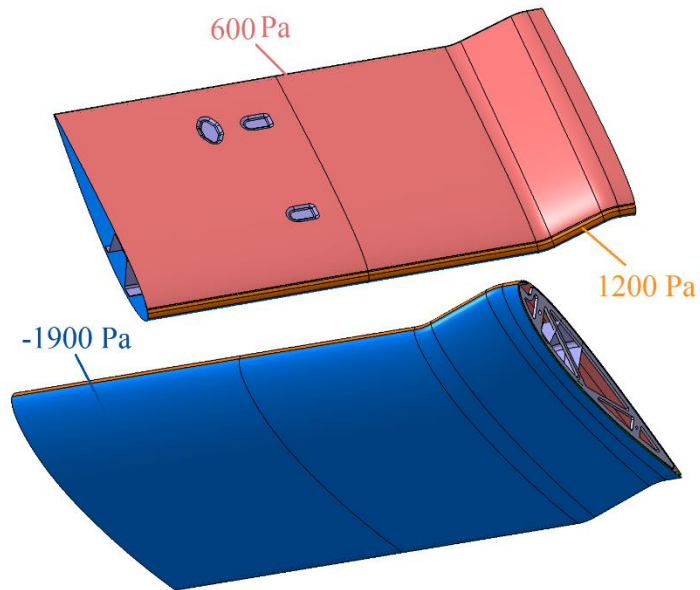


Figure 120: Pressure on front wing main

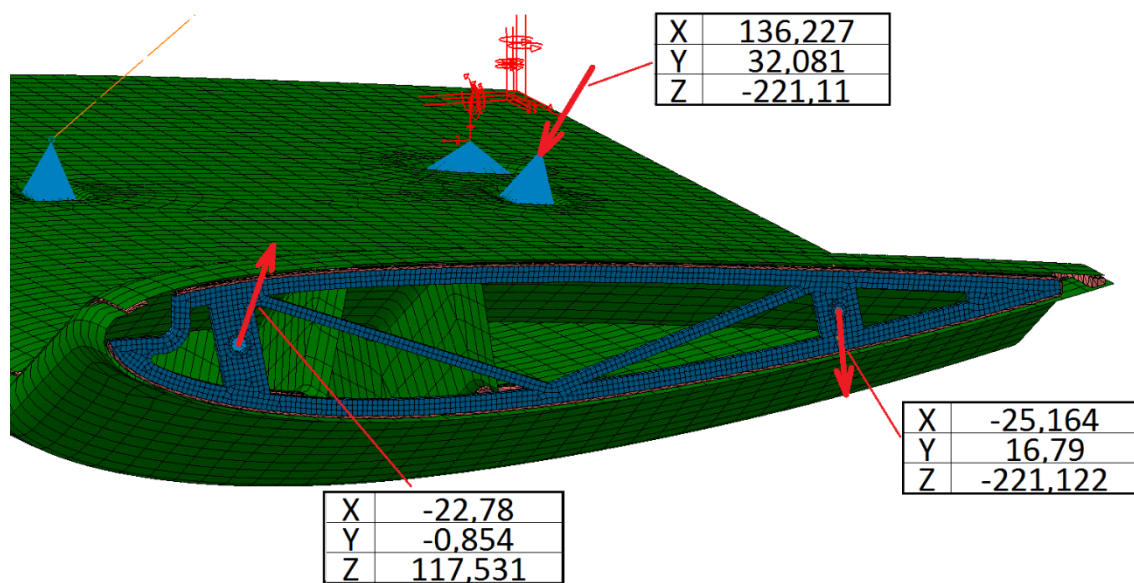


Figure 121: Forces transmitted from other elements

4.4.3.3. Ply sequence

Here I also explain the final solutions, which are the results of a long iteration procedure. As shown on **Figure 122**, on the red area the deflection was too high, therefore I put core there to increase stiffness.

Zone	Ply-sequence
	$[\pm 45^\circ f / 90^\circ UD / 0^\circ UD / \pm 45^\circ f]_T$
	$[\pm 45^\circ f / 90^\circ UD / \text{core} / 90^\circ UD / 0^\circ UD / \pm 45^\circ f]_T$

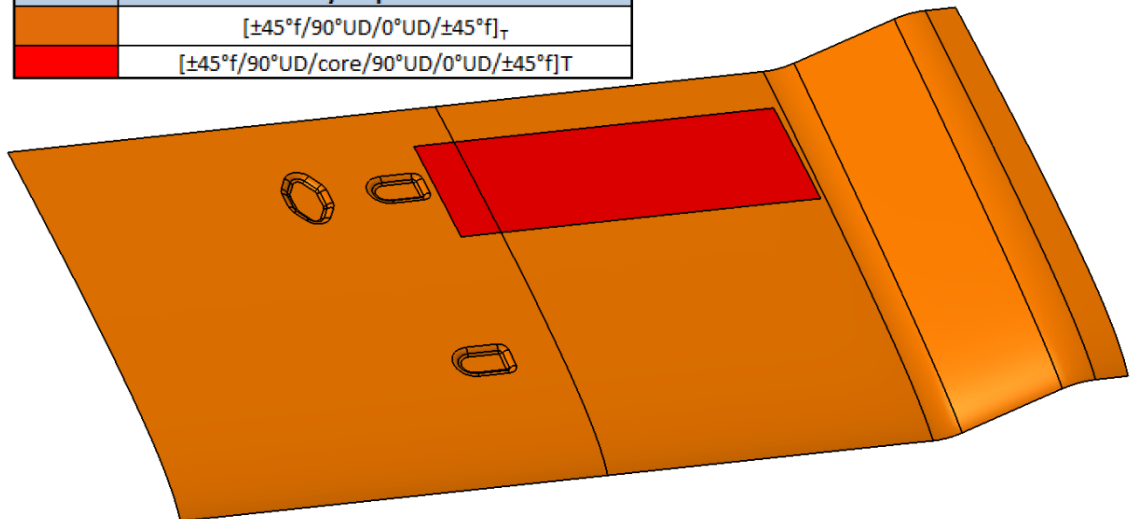


Figure 122: Ply-sequence of Upper Shell

The lower shell is similar to the upper, but instead of core it was enough to use an additional ply of UD carbon (which is lighter) on the green and blue areas for stiffening.

Zone	Ply-sequence
	$[\pm 45^\circ f / 90^\circ UD / \pm 45^\circ f]_T$
	$[\pm 45^\circ f / 90^\circ UD / 0^\circ UD / \pm 45^\circ f]_T$
	$[\pm 45^\circ f / 90^\circ UD / 90^\circ UD / \pm 45^\circ f]_T$

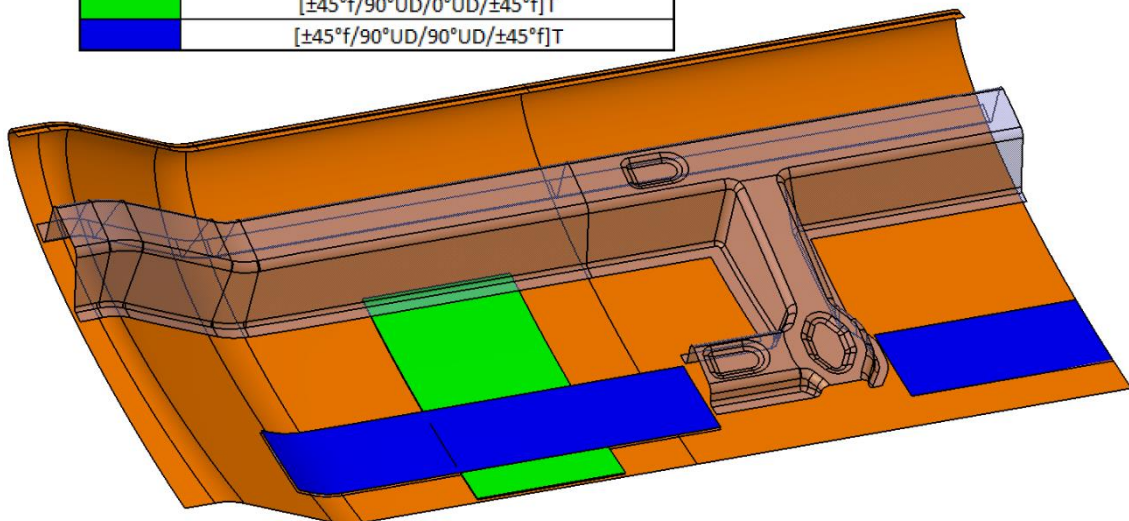


Figure 123: Ply sequence of Lower Shell

Figure 124 shows the ply-sequence of the Omega. As shown, additional reinforcement is needed around the mounting points. The fibre directions are optimised for maximum stiffness. On its upper surface only transverse tensile stress is generated, therefore only $0^\circ UD$ carbon is put there.

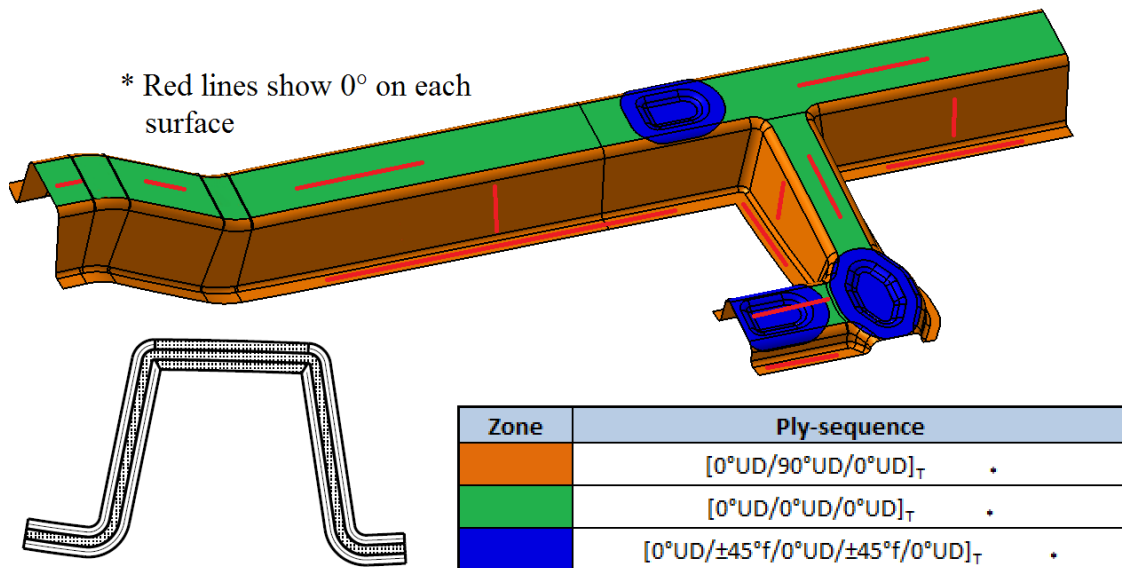


Figure 124: Ply sequence of Omega

4.4.3.4. Evaluation

As I expected, high values of Tsai-Wu index appear around the mounting points, and besides these areas, the probability of composite failure is not critical.

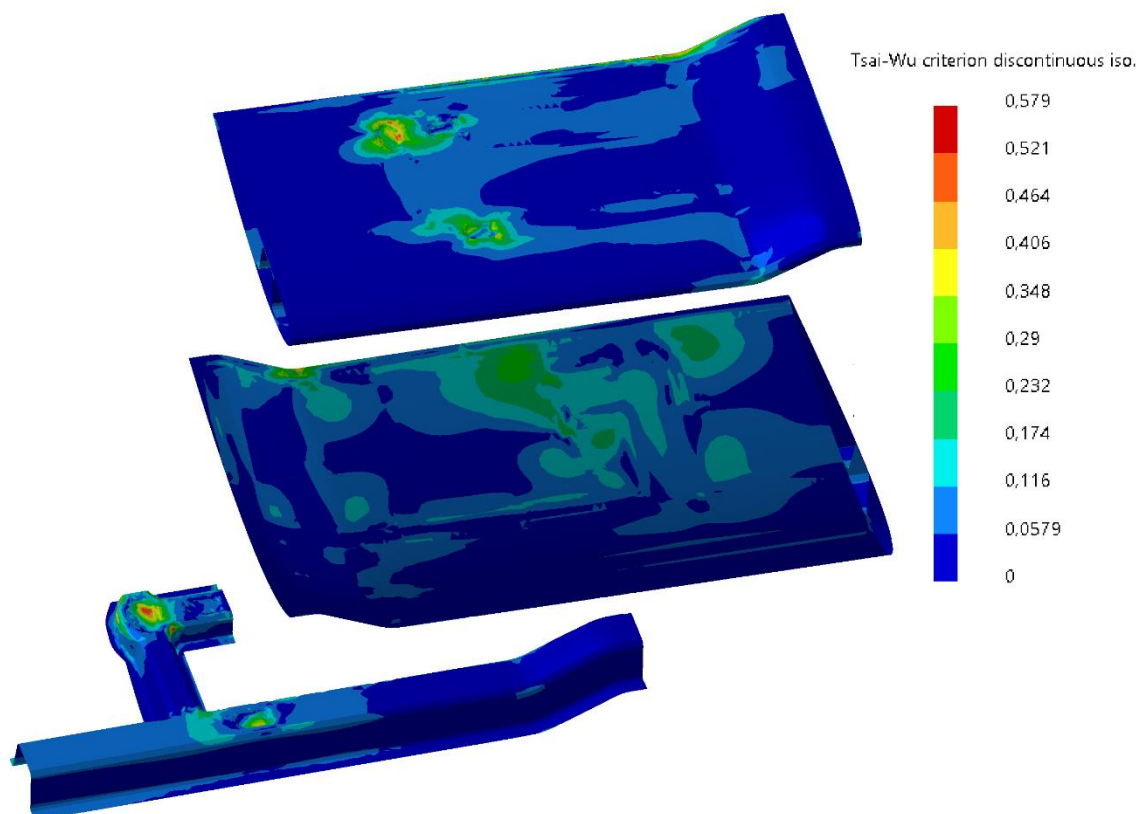


Figure 125: Tsai-Wu index

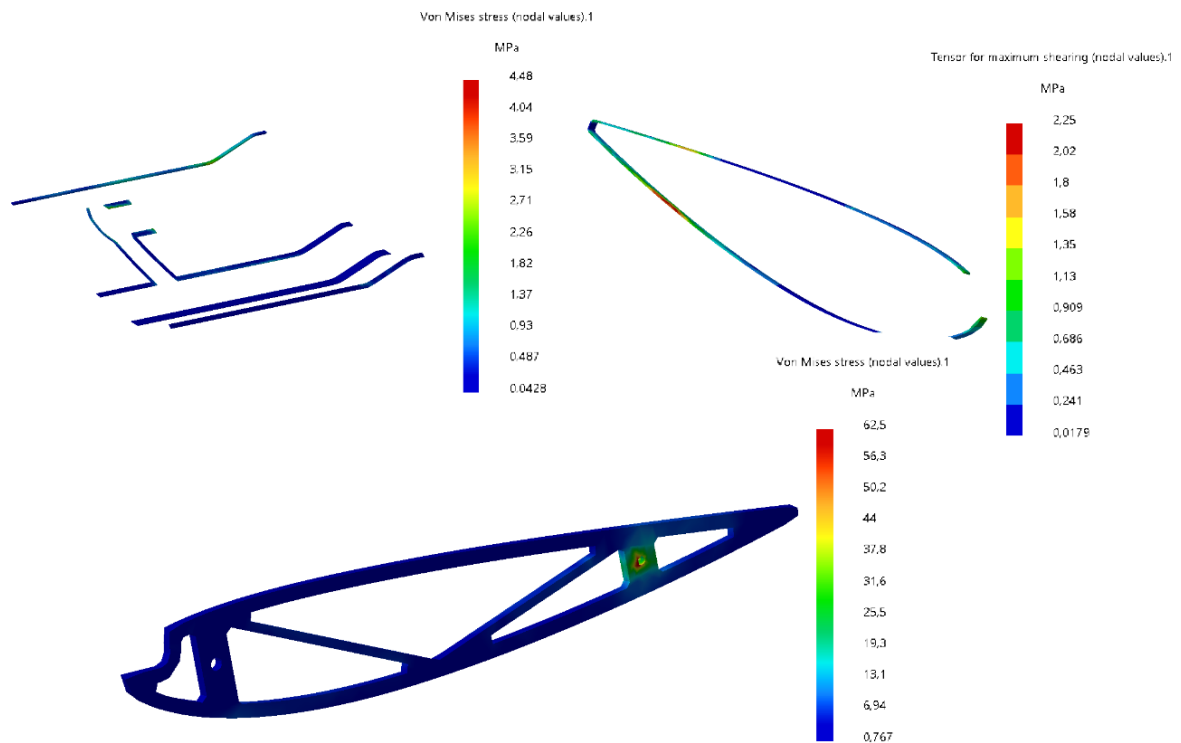


Figure 126: Von Mises and shearing stress

Summarized results:

Component	Material	Examined	Value	Limit	Safety factor
Upper shell	CFRP	Tsai-Wu	0,579	1	1,73
Lower shell	CFRP	Tsai-Wu	0,371	1	2,70
Reinforcement	CFRP	Tsai-Wu	0,453	1	2,21
End-insert	AlSi1MgMn - EN AW 6082 T6	Von Mises	62,5	250	4,00
sheared adhesive	Loctite 9466	Shearing stress	2,25	10	4,44
tensed adhesive	Loctite 9466	Von Mises	4,48	8	1,79

Stiffness is also more critical than strength in this case. We defined the maximum deflection at the side to be 3mm, to avoid the endplates to touch the ground during extreme cornering conditions. As shown on **Figure 127**, the maximal deflection is only 1,7 mm at the side, but the overall maximum is 2,8mm. I have made several variations, and I experienced that the steel wire has a great effect on the stiffness, because the deflection with the same ply-sequence without the wire was more than 5mm, and reaching 3mm could have only been achieved by adding much more weight to the composite shells.

