POLITECNICO DI TORINO

Degree Course in Automotive Engineering

Master Degree Thesis

SC19: Monocoque Design

Supervisor: Prof. Andrea Tonoli

Candidate: Francesca Jourdan

December 2019

A Mimi e a Nonno Evasio.

Contents

Introduction

SC19 is a formula style, open wheel, electric race car designed and built by Squadra Corse Polito to take part to Formula SAE competitions. These races, which are attended by universities from all over the world, thanks to both static and dynamic events, test not only the vehicles performance on track, but also innovations, practical engineering, businesses analysis and project and team management. In this thesis the most relevant design aspects of the SC19 monocoque will be treated. The monocoque is made by sandwich composite panels: a sandwich structure consists of two high strength skins separated by a core material which function is to increase the thickness of the laminate and so its stiffness maintaining a low weight. Low weight is crucial to make a successful race car: weight reduction must be evaluated by finding the trade off between performance, structural resistance and stiffness.

Chapter 1. In this chapter will be explained the carried analysis on the previous year results of Squadra Corse, since it is fundamental in order to improve that of the incoming season. Targets were set to the overall project: it is very important to think of the vehicle as a combination of assemblies, which must be in harmony with each other, therefore it is necessary that each of these will be designed for the same common goals. For this reason in Chapter 1 the design objectives for the 2019 project will be quickly analysed.

Chapter 2. It gives a summary of the reference rules for the design of a composite frame, so as to be easy to consult if necessary, since regulations will be mentioned in the next chapters.

Chapter 3. The specific objectives to which the monocoque design has been oriented will be explained divided into objectives inherent to the functionality of the vehicle and those related to its performance and finally defined.
The same weight distribution analysis, made on chapter 1 considering the assemblies present in the vehicle, was carried out, is here performed between the components considerer of monocoque "assemby", so that the to determine more precise weight targets to the chassis department.

Chapter 4. Based on the targets explained in the previous chapter, the main aspects of the SC19 monocoque design will be here discussed. Laminates optimization and new design solutions were

adopted to reach an overall vehicle weight reduction target, enhancing the dynamics performance of the SC19. This, however, must not weaken the stiffness of the frame: it will be explained how the torsional stiffness of the monocoque was evaluated with a FE model and then later tested.
Before those performance features, the car must be easily maintainable: accessibility to repair or replace fault components in a reasonable time during race must be insured.
Also ergonomics for the drivers must be taken into account and studied so as to allow them to reach better driving performance.
These two aspects have been set according to the problems encountered during the previous year and good results under both aspects have been reached, becoming strong points to be carried over of the SC19 vehicle.

Chapter 5. In the first part of this chapter an overview on the hand-lay up process is made. Then the manufacturing process of the monocoque will be described in detail since performed in complete autonomy by team members.

Chapter 1

The project

Before starting with the design of the new vehicle, it is necessary to define the aims of the project. It is in fact of fundamental importance think to the vehicle as a whole, so as to define common objectives between the various departments, without making room for an improvement of the single component, but thinking about how the single assemblies are fit together and how they work and influence each other performance, in order to improve that of the whole vehicle. Then what will be said in this chapter is a necessary premise to understand what will be discussed in detail in the next chapters, about the design choices concerning the monocoque.

Among all the aspects that can be considered as a success of the previous year's project, the most important is surely the score obtained during the competitions of the season. For this reason, it was decided to carry out a detailed analysis of the scores obtained at the races, in particular the one of Formula Student Spain held in Barcelona. As a term of comparison, two top teams at world level were considered: Rennteam Stuttgart and ETH Zürich, both first overall EV classified respectively in FSS and Formula Student Germany. To understand what will be said, it is better to briefly explain how the competitions are structured in order to understand how the scores were assigned.

Competition format: general overview

During the competitions, the teams are evaluated on two different types of tests: the dynamic events, which as the name indicates are those that take place on the track, and the static ones, that on the contrary are carried out by the team members out of track without switch on the vehicle.

Dynamic events

Acceleration: during this test car must accelerate for 75 meters along a straight path on a flat surface.
The score is determined by the difference between the worst and the absolute best time recorded,

bearing in mind that the highest time taken into consideration by the judges must not exceed 5.8 seconds, equal to an average speed of 46.55 km/h. The score obtained by the first theme is 75pt.