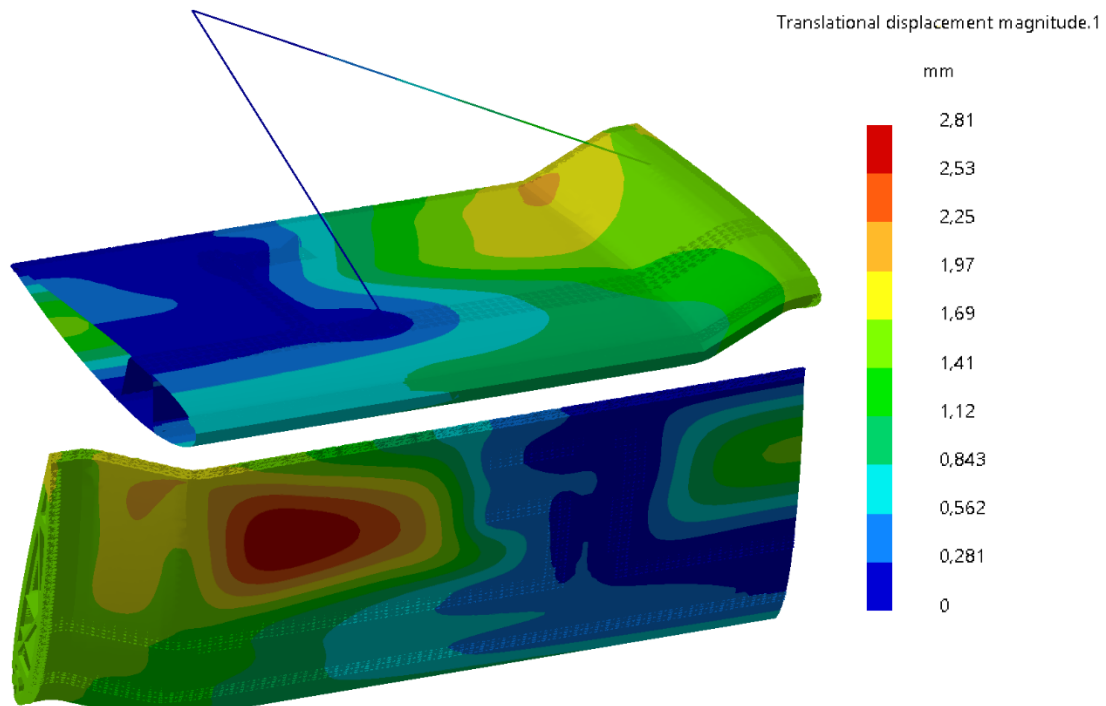


Figure 127: Deformation

4.4.4. *Undertray*

The CFD simulations showed, the suspension parts under the monocoque worsen the airflow so much, that a new undertray geometry would generate more downforce only by some Newtons. Therefore we decided, not to design a new geometry and manufacture its mould. But we didn't want to use the undertray of the 2013 car either, because it was too heavy as for its loads. So we decided to manufacture a new undertray with the old geometry but with a new ply sequence, thus we could use the already finished mould.

The determining method of the new ply sequence was similar to the previously written FEM methods.

The result of the simulations:

- The weight of the 2013 car's undertray was 9,7 kg
- The weight of the 2014 car's undertray was 4,3 kg in the simulations
- The weight of the 2014 car's undertray was 4,5 kg after finishing



5. Manufacturing

5.1. Moulding - tooling

5.1.1. *Prologue*

Composite fabrication processes involve some form of moulding, to shape the resin and reinforcement. Basically these are the first steps of producing the final product: the designing and the manufacturing the moulds. A mould tool is required to give the unformed resin /fibre combination its shape prior to and during cure. Making high-grade moulds is really important, because it determines the quality of the composite product's surface. As we learned from the last year's problems, our wings' moulds functions were not only to give the product's shape, we used these as tools also.

We can split the whole process - from the CAD model of the product's final geometry, until finishing the moulds – into 3 main phases. The first phase was to mature the requirements, to determine the exact functions of these moulds, the second phase was the design itself, when we got the final surface model of the product, and started to draw the geometry of the moulds, and the third phase was the mould fabrication.

In addition, we had to look for another moulding type too, because of the small rear wing flaps.

5.1.2. *Basic concept, requirements and facilities*

Before starting the design, we had to know some details to create the moulds and mature the requirements of the usages.

First we clarified some details in our facilities:

- Number of moulds
- The raw materials
- Type of CNC machines
- Surface finishes after milling

And we had to determine the requirements for the moulds

- Basic concept
 - Avoiding undercuts
 - Sufficient rigidity
 - Number of tools for a wing shell
- Surface elongation, product's edge indicator
- Mould as positioning tool also

5.1.2.1. Material selection

Because we manufacture a prototype car, which means we fabricate only one or in rare cases two products from one mould, we don't need such tough material like aluminium or steel for mould, wherewith you can manufacture 500 products of more. Therefore we had two chances for mould material, the Medium Density Fibreboard and the tooling block. Finally we chose the MDF, because we have experiences with this material from previous years and it is much cheaper than the tooling block. The other benefits of this material are that it is easily workable, it is dimensionally stable and more heavy-duty than the foam moulds. The disadvantages of the material are that the surface quality after milling need to improve and it needs protection from the wet areas, it is sensitive for the liquids.



Figure 128: MDF tables

The MDF tables basically can be purchased in quite

big tables, with limited thickness (**Figure 128**) - and our moulds are always thicker than these thickness - that is why we had to build the moulds with using more layer of them. Before the machining, these layers had to bond together with a sufficient rigidity glue to reach the expected stiffness for the milling. As for our prior experiences in choosing the proper adhesive, we used polyester adhesive and Butanox M50 catalyst for curing. This mixture provides enough strength, but the cost of it is favourable.

5.1.2.2. Type of the CNC machines

Before every design process, it is always an essentially important topic, to know your opportunities for the manufacturing. Therefore at the beginning of this project we collected our facilities for the machining. As result of this, we knew that, there are 2 machines, each wholly different attribute. We had opportunity to machine the moulds on a 3-axis CNC machine and on a 2D milling machine. It was obvious, the 2D milling machine cannot mill a sculptured surface, so every wing moulds were made on the 3D axis CNC machine, except, the moulds for the endplates.

5.1.2.3. Surface treatment after milling

The pure, milled MDF's surface is not ready for using it as composite mould. The surface is not enough smooth, it is porous and full of with little filaments because of the MDF-s structure, as shown on **Figure 129**. For this problem, the solution is to polish the surface first, and then paint it to reach the needed surface quality. It is a significant step also, because it is the last treatment for the moulds, so the final product's surface quality depends on the paint job's quality and it also makes the product removal easier after curing.



Figure 129: Milled MDF surface without treatments

5.1.2.4. Basic concept

As mentioned sooner, to be able to manufacture the products, it needed to cut the shells into 2 pieces. Aspects of the manufacturing and the mould, it would be better to separate these surfaces at the leading edge, but we had to consider the aerodynamics regards also.

As the result of this decision, we needed to use 3 moulds to make the final geometry, one for the upper shells and two for the bottom shells. In the case if we would made the mould in one piece for the bottom shell, it would be undercut at the leading edge, a 3-axis CNC machine could not milled that area, it would be hard to made the surface finishes and after the product manufacturing, we were not able to remove it the product.

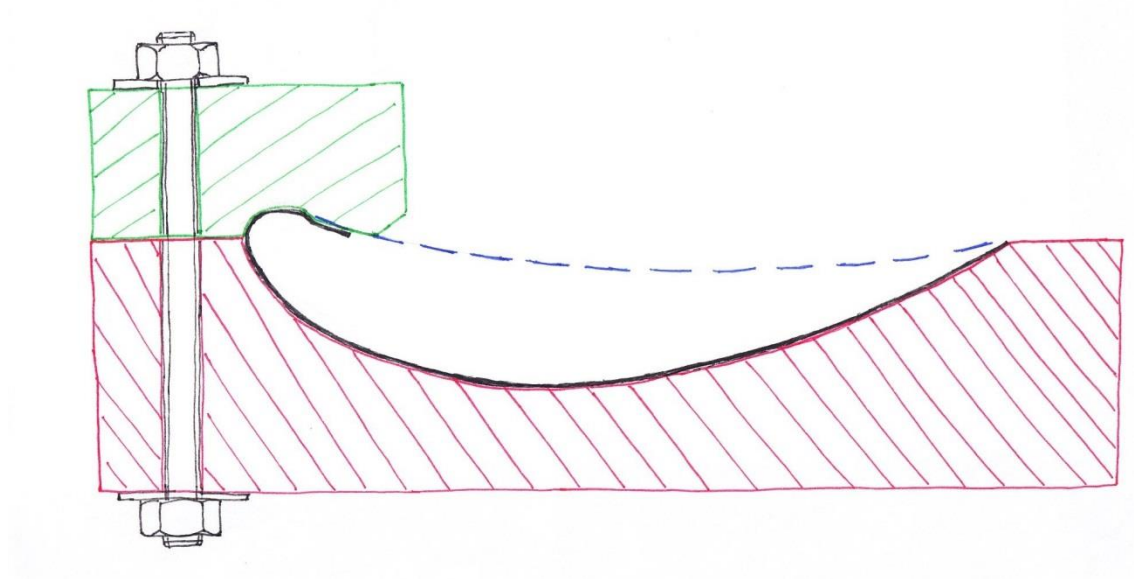


Figure 130: Bottom shell's moulding

As you can see on the Figure 130, to avoid these problems, parting plane was placed at the middle of the leading edge. To fix together the two parts, we used threaded rods, washers and nuts.

Although we use MDF for the moulds, we have to ensure, these will be rigid sufficiently, because a little deform could cause inaccurate product. As for our experiences, we determined the minimum thickness should be minimum 30 mm between the lowest point of the surface and the bottom of the moulds.

5.1.2.5. Surface elongation, product's edge indicator

During manufacturing a reinforced composite part, it always needs to have allowances on the product, and cut these during the finishing phase, because you cannot laminate parts with accurate edges of dry plies. Therefore, during mould designing it is suitable to elongate the surfaces near the final product's geometry. Usually a 30-50 mm place is enough for the unnecessary parts and another 15-25 mm required for the tacky tape, which is used for sticking the vacuum bag onto the mould.

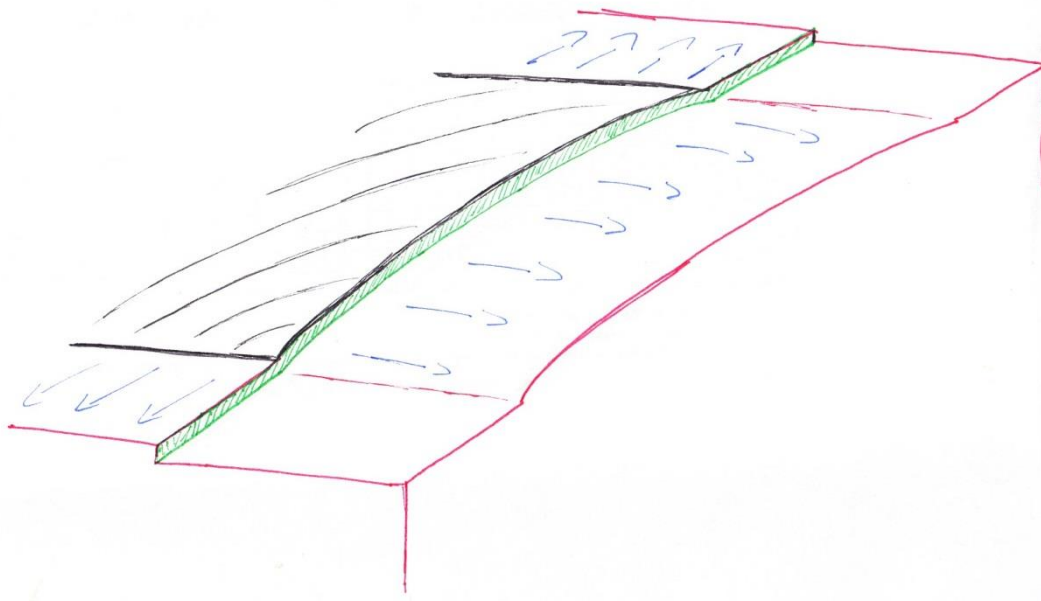


Figure 131: Concept of surface elongation and edge indicator

In addition, it is always worth to design an indicator edge onto the moulds surface to show the required verge of the products. **(Figure 131)** During the fabrication process it helps not to make too much waste, by showing laying up borders and during the finishing phase it also helps, because the indicator's geometry stays on the cured, but unfinished part and shows the cutting edge.

5.1.2.6. Moulds as positioning tool

In 2013 – while making the 2013 car's aero package - when we joined the two shells together, sometimes the parts slipped relative to each other, because we could not ensure the positions until the curing phase's end, which caused inaccurate final wing surfaces. To avoid this problem, we invented, the moulds should work as tools also, to position the surfaces during the bonding process and until the adhesive's curing too.

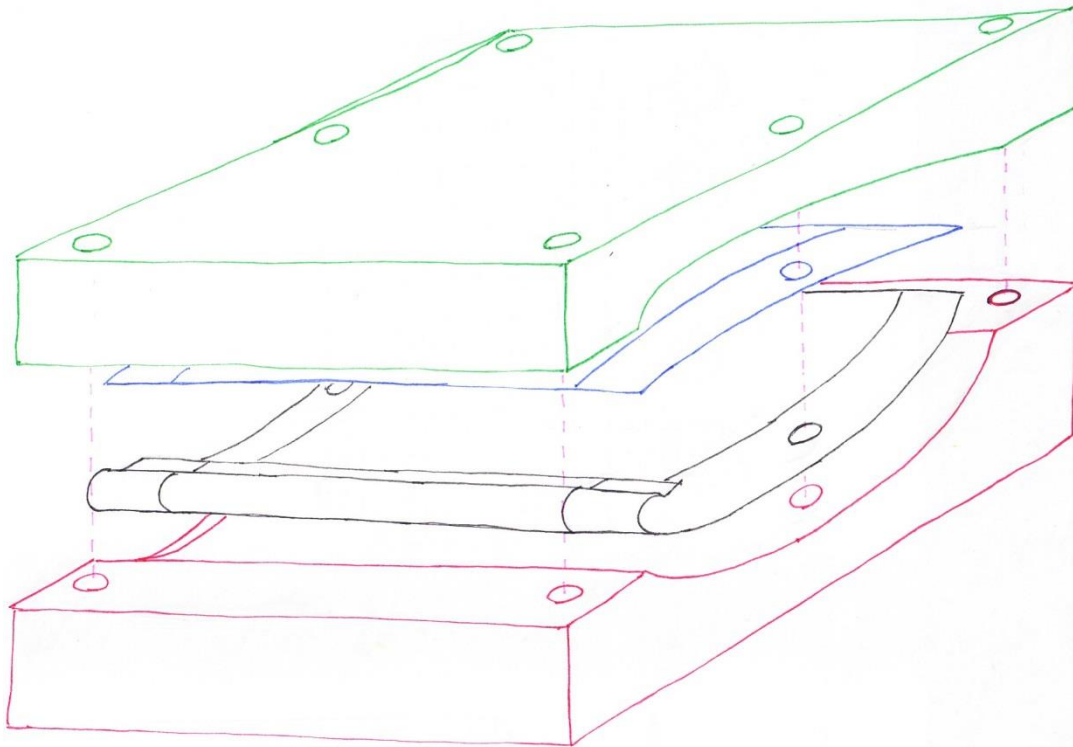


Figure 132: Moulds as positioning tool

The implementation of this idea is quite simple. First step is to secure the shell position as for the mould. As you can see on the **Figure 141**, the moulds and the shells have holes on the same place, on the elongation area. Into these holes we put pins, which prevent the displacement of the elements. In addition, the moulds of the upper shells had to design to fit onto the moulds of the bottom shells' parting planes, because after applying the adhesive, it need to place there, and verify the position by threaded rods.

5.1.2.7. Number of moulds

After we determined the details and requirements, we could already estimate the quantity of the necessary moulds for this project. We needed this to be able to coordinate dates for the manufacturing processes to go on everything smoothly, not to wait for the makers' a free time in their schedule. Also necessary to know what sources the moulding need.

Element	Mould for
Main Element	Bottom shell's no.1 Bottom shell's no.2 Upper shell Omega
First Flaps	Bottom shell's no.1 Bottom shell's no.2 Upper shell
Second Flaps	Bottom shell's no.1 Bottom shell's no.2 Upper shell
Endplates	Right endplate Left endplate

Figure 133: MDF Moulds for the first wing elements

To save the time which goes by the installation of the unwrought part in the CNC machine, we made the symmetrical parts of the first wing's middle and upper flaps in one mould, near to each other. We could also save material, milling- and product manufacturing time with this decision.

Element	Mould for
Main Element	Bottom shell's no.1 Bottom shell's no.2 Upper shell Omega

Figure 134: MDF Mould for the rear wing elements

As you can see on the **Figure 134**, we made MDF moulds for rear wing's main elements too, but the flaps were made with a different technology.

5.1.3. *Designing*

The details were already clarified, that is why the design process was just to observe these aspects and draw the CAD models. Because the mechanical design and the FEM analyses were made in Catia V5, it was rational to design the moulds also in it.

The Catia V5 also has another benefit, what makes it better for designing moulds, than the other CAD softwares. It has a feature called multibody modelling, and with this, it is possible to draw the 3 bodies in one part for the shells without using assembly. With this advantage, we were able to make parametric models for both moulds easily and in case of a problem it was easy to modify them.

The designing process was the same for all of the moulds, tools. Therefore we write off only one element's process.

The design's first step was to define the parting plane, and to elongate the surfaces in all direction where it is possible. These elongated surfaces determined the lengths and the widths. **(Figure 135)**

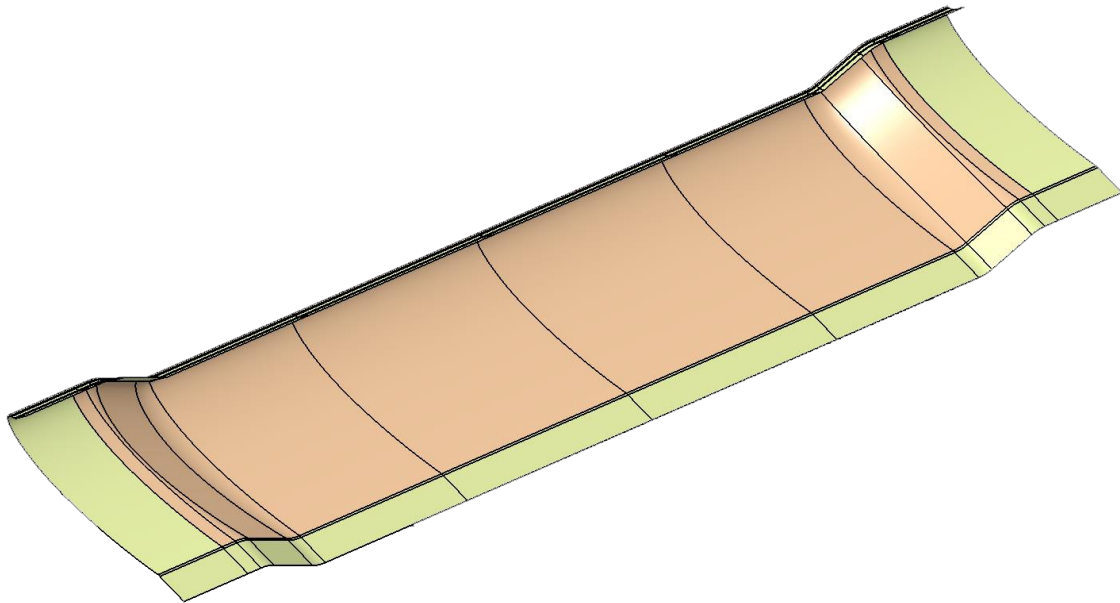


Figure 135: Surface elongations

Then, the next step was to mature the thickness, kept in mind the minimum value. **(Figure 136)**

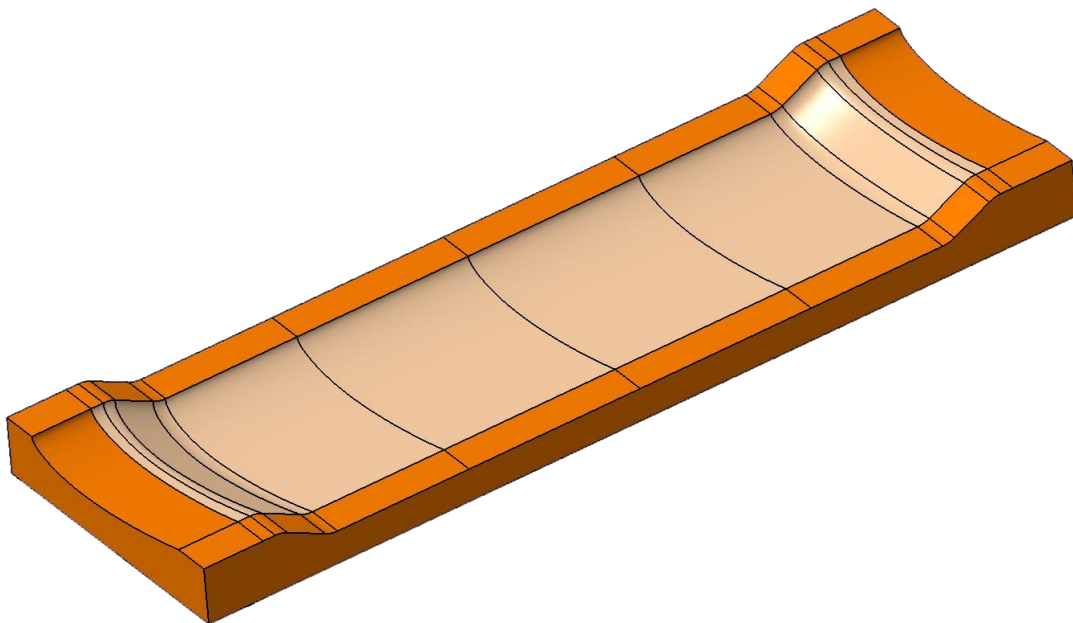


Figure 136: Creation of mould's body

For last step we put the indicator edge and the holes for positioning onto the models. **(Figure 137)**

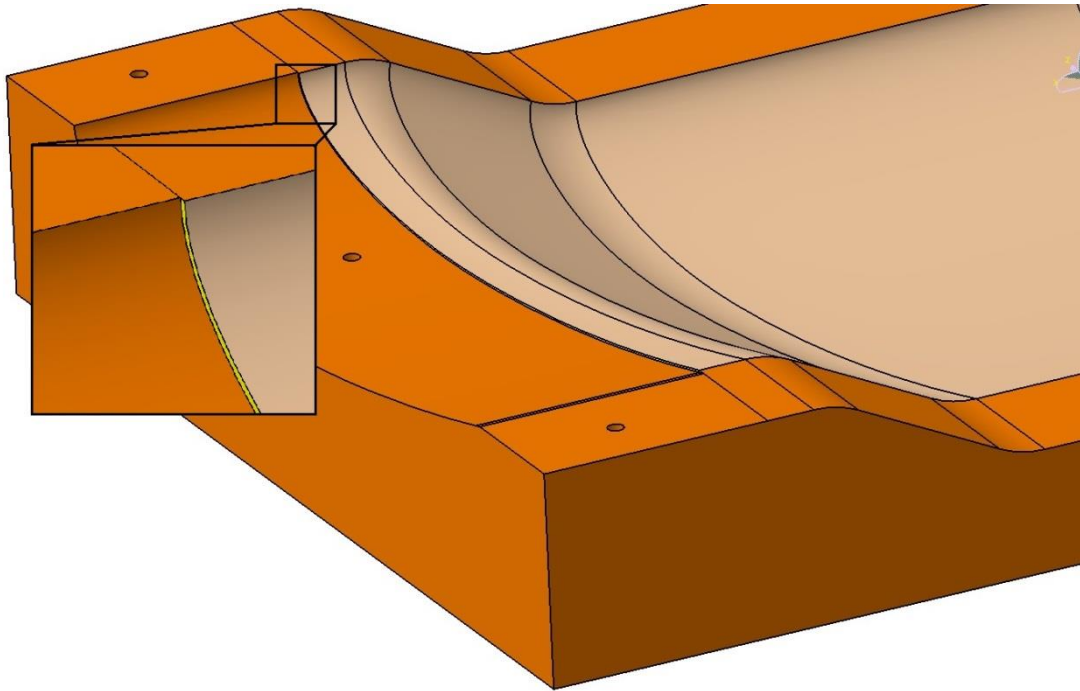


Figure 137: Indicator edge & positioning holes

At the end of the design, it needed to be verified if there is no undercut on the mould. As we finished the elements for one wing shell, these coherent moulds were joined together in the model, to check if these parts would be able to fit. Having finished all moulds for a wing element, we also checked if they join perfectly. (**Figure 138**)

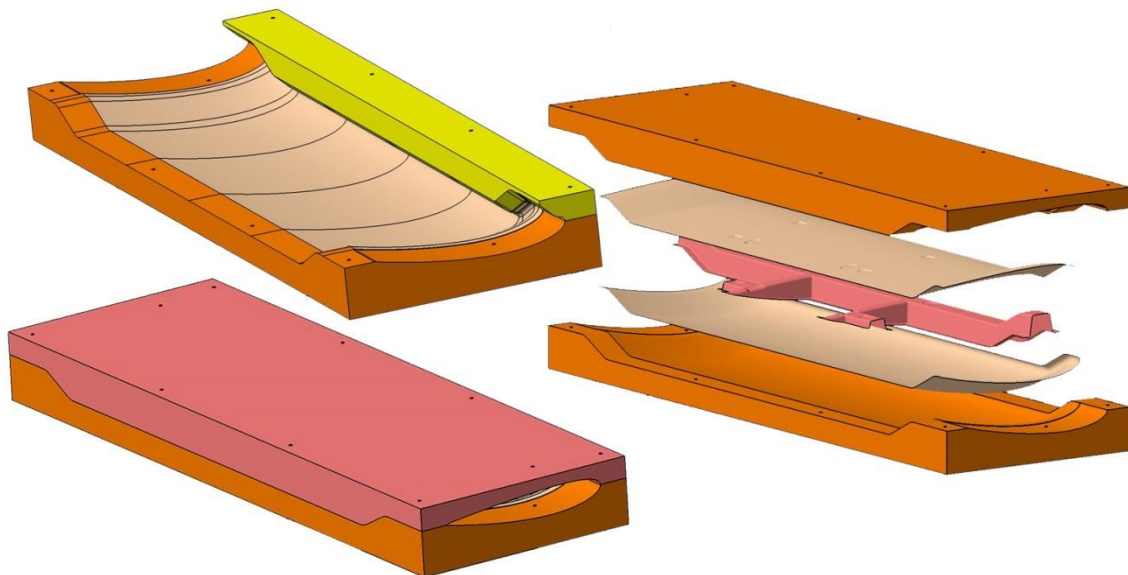


Figure 138: Verify the fitting of the moulds

As mentioned before, the MDF tables can be purchased in different thicknesses, but the thickest table is still not enough for a tool by itself. This is why it was required to design

the slicing with the used table thicknesses. To be efficient, we used 2 types of tables as for the thicknesses: 40mm and 28mm. With these sizes, we could optimize the total thickness of the unworked mould, to be as close to the final surface as it is possible, but these chosen sizes were also enough thick to have only a few bonding planes per moulds. Milling time and MDF material could be saved with this. We needed to keep a minimum distance from the surfaces, in case of bonding or installing inaccuracy. This minimum was 5 mm. As show on the **Figure 139**, we always verified these aspect in the model. Another requirement during the slicing was to avoid the bonding planes, where the original geometry arc's is not steep enough, because the milling tool would rip the thin layers at a flat arc, which debases the surface quality.

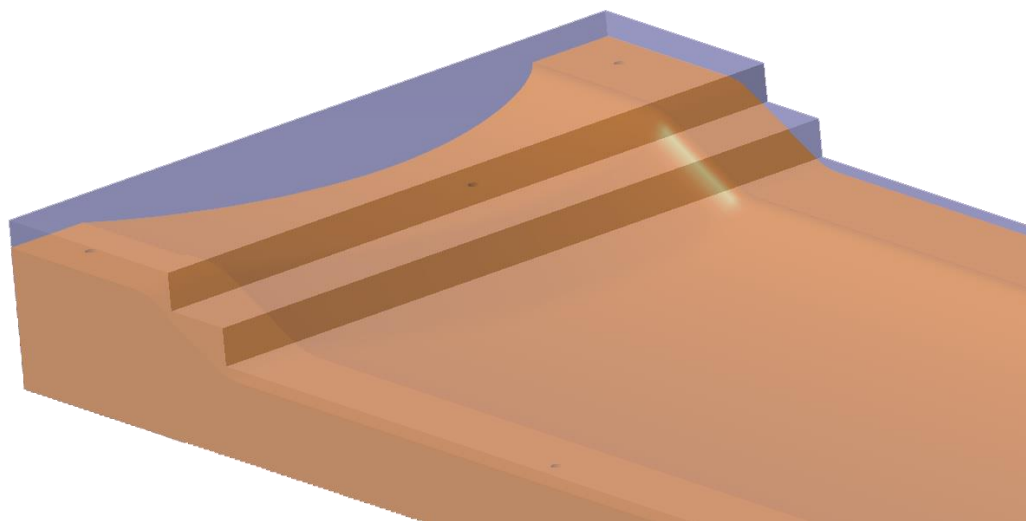


Figure 139: Verifying the pitching of mould's and MDF tables

5.1.4. *Manufacturing*

The manufacturing of the moulds were happened like we written off. We purchased the dimensioned MDF tables. Later we bond them together. We wrote the CNC programs also. After our supporters milled the elements and we made the paintworks, with a help of another supporter. When we had all the moulds finished, the coherent ones were fixed together and they were ready for product manufacturing.

5.1.5. *Rear wing flap elements*

To achieve an effective rear wing, the simulations shown that the middle and the upper flaps' profile have to be thin and long. But when we thought on the manufacturing of these elements, we realized there would be several problems during manufacturing with the previous technologies, which would have worsen the quality of products.