Skid-Pad: the test assesses the car's cornering ability. The track recalls the figure of an 8 with two circles of 15.25 meters bordered by cones both to the right and to the left. The car, once entered the route, must make a turn of the right circle, to establish the direction of travel, at the end of which it must complete a second, which is timed by the judges. Once the second lap is over, the car must do the same two laps in the other half of the "8". After the fourth lap, the car leaves the track. Both the maximum score and the ranking is determined in the same way explained for the acceleration test and the run time considered is the average time of the timed left and the timed right circle plus penalties which are added after the averaging.

Autocross: it is a sprint test to be performed on two laps of the circuit, shorter than 1.5km, to evaluate the car's handling. The circuit includes short straight stretches (no more than 80m), curves with constant radius (up to 50 m in diameter), hairpin bends (minimum 9 m external diameter), slaloms, chicanes and variable radius curves. For the score the best time is worth on two tests carried out by two different drivers and they are assigned to the first classified 100 points.

Endurand and Fuel Efficiency: the endurance test is the event that closes the race weekend, and aims to assess the overall performance of the prototype. For this reason it undoubtedly represents the main event of a Formula SAE competition. It takes place along a path very similar to the one in which the autocross test is run, for a total of 22 km. Team members are not allowed to intervene on the vehicle during the test, while a mid-test driver change is expected during a three-minute rest period. The starting order is based on the results of the autocross. The overall time of the endurance is given by the sum of the times of each driver, to which are added the possible penalties, compared with that of the fastest team on the track. A maximum of 325 points is available for this event.

In the same context of endurance a ranking is drawn up, and consequently points are awarded for the fuel economy, where 100 pt are assigned to the most efficient vehicle. For EV, the endurance energy is calculated as the time integrated value of the measured voltage multiplied by the measured current logged by the data logger. Regenerated energy is multiplied by 0.9 and subtracted from the used energy.

Static events

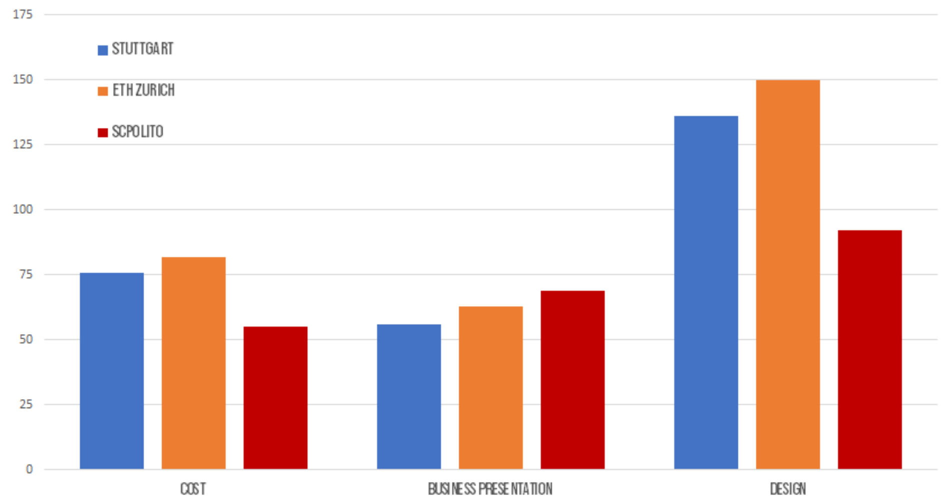
Cost Analysis: the objective of the cost and manufacturing event is to evaluate the team's understanding of the manufacturing processes and costs associated with the construction of a prototype race car. This includes trade off decisions between content and cost, make or buy decisions and understanding the differences between prototype and mass production. During the competition, a discussion with the judges will take place, next to the team's vehicle. The discussion is split into two parts: the Bill of Material (BOM) discussion, to evaluate the team's ability to prepare an accurate engineering and manufacturing BOM for the complete vehicle; and a secon cost understanding discussion. The aim of this latter is to evaluate the general cost and manufacturing knowledge of the team. The maximum score for this event is 100 pt.

Business plan presentation: is aimed at assessing the team's ability to develop and deliver a broad and comprehensive business model which demonstrates the team's product, a prototype race car, could become a rewarding business opportunity. The event is judged