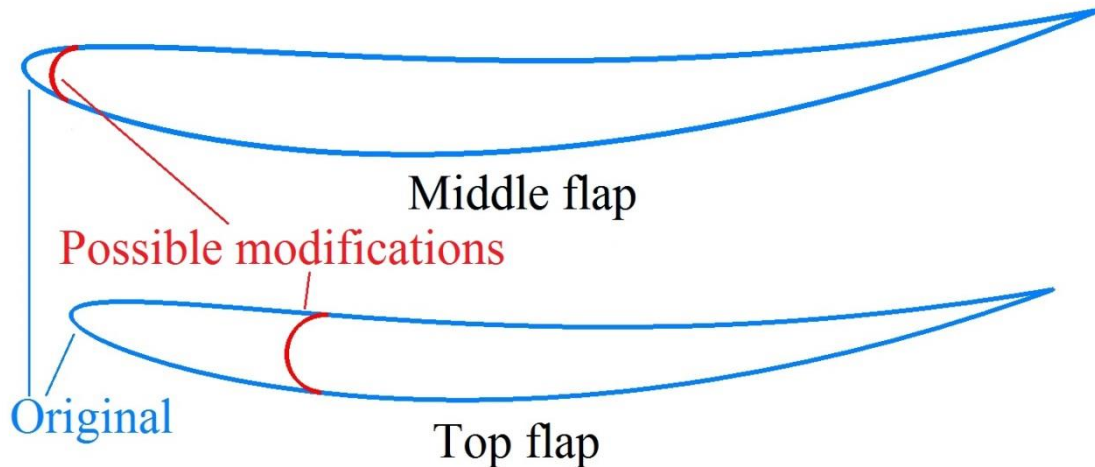


Figure 140: Possible modifications on the profiles

The problems would be:

- The leading edge of these elements are really small and we could not place the carbon fibre layers into this spot As mentioned sooner, at least an 5mm radius required, but it would absolutely transform the optimized profiles as shown on the **Figure 140**
- We also could not create a bonding surface on these thin elements.
- The joining of the two shells would be inaccurate at such small elements

So we had to look for another method for fabrication. After a little searching, we found a technology which is used for mainly manufacturing RC plane's wings, but a very similar technology is being used in motorsports too.

Basically this is a two-moulded method too, but the wings were not made from two shells and bonded together, in this case, the wings were made in one manufacturing step.



Figure 141: Foam moulds with foam core



The moulds were made of foam and fabricated by a CNC foam cutter, which can cut different 2D profiles from prismatic foams. As you can see on the **Figure 141**, after cutting we had 3 parts, an upper and a bottom mould, and a middle element, used as core inside of the wings.

Because the foam's surface is also porous like the MDF's surface, it was also required a kind of surface treatment to achieve a smooth mould surface. The foam moulds are not so rigid, that is why we could not use painting as treatment, because it would crack during a possible deformation of the foam. We decided to stick a thicker nylon film onto the surfaces.

5.2. *Selection of fabrication method*

5.2.1. **Options**

There are numerous methods for fabricating composite components. Some methods have been borrowed (injection molding, for example), but many were developed to meet specific design or manufacturing challenges. Selection of a method for a particular part, therefore, will depend on the materials, the part design and end-use or application.

Considering the tooling costs, it was clear from the beginning of the project, we will use open moulding technology, which immediately excluded some manufacturing methods, like conventional RTM. The benefit of the open moulding technology is, it requires only one, or in worse case two moulds.

Open contact moulding in one-sided moulds is a low-cost, common process for making fibreglass composite products. Typically used for boat hulls and decks, RV components, truck cabs and fenders, spas, bathtubs, shower stalls and other relatively large, noncomplex shapes, open moulding involves either hand layup or a semi-automated alternative, spray-up. [18]

The disadvantage of the open moulding processes: the B-side surface of the parts, will not be always so accurate and smooth like it would be at closed-mould methods. Naturally, this property can be improved by using pre-preg plies or with vacuum bagging, therefore we needed to examine these possibilities also.

With these facilities we could take into account four manufacturing methods. These methods basically hand lay-up processes. Hand lay-up is the most basic fabrication method for thermoset composites, it's typically consists of laying dry fabric layers, or "plies," or pre-preg plies, by hand onto a tool to form a laminate stack. Parts fabricated with hand lay-up are accurate, tough, and have quite good A-side detail. These processes differ mainly only in the application of the resin or in the curing method.

5.2.1.1. **Hand lay-up**

Hand lay-up FRP (Fibre-Reinforced Plastic) composite panels and parts are created by applying liquid resin atop the surface of an open-faced mould. The resin is applied by hand, and incorporates reinforcement via fibreglass, Kevlar, or carbon-fibre layers of cloth, which are carefully applied and brushed into the open mould. Typical fibre volume is around 25 percent with hand layup. To improve the impregnation ration, an

option is a roller impregnator, which pumps resin into a roller similar to a paint roller.
 [19]

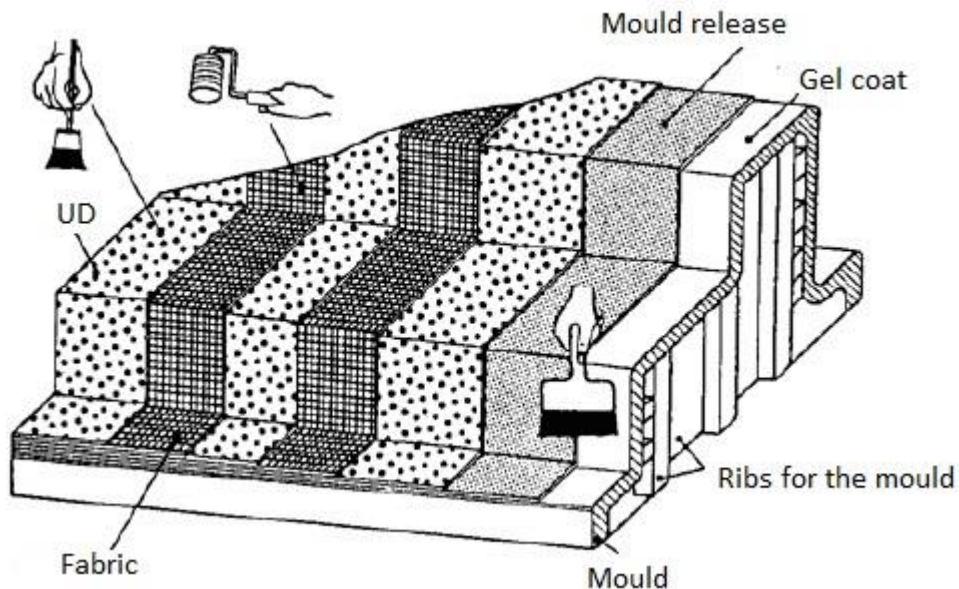


Figure 142: Hand Lay-up[20]

5.2.1.2. Vacuum bagging

Essentially the vacuum bagging is the same procedure like the hand lay-up method, but it doesn't stop after applying the plies with the resin. When the lying is finished, 2 other layers are installed onto the top plies, a peel ply and a resin flow mesh, thereafter a vacuum bag is placed on the mould's outer edge. This bag connected to a vacuum system which removes out the unnecessary resin and makes a more accurate B-side surface by using the resin flow mesh and the vacuum bag. With this technology, usually the available highest fibre volume is around 55%-60%.

5.2.1.3. Vacuum-assisted resin transfer moulding

The vacuum-assisted resin transfer moulding (VARTM) consist the same layers than the vacuum bagging, but in this procedure, dry plies are laid in the mould, and the resin applied later. Vacuum-assisted resin transfer moulding (VARTM) refers to a variety of related processes that represent the fastest-growing new moulding technology. The salient difference between VARTM-type processes and RTM is that in VARTM, resin is drawn into a preform through use of a vacuum only, rather than pumped in under pressure. VARTM does not require high heat or pressure. For that reason, VARTM operates with low-cost tooling, making it possible to inexpensively produce large, complex parts in one shot.

In the VARTM process, fibre reinforcements are placed in a one-sided mould, and a cover (typically a plastic bagging film) is placed over the top to form a vacuum-tight seal. The resin typically enters the structure through strategically placed ports and feed lines, termed a “manifold.” It is drawn by vacuum through the reinforcements by means of a series of designed-in channels that facilitate wetout of the fibres. Fibre content in the finished part can run as high as 70 percent. Current applications include marine, ground transportation and infrastructure parts. [18]

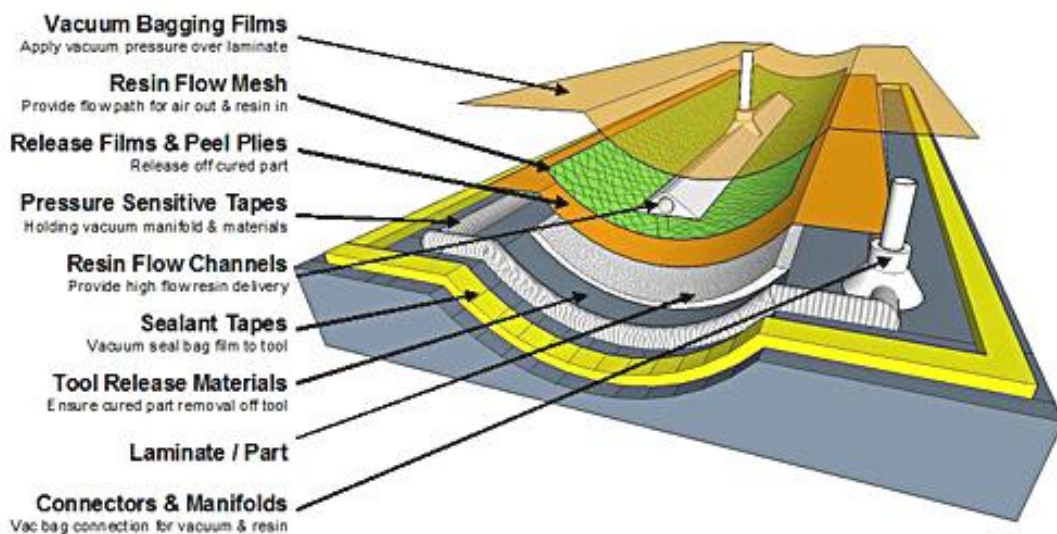


Figure 143: Vacuum-assisted resin transfer moulding[21]

5.2.1.4. Using pre-preg

Pre-preg construction with autoclave, oven, or compression moulding methods are reserved for parts and assemblies that require the highest strength to weight ratio achievable. Military aircraft, wind turbines, Formula 1 race cars, and laboratory centrifuge buckets are just a few examples of products that take advantage of pre-preg carbon fibre's strength to weight ratio. In pre-preg construction, woven carbon fibre fabric is pre-impregnated with an epoxy resin system that requires elevated cure temperatures typically above 250 deg F. Because the amount of resin impregnated into the fabric is closely controlled to its optimum amount, pre-preg materials yield components that are lighter than parts manufactured using wet layup techniques. Additionally, because pre-preg does not cure at room temperatures, fabricators have considerable more "open time" to complete the lamination process, assuring that the fibre's orientation is meticulously aligned to optimize the strength of the part. Curing cycles are achieved with carefully controlled temperature cycles in ovens or autoclaves.

Depending on the part size and resin properties, full cure can be achieved in as little as 1 – 2 hours. Tooling for pre preg parts can be manufactured from aluminium, high temperature carbon fibre, or tooling block. [18]



Figure 144: Autoclave

5.2.2. *Decision matrix*

Every of the listed methods have benefits and disadvantages. To find the best solution, we made a decision matrix with aspects of manufacturing, and aspects of the final product's quality. The interval was from 1 to 10, and the higher number means the better solution.

Aspects	Weighting factor	Fabrication method			
		Hand Lay-up	Vac. bagging	VARTM	Using pre-preg
Weight	1	3	6	8	10
Product's quality	1	5	7	8	10
B side surface quality	0,7	4	8	9	10
Costs	0,9	10	7	7	4
Previous experience	0,7	7	10	8	4
Availble facilities	0,8	10	10	10	4
Complexity	0,6	10	6	5	6
Summary		38,7	43,5	<u>45,2</u>	40,2

Figure 145: Decision matrix of the manufacturing method



As shown on the **Figure 145**, the VARTM method had the highest score, ahead of vacuum bagging. Eventually we used both processes during the fabrication.

5.3. Manufacturing

In accordance with the previous decision matrix the majority of the products were made with VARTM method. Therefore we decided to write off the manufacturing of the under tray in this documentation, because this fabrication was the best documented by pictures. But all the other parts were made with the same steps, except for the rear wing's flaps, which made by a kind of vacuum bagging method.

We performed every manufacturing process in Department of Polymer Engineering's Composite Centre, because it provides proper place for these work, with the proper facilities.

5.4. Mould preparation

The painted moulds are not immediately ready for the layup. Further treatments needed to prepare the surfaces of the moulds suitably for the fabrication. The first step is to clean the faces from the pollutions and from the fingerprints.

After drying, we could start to apply the mould sealer. The duty of the mould sealer is to improve the surface quality by closing the microporous and correct the minor blemishes, scratches. It offers extra mould protection and enhances mould release performance.

We used the Axel Xtend XTR mould sealer, which is an uncoloured liquid, recommended for treating FRP moulds. As for the description, the application takes overall around 1.5 hours, to achieve the best performance of this product. We had to apply 2 coats of XTR with paper clothes, allowing approximately 15-20 minutes between each coat and to allow a minimum of 30 minutes before applying mould release.[21]

For mould release we used Formula Five Mould Release Wax, which is a general purpose release agent that blends carnauba with modern polymers and special hydrocarbon waxes. It is recommended as a part of a multi-cycle process designed to ease the release of parts from mould surfaces. In use, 2-3 layers application are needed. Every layer had to be applied with dry rag, and when the layer dried, it was necessary to wipe away the excess.[22]

5.4.1. *Application of the layers*

The direction of the fibres depends on the applied loads, therefore the most important was to keep in mind during the whole ply-cutting and lay-up, the fibre orientations has to be perfect on the product. At the outer layer, called decor layer, which basically you can see on the product's surface, also important to pay attention to the appearance beside the structural role, while applying these fabric plies.

The patters usually were not so complicated, majority of them were only rectangles, so we didn't have to make and print too templates for the fibre cutting. In several occasion the width of the rolls were not enough for one layer, therefore we had to make it from more pieces, paying attention for the allowances, to secure the same structural properties.(**Figure 146**)



Figure 146: Aramid-Carbon fibre layer created of several pieces

As mentioned earlier, we used in core materials the products, which we had to prepare also. As you can see on the **Figure 147**, we shaped up chamfers on the edge of core element, to avoid resin-rich areas, and we drilled many little holes in the foam, because it is a solid material and it would close the flow of the resin between the layers. It is significant to avoid the resin-rich areas, because the mass of the resin more than the foam's and

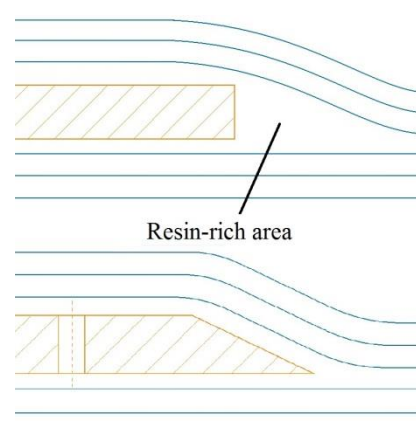


Figure 147: Core material without and with chamfer

without the chamfers there would be a lot of unnecessary weight in the products and it would also worsen the part's strength.

As shown on **Figure 148**, we stabilised the layers permanently to measure and to place them onto their final spot to check if the plies and core materials are appropriate.

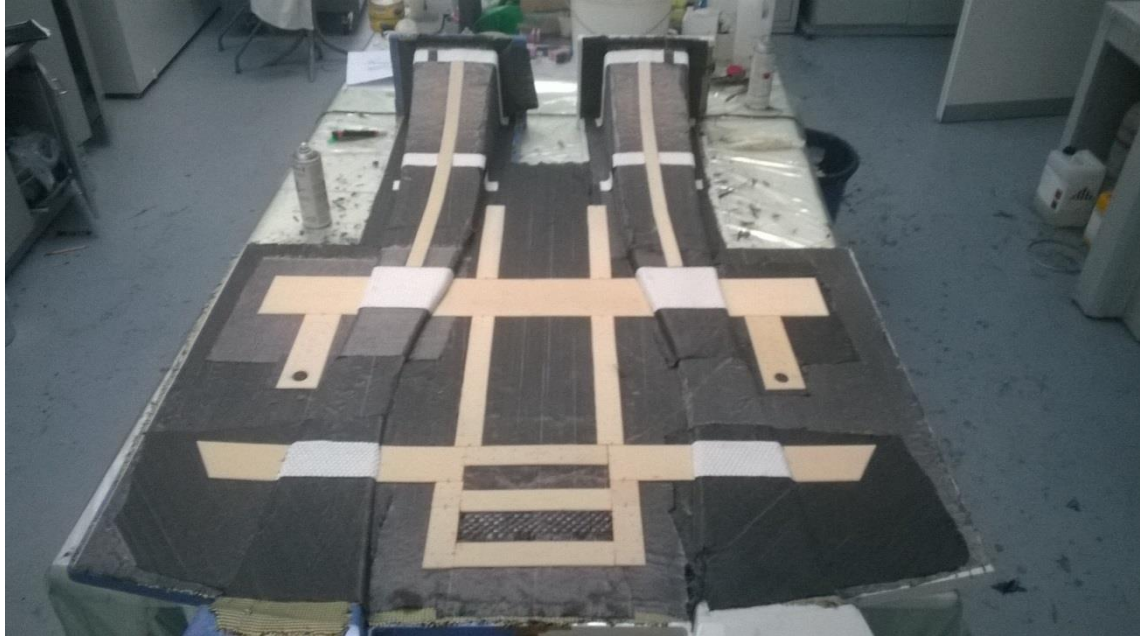


Figure 148: Checking core materials' place

When the layers and the core materials were ready, we started the lay-up. As we worked with dry plies, we had to fix them onto the mould's surface somehow. Thereunto we used Aerofix 2 adhesive spray. It is a high tack, high coverage, fast drying, translucent adhesive for permanently attaching various materials. During applying the adhesive, we had to take care of not using too much of it, because it would also worsen the composite properties.

5.4.2. Peel ply

When all the fibre layers were placed, the following layer was the peel ply. The peel ply is a thin fabric cloth, which has to lay-up in several pieces with 5-10 cm allowances, but in one layer. To fix these pieces, we used adhesive spray too. The benefits of the peel ply: it protects the uncured placed fibre layers from dirt, dust, while applying the remaining equipment, it helps to remove the unnecessary resin from the laminate after curing, and it leaves a smoother finish on the laminate.

5.4.3. Resin flow mesh, Resin flow channels

The duty of the resin flow mesh is to secure the flow of the resin under the vacuum bag during the injection. The duty of channel is to feed and lead out the resin from the vacuum system. At the majority of the product, it was not a problem to place these elements sufficiently, but at a such large element ($2,13 \text{ m}^2$), it needed to design the flow of the resin too, because the inadequately installed meshes, channels could eventuate dry areas and also resin supersaturated areas on the final product.

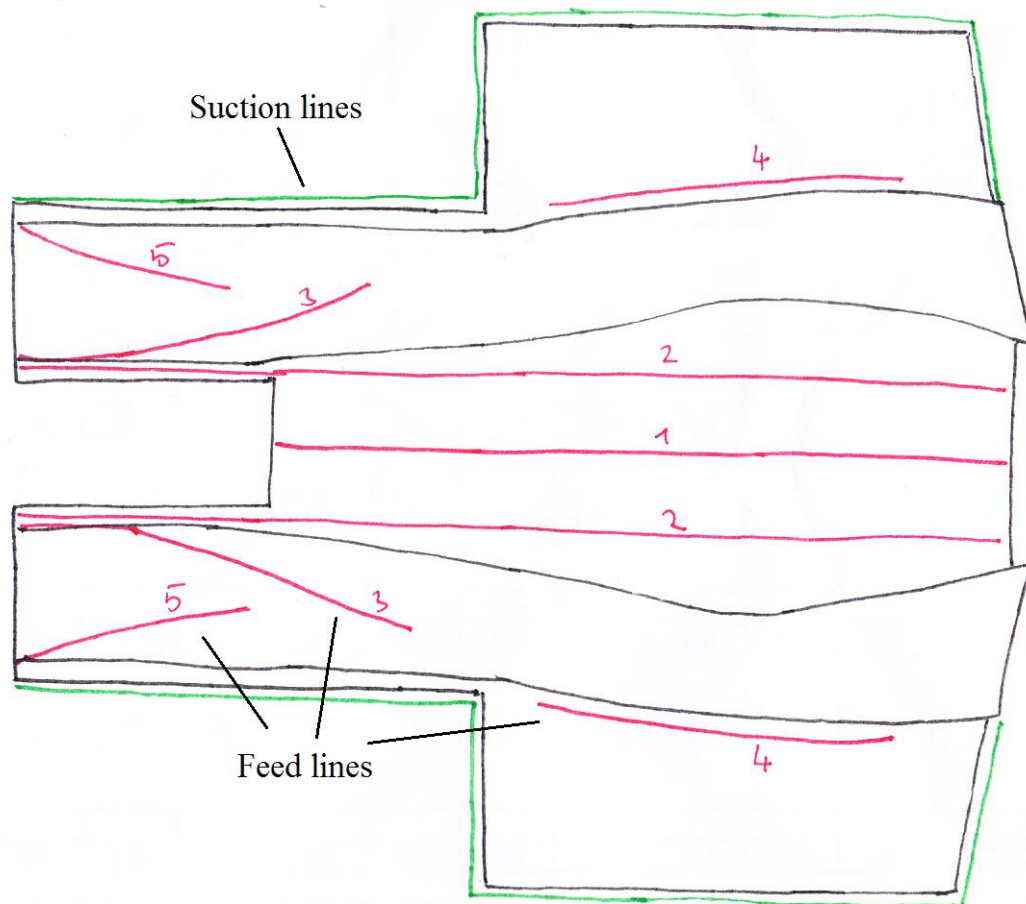


Figure 149: Design of the resin flow mesh placing

As you can see on the **Figure 149**, we used several places to feed the resin. At these areas we used more layers of the mesh, to accelerate the flow. To control the flow, we used valves in every feed and lead out line. We had to open and close the feed lines one after the other, but the suction line was permanently open. On the **Figure 149**, the numbers sign the sequence of the opening.

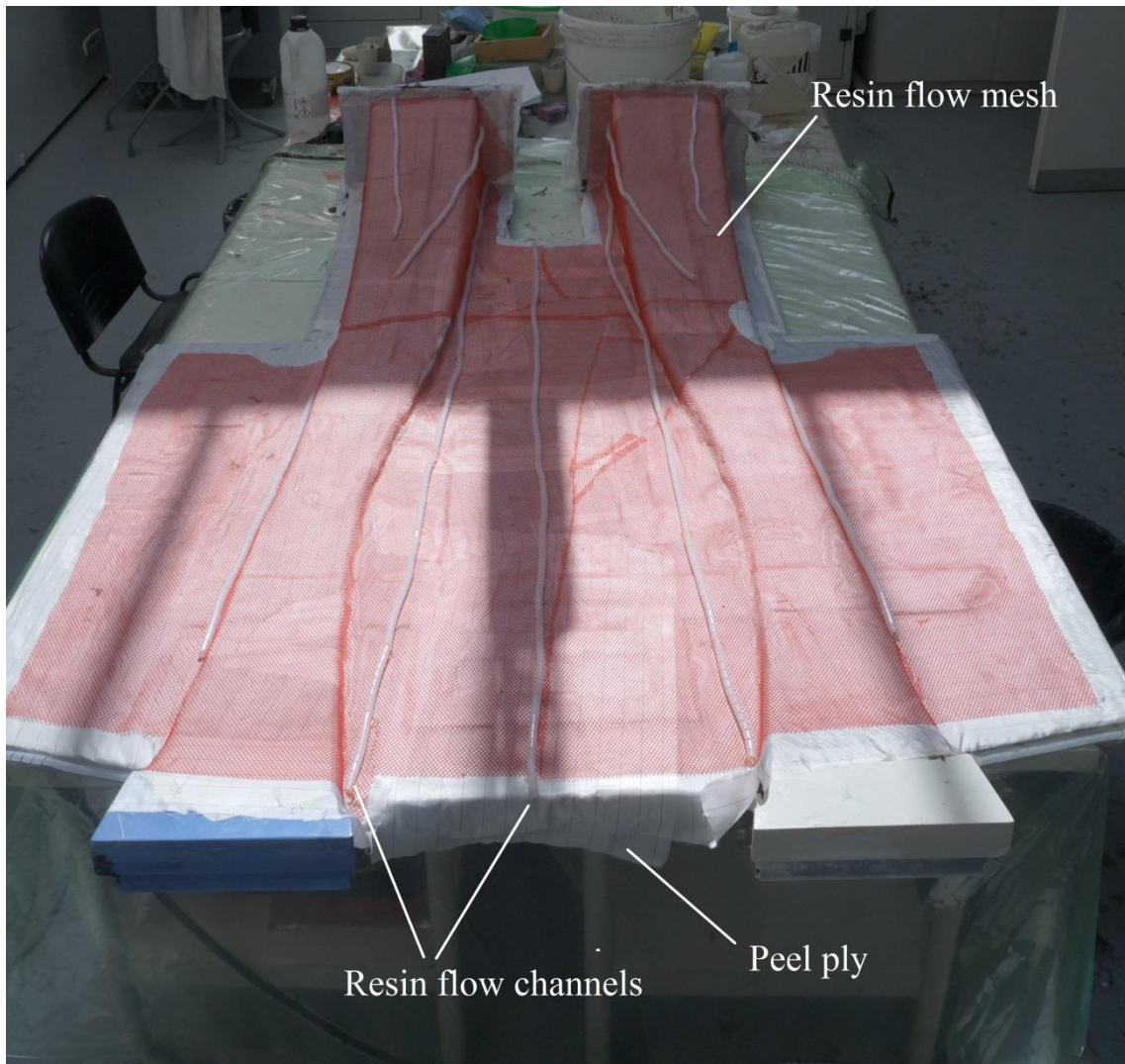


Figure 150: Before vacuum bagging

5.4.4. *Vacuum bagging*

The last step of preparing for resin transfer is the vacuum bagging. This vacuum bag is a quite tough polymer film, because it has to resist the bigger pressure, even in higher temperature. As every process, it requires a lot of care. The most important is to pay attention not to harm the bag, because a tiny hole can lead air in the resin, as you can see on the **Figure 151**. In addition it is also important to have enough allowance on the final size of vacuum bag



Figure 151: Air bubbles in the resin

for creases in the fillets and on the curved surfaces. Because if the vacuum bag stretches, it can cause resin-rich area under the bag, or in worse case, the vacuum bag can torn off.

To fix the vacuum bag onto the mould, we used tacky tape. These tapes are used to seal vacuum bags to mould surfaces during resin transfer. We placed these tapes on the surface which was designed for this function on the mould.

5.4.5. *Resin transfer*

Before we started the resin transfer, we had to test, that the vacuum-system operates well, to ensure, if it could keep the expected vacuum, without leaking. When we found everything fine, we adjusted the right pressure and we started to mix the resin.

We used ipox ER 1052-5 epoxy resin for matrix material, which is suitable for injection, because of its low viscosity. And for catalyst we used ipox EH 2298. The mix ratio was 100g resin with 35g catalyst.

To achieve the proper homogeneous mixture, we had to weight out the two components tenth of a gram accurately and mix it for 5 minutes, wait 1 minute and mix it for another 5 minutes.



Figure 152: Resin transfer

When resin was ready, we could turn on the suction-pump and start the resin transfer, taking care of the proper flow, controlling with the valves, as previously designed. You

can see on the **Figure 152**, as the 3 and 4 feed lines were opened, the 1 feed line was already closed and the 5 feed line closed so far. When the impregnation was considered appropriate, we turned off the suction-pump and closed the valves.

5.4.6. *Curing*

Several curing methods are available. The most basic technic is simply to allow cure at room temperature. Because of the moulds' sizes – even the smallest mould is 1200x100x100 mm – we had to use this method. We usually allowed the moulds at least 24 hours for curing on room temperature, before we could unmould them. As you can see on the **Figure 153**, it was not a problem, that we didn't used oven for the curing. The oven just accelerates the curing, but if we allow the products for many hours, we can achieve almost the same properties.

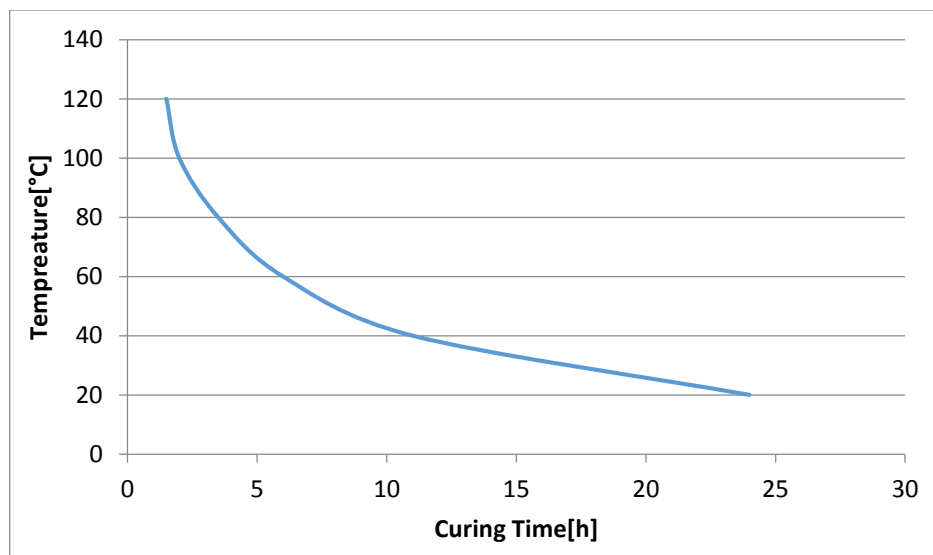


Figure 153: Average Temperature – Curing Time function

5.4.7. *Flap manufacturing*

As mentioned sooner, two flaps of the rear wing were made by two sided foam mould technic. Therefore we couldn't manufacture it with VARTM method, because we had to place the moulds with the layers into the vacuum bag, so we couldn't control the resin flow properly, which is the basis of VARTM.

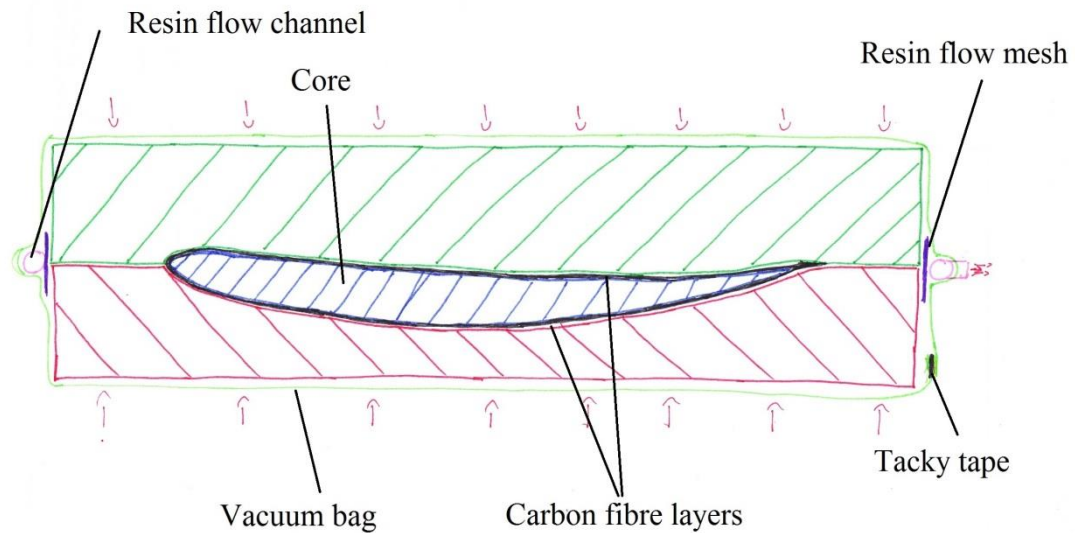


Figure 154: Basic concept

We decided to use a kind of vacuum bagging method. You can see the basic notion on the **Figure 153**. The vacuum keeps these moulds together and because the foam can deform a little, it can stick on the product's surface, to ensure the plies position during the curing.



Figure 155: Resin application by hand

Because we used the same equipment, we only list the steps of the manufacturing.

1. Mould preparation
2. Mixing the resin and cutting the carbon fibre plies
3. Resin application onto every ply by hand with brush(**Figure 140**)
4. Applying resin flow mesh and channel
5. Vacuum bagging
6. Placing the system under vacuum and removed the unnecessary resin

Curing

5.5. Product finishing

After opening the mould we still had to do several processes with the composite parts before we could install them into the race car. These processes include removing the extensions, bonding the inserts, drilling the holes and if it is necessary proper surface treatment. This chapter will give detailed information about product finishing.

5.5.1. Diffuser Finishing

After the curing of the part we could use the above mentioned peel ply to remove all the technology consumables. For this task it was essential to wear protecting glasses as the unreinforced resin splinters which could harden above the peel ply is potentially dangerous for the eyes. This process is shown on **Figure 156**.



Figure 156: Removal of the auxiliary materials

The removal of the product was done using wedges. Because it was a simple geometry and also we used a proper mould release with the greatest care it was a quite easy process.

Compared to the wings we had much less finishing work on the diffuser after removing it from the mould. The indicator edges were clearly visible and we could use these markings to make precise masking for cutting the edges. The masked diffuser is shown on **Figure 157**. After masking excess material removal was carried out with an angle grinder. For the final half millimetre we hand sanded the edges to the final size.

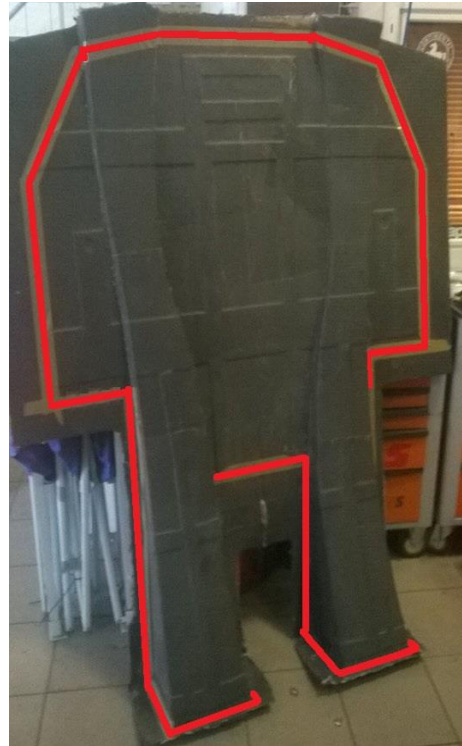


Figure 157: Before trimming to final size

Finished edges were covered with plastic tube to provide the required edge radius, as it is stated in the FSAE rules:

“ T9.3 Minimum Radii of Edges of Aerodynamic Devices

T9.3.1 All wing edges including wings, end plates, Gurney flaps, wicker bills and undertrays that could contact a pedestrian must have a minimum radius of 1.5 mm (0.060 inch). “ [23]

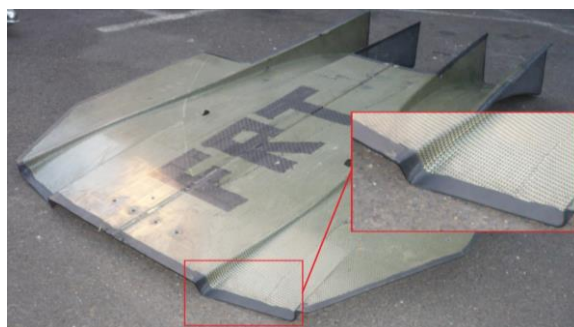


Figure 158: Edge protection

When the part was finished we made the necessary holes and added bolts to fix the diffuser underneath the car.

5.5.2. *Wing profile finishing*

Finishing the wing profiles is a multiple stage process.

First we made the three parts for the wing: two outer shells and the omega shaped spar. We had to cut the longitudinal edges in order to use the moulds as a positioning tool.

We could use the imprints of the part made by the indicator edges of the tool to cut all the 28 edges precisely. We used a Dremel multifunctional tool for the work because we only had to cut thinner composite parts and it is a more precise device, as it can be seen on **Figure 159**. To achieve a smooth finish we sanded the final millimetre by hand. The same work was done on the omega shaped spar.



Figure 159: Cutting with Dremel

Bonding process:

Before joining the two halves together we had to bond the insert inside the omega shape which we could not reach later.

We had to prepare the surfaces before applying the adhesive to achieve a good bond. Our aim was to make the surface as rough as possible by sanding it thoroughly with 30 grit sandpaper. Any contamination would decrease the quality of the bond (dust, grease) so we cleaned it with Loctite 7063 solvent based spray.

We used Loctite 9466 which is an increased strength two component epoxy adhesive. Using a static mixer head we were able to mix and dose the adhesive evenly. We also spread the paste with a plastic spatula as you can see it on **Figure 160**.



Figure 160: Bonding procedure

We drilled locating holes into the moulds where we had excess material. Using locating pins we could precisely position each part as it can be seen on **Figure 161**. After the 24 hours curing time we removed from the mould the semi-finished wings. We trimmed off any burrs after the bonding process.



Figure 161: Positioning jig

Bonding inserts into the wing sides:

We cut the wings to final width also using the Dremel tool. After that we added the inserts into the wing sides using the same adhesive.



Figure 162: Cleaning the inserts

These inserts were made by waterjet cutting which results in an appropriate surface quality. So after cleaning with Loctite 7063 (which is shown on **Figure 162**), we could bond them into the wing shell. (The shell itself was roughened before the bonding.)



Figure 163: Bonding the wing ends

To hold an even and previously defined gap we placed thin wires as spacers which were cut and sanded flush after the adhesive was cured, as it can be seen on **Figure 164**.

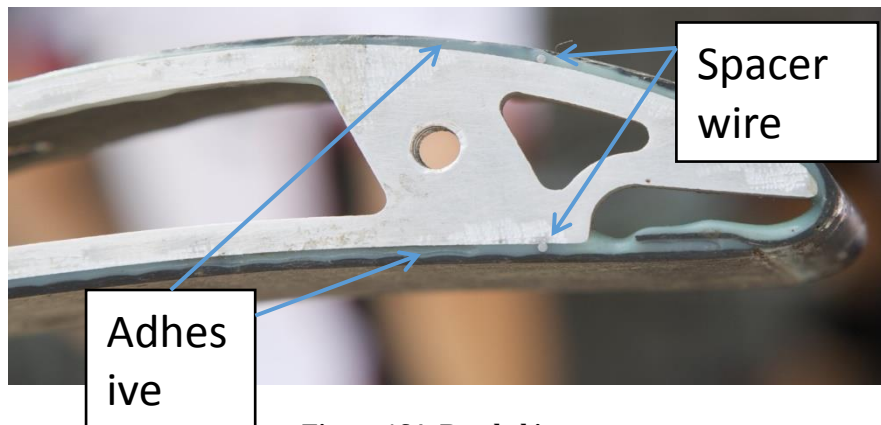


Figure 164: Bonded insert

Flap finishing:

As the two flaps of the rear wing were made by another technique, the finishing process was different to the others. After opening the moulds, we cut the unnecessary edges and then we could bond the inserts into the wing sides.

Endplate finishing:

Now we were ready to add the endplates which were prepared in a similar way as the other wing elements. We cut the edges with the Dremel, hand sanding to final size, drilling holes of the appropriate size and location.

Painting:

After everything was assembled we brought the wings to a paint shop where scratches, indentations and gaps were filled with putty. It was important to provide good aerodynamic surfaces and good aesthetics as well. For the very last step multiple layers of thermosetting coating was applied which gave a smooth and beautiful finish. The finished surface is shown on **Figure 165**.

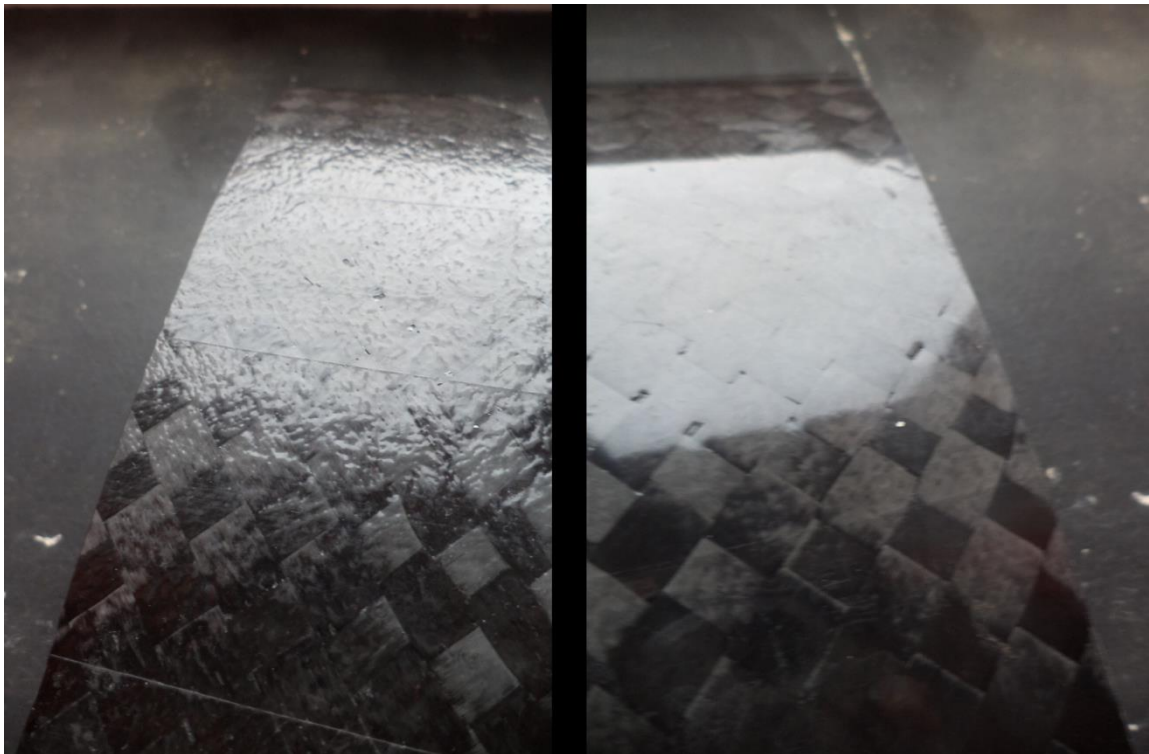


Figure 165: Before and after painting process

Preparing the mounting points of the wings:

The outer part of the middle insert is held in place by a layer of adhesive and two rivets. This insert serves as the mounting point for the universal joint which attaches the wings to the chassis.

We used bolt joints in all positions where removability was required for example where the endplates are attached to the wings and where the wings are attached to the chassis. Also we used some steel wires as it can be seen on **Figure 166**, to make the wings stiffer and prevent flexing of the front wing which would result in unpleasant scraping on the ground. This wire goes between the intrusion plate and the wing end insert.



Figure 166: The finished front wing

5.6. *Manufacturing summary*

An enormous amount of work was required before the part came to life. From the drawing board to the final purpose when we could integrate the part into the racecar several steps had to be completed.

Below there is a summary of the estimated amount of workhours:

- CNC machining time 165 hours
- mould preparation 11 hours
- infusions 71 hours
- trimming, sanding and bonding 16 hours
- coating (painting) 18 hours

The whole manufacturing process lasted more than 270 hours.

The aerodynamic package was ready to being fitted to the car and go for the first metres, creating downforce.

6. Validation

Validation of the aerodynamic package was delivered through lap time simulations and testing. The team uses Optimum Lap (developed by the Optimum G brand), which enables us to simulate lap times with ideal track conditions on a given track and with given vehicle parameters. The software also provides data about the speed distribution, the optimal braking and acceleration positions and intensities, and can also simulate the lap time lost with the energy loss during a session. The main advantage of the software is that it simplifies the process for comparing different parameters and set-ups, because with a batch run – which sweeps a given parameter along a range and simulates the car with each one of them – we can determine the best parameter for the given vehicle. For example with this process we can examine the downforce's effect on the lap time.

On the following images I'm going to show some examples of the software output. The first image shows the base car's speed distribution on the Formula Student Hungary's official Autocross track. Examining the second image also we can determine that the vehicle has to slow down, brake hard for the corners. This braking intensity can be decreased with an improved grip and downforce provided by an aerodynamic package.

FSH Autocross 2012 - Speed [km/h]

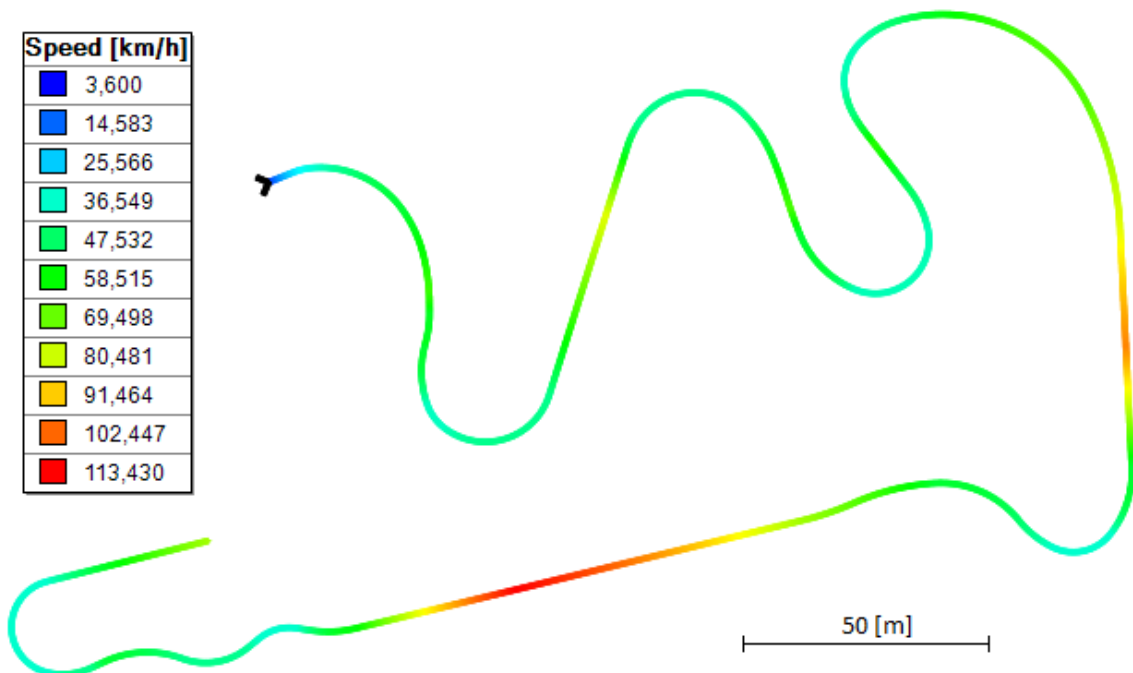


Figure 167: The speed around the FSH's official Autocross track

FSH Autocross 2012 - Brake [%]

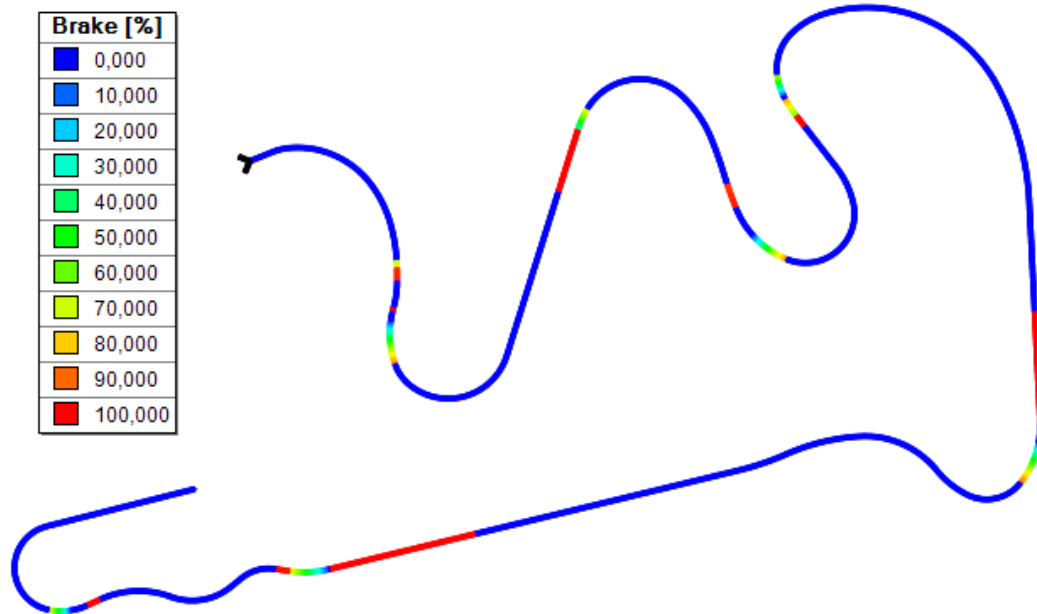


Figure 168: The braking intensity around the FSH Autocross track

On the next image we can see that the vehicle achieves an optimal lap time through maximizing the power output on the track, constantly accelerating on the straights and corner exits.

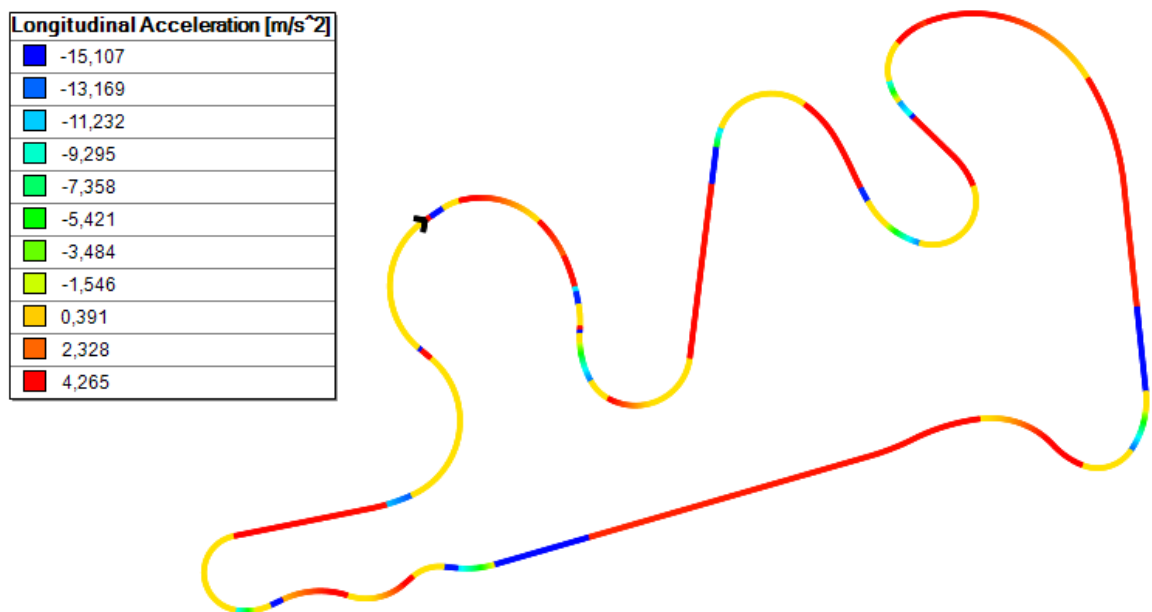
FSH Endurance 2012 - Longitudinal Acceleration [m/s^2]

Figure 169: The longitudinal accerelation around the FSH Endurance track



As through the numerical calculations of CFD, with Optimum Lap we're also just approximating the behaviour of the vehicle with given parameters, that's why I used the output of the CFD calculations as the lap time simulations' input for downforce and drag coefficients. The characteristics for the electric motors, transmission and other parameters, such as tyre data were provided by the teammates.

Because our main event is the Formula Student Hungary in Győr, the lap time simulations were executed for it's official tracks and of course the official "template" Formula Student tracks for Acceleration and Skid-pad. First I'm going to compare the base car's simulation times with the actual track times from the 2013 Formula Student Hungary.

For the Acceleration event the actual acceleration of 4.09 won against the 4.49 seconds of the simulation, which is 9.86% difference between the results. This is because of various reasons: on the race we use another suspension set-up for this event – higher ground clearance on the front, higher pressure for smaller contact patch on the front wheels -, which increase the weight transfer to the rear, thus improving our car's acceleration.

On the Skip-Pad event the results showed very good similarity, the lap time on the race was 5.24 second while the simulated time was 5.27, thus the difference being only 0.51%, which is acceptable.

The Autocross results showed some difference, about 5.74%. The team's best result on the 2013 FSH competition was 38.39 seconds, while the calculated lap time was 36.19 second. This difference of more than 2 seconds can be explained with the following: the driver doesn't go in the ideal track, on the race there was a somewhat rainy weather so the tyres weren't on ideal working temperatures, and the track was also kind of dirty. On the other hand the simulation completes an ideal lap, meaning optimal braking and acceleration, maximal grip and zero driver reaction times.

For the Endurance event the vehicle's Optimum Lap model has to changed, because during this event we decrease the energy consumption of the motors to make them last through the whole 22 kilometres. The motors' torque characteristics were set back from 400Nm to 200Nm, thus getting the same lap times through the simulations as on the actual competition. While the average lap time on the event was 40.18 the simulation

showed a track time of 40.84 seconds. We can determine that the Optimum Lap approximates the real track times quite accurately. The next table shows the compared actual and simulated lap times.

Event	FSH 2013 data	Optimum Lap FREC003 simulation
Acceleration	4.09	4.49
Skid Pad	5.24	5.27
Autocross	38.39	36.19
Endurance	40.18	39.84

Figure 170: Comparing the race and simulation data for the base car

The summer of 2014 wasn't cloudless for the BME Formula Racing Team. Though we had many kilometres of test sessions, the rainy weather on the Formula Student Hungary wasn't rewarding for the team. Testing Acceleration showed us that the Optimum Lap's time of 4.35 seconds for the car with the aerodynamic package was still a little off compared to the average test data of 4.05. On the FSH event's acceleration heat our time was 4.304 which is very accurate to our simulation data. The tests and simulations also showed us that the acceleration event's time was slightly decreased compared to the base car's test time of 4.18 and simulation time of 4.49.



Figure 171: Testing the aerodynamic package

On Skid-Pad the difference between the average test time of 5.14, the calculated 5.12 and the 5.235 seconds of race data showed good accuracy in our methods. There was



also a minor improvement compared to the base car's times of 5.32 of testing and 5.27 of simulation.

The problem came with the Autocross event. The heavy rain increased our lap time by about 10 second, giving us a final Autocross time of 45.32 seconds. The tests in dry weather showed us an average time run time of 34.06, while the simulations calculated a time of 34.01 which was also very close. We can see a major improvement on this event, because the average test time with the base car was 35.94, and the simulated track time was 36.19.

Sadly the team couldn't finish the Endurance event because of an accumulator problem. For the car with the aerodynamic package the average test data showed a lap time of 37.58 seconds, while the simulations run time was 37.22 seconds. The base car completed the test runs with an average time of 40.37 while the Optimum Lap's calculated time was 39.84.

The event times can be seen on the following table. The Difference row shows the decrement of lap time with the aerodynamic package.

Event	Test	OptLap	FSH 2014
Acceleration No Aero	4.18	4.49	-
Acceleration Aero	4.05	4.35	4.304
Difference	0.13	0.14	-
Skid Pad No Aero	5.32	5.27	-
Skid Pad Aero	5.13	5.125	5.235
Difference	0.19	0.15	-
Autocross No Aero	35.94	36.19	-



Autocross Aero	34.06	34.01	45.32
Difference	1.87	2.18	-
Endurance No Aero	40.37	39.84	-
Endurance Aero	37.58	37.22	DNF
Difference	2.80	2.62	-

Figure 172: Comparing the test, simulation and race data

On the following I'm going to show some pictures from the Optimum Lap software's finished simulations. The first one shows an Acceleration simulation for the FREC-004 with the aerodynamic package. The second picture displays the Skid-Pad simulation of the base car, while the third is with the aerodynamic package.



Figure 173: Acceleration along the official 75 metres (FREC-004)

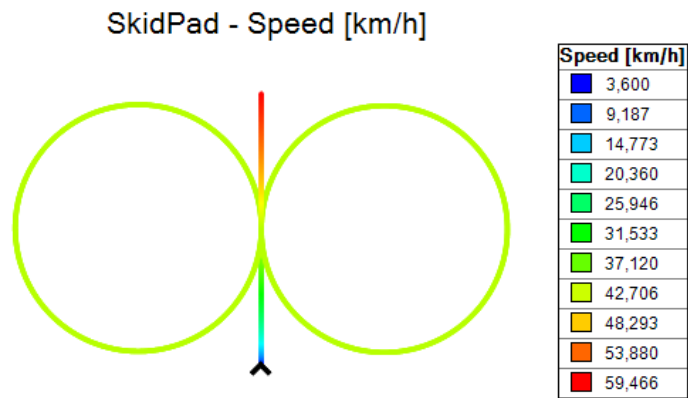


Figure 174: Skid-Pad with the FREC-003

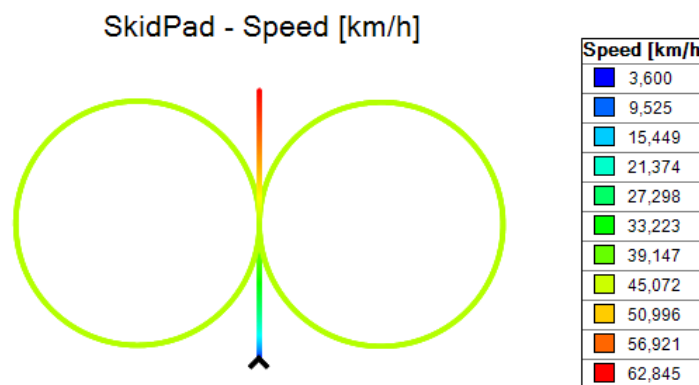


Figure 175: Skid-Pad with the FREC-004

The fourth and fifth pictures show an Autocross run with and without the aerodynamic kit. The increased cornering speeds show the benefit of the package.

FSH Autocross 2012 - Speed [km/h]

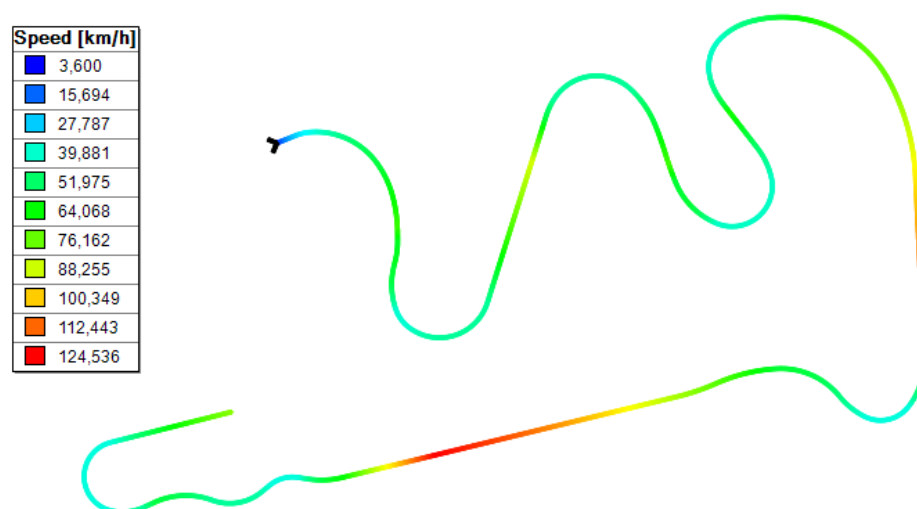


Figure 176: FSH Autocross with the FREC-004

FSH Autocross 2012 - Speed [km/h]

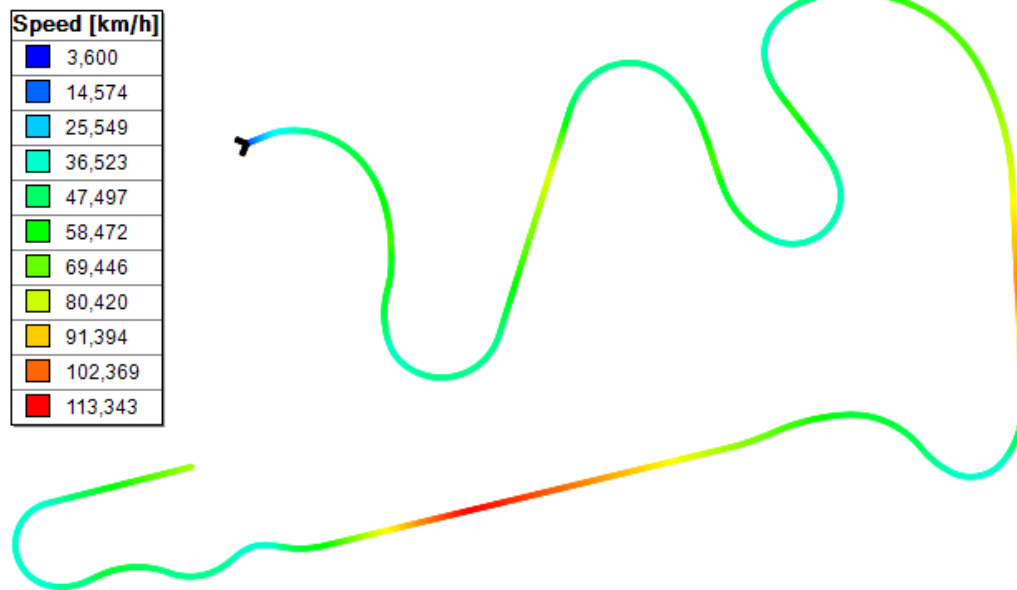


Figure 177: FSH Autocross with the FREC-003

The next two pictures show the Endurance lap times for the base and aero car respectively. The maximal lateral acceleration also shows the benefit of better grip through the increased downforce of the aerodynamic kit.

FSH Endurance 2012 - Lateral Acceleration [m/s²]

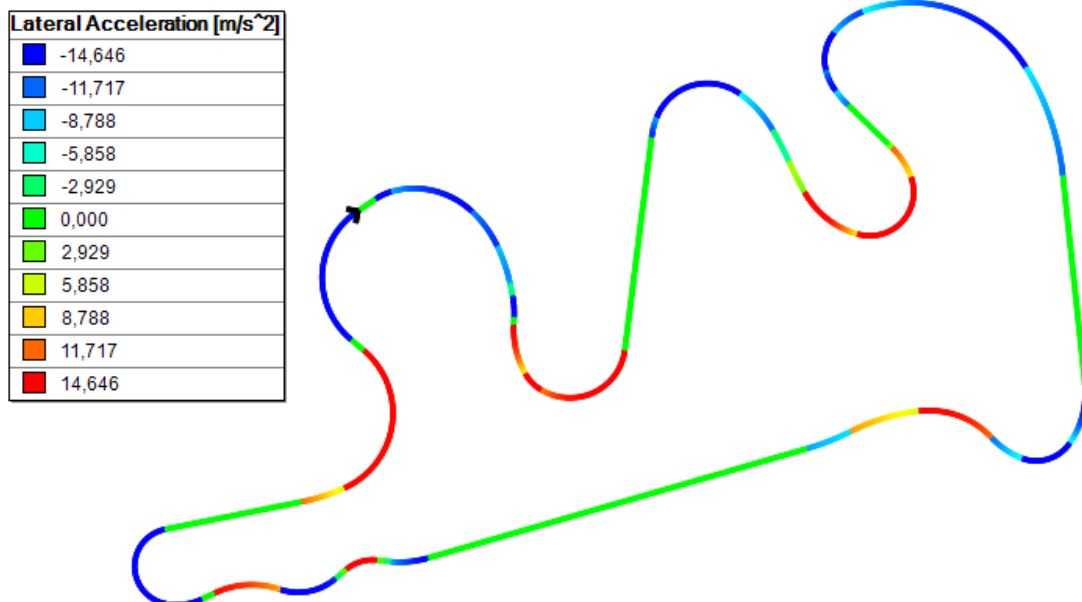


Figure 178: FSH Endurance with the FREC-003

FSH Endurance 2012 - Lateral Acceleration [m/s^2]

Lateral Acceleration [m/s^2]	
	-18,800
	-15,189
	-11,577
	-7,966
	-4,354
	-0,743
	2,868
	6,480
	10,091
	13,702
	17,314

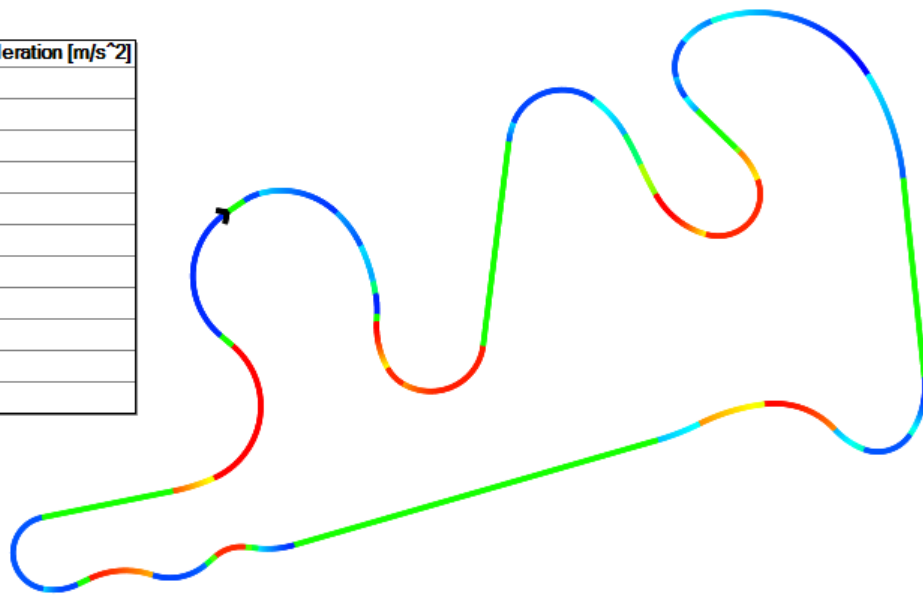


Figure 179: FSH Endurance with the FREC-004



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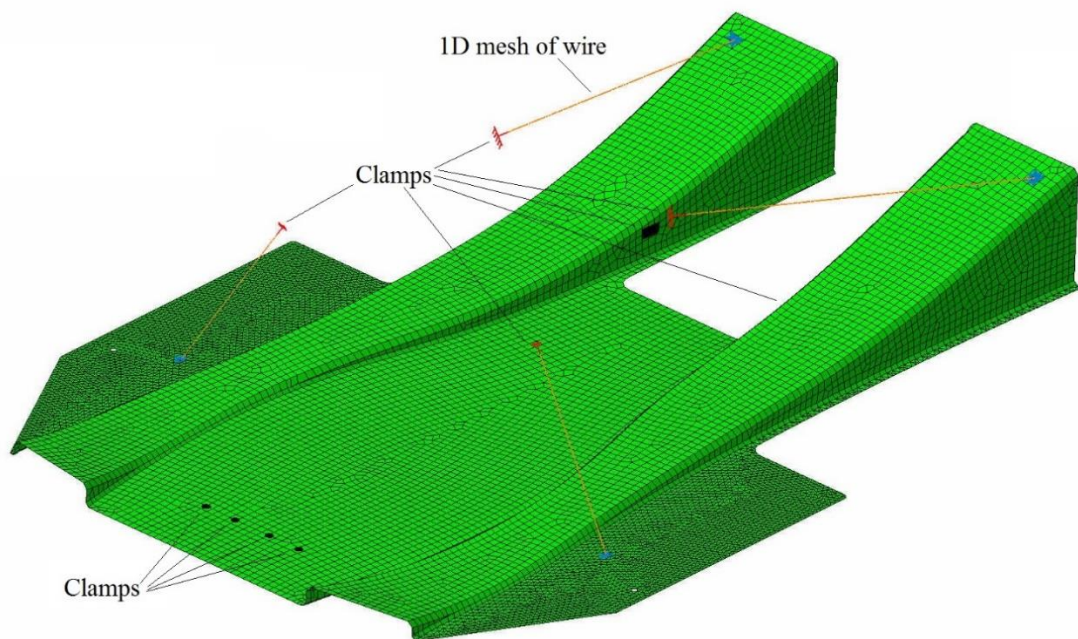


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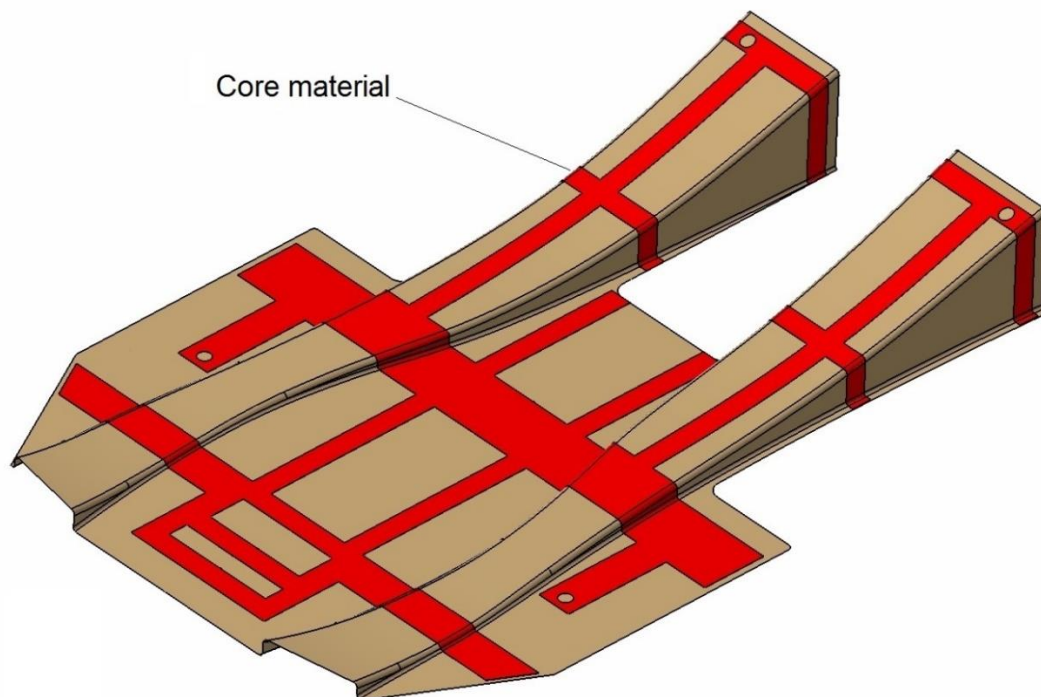


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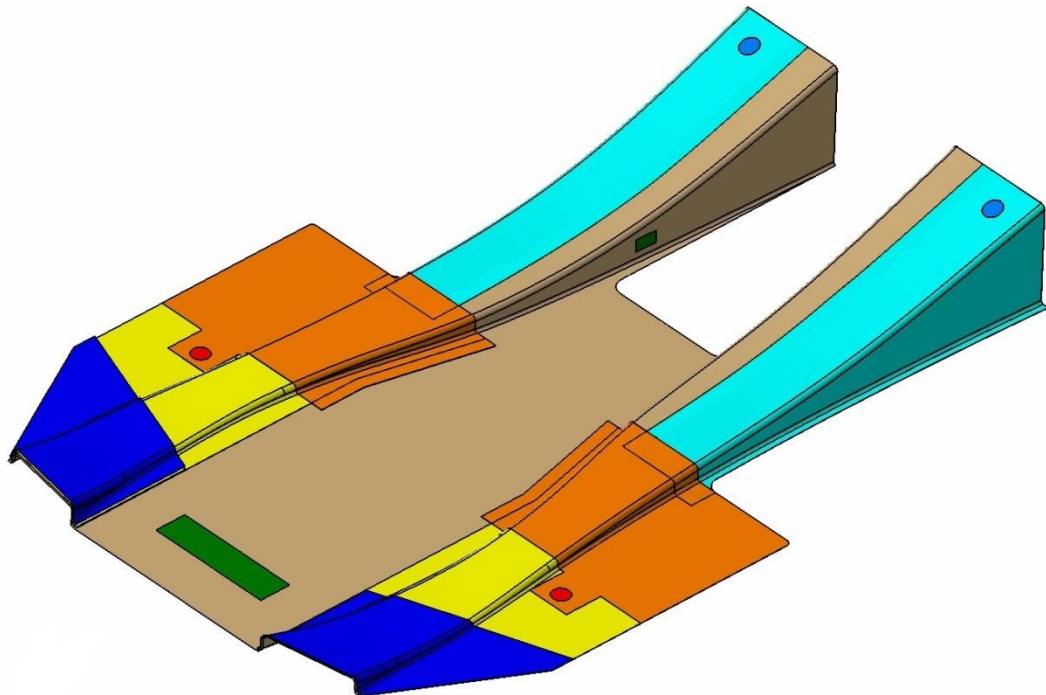
Photo appendix



Appendix 1: Constraints of undertray

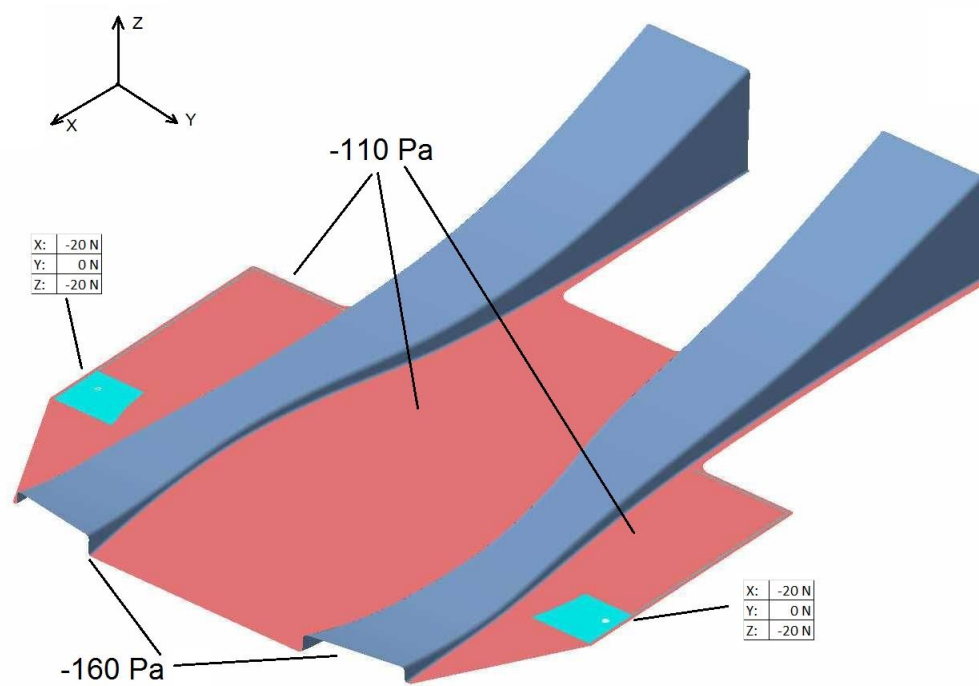


Appendix 2: Core in undertray

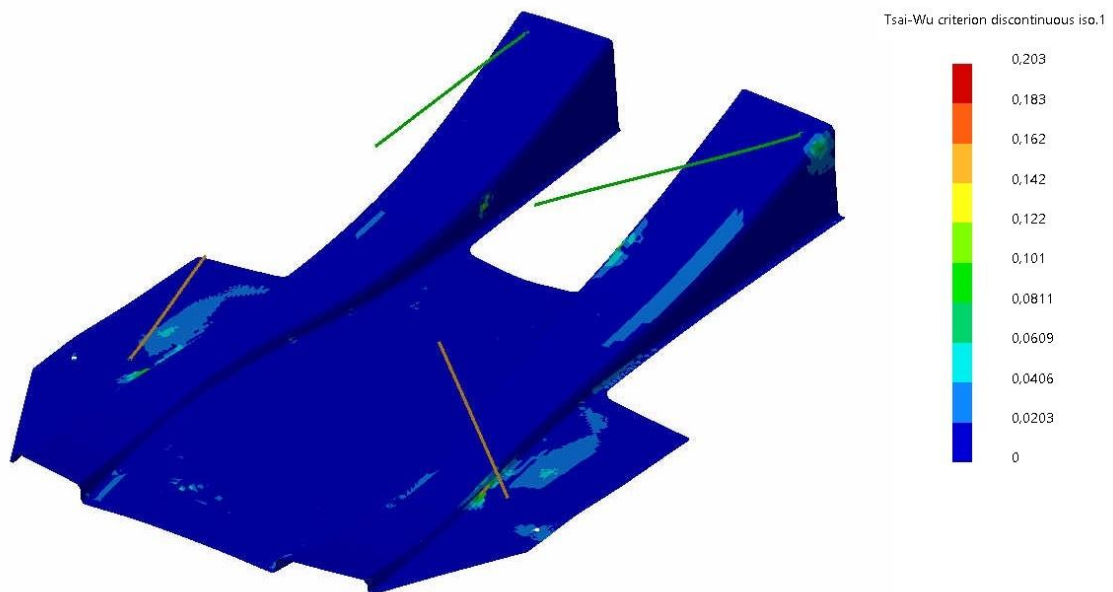


Zone	Ply-sequence
	$[45^{\circ}a/0^{\circ}UD/Core/45^{\circ}f]_T$
	$[45^{\circ}a/0^{\circ}UD/45^{\circ}f/Core/45^{\circ}f/45^{\circ}f]_T$
	$[45^{\circ}a/0^{\circ}UD/Core/90^{\circ}UD/45^{\circ}f]_T$
	$[45^{\circ}a/0^{\circ}UD/90^{\circ}UD/Core/90^{\circ}UD/90^{\circ}UD/45^{\circ}f]_T$
	$[45^{\circ}a/0^{\circ}UD/90^{\circ}UD/45^{\circ}f/Core/45^{\circ}f/90^{\circ}UD/90^{\circ}UD/45^{\circ}f]_T$
	$[45^{\circ}a/0^{\circ}UD/45^{\circ}UD/Core/90^{\circ}UD/45^{\circ}f]_T$
	$[45^{\circ}a/0^{\circ}UD/45^{\circ}f/Core/45^{\circ}f/45^{\circ}f/45^{\circ}f]_T$
	$[45^{\circ}a/0^{\circ}UD/Core/45^{\circ}f/45^{\circ}f]_T$

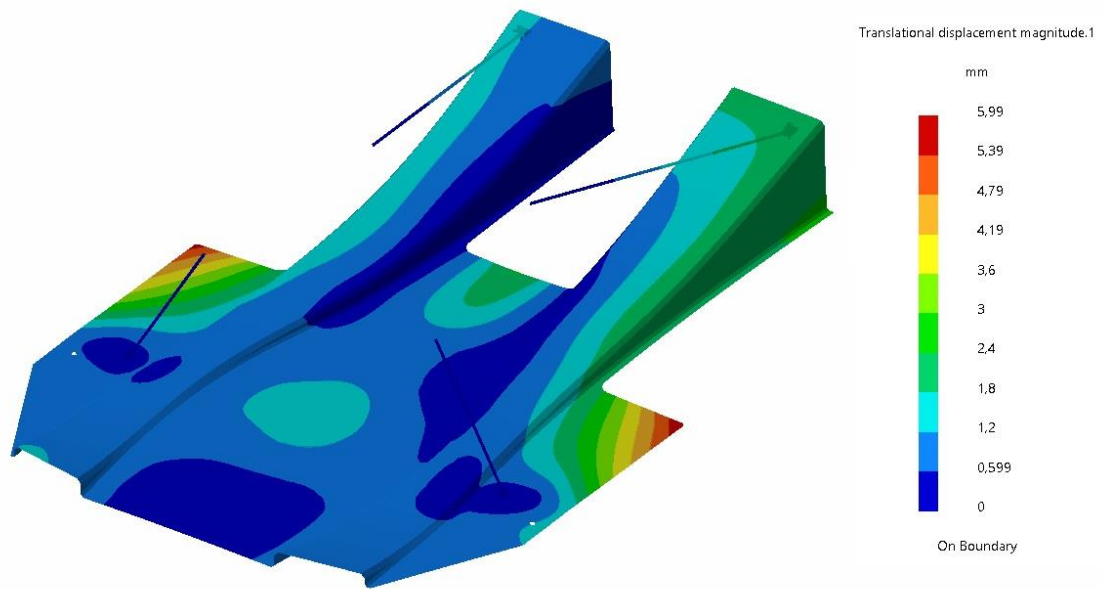
Appendix 3: Ply-sequence of undertray



Appendix 4: Loads of undertray



Appendix 5: Tsai-Wu of undertray



Appendix 6: Deformation of undertray



Appendix 7: BME Formula Racing Team; RollOut event (2014. 07. 05.)



Appendix 8: FRT FREC-004; Side view



Appendix 9: Test session (2014. 07. 27.)



Appendix 10: Team photo, Formula Student Hungary (2014. 08. 25.)



Appendix 11: Design Event, Formula Student Hungary (2014. 08. 26.)



Appendix 12: Formula Student Hungary, Autocross event (2014. 08. 27.)



Appendix 13: Formula Student Hungary, Autocross event (2014. 08. 27.)



Appendix 14: Rear wing



Appendix 15: FRT FREC-004



Appendix 16: FRT FREC-004



Appendix 17: FREC-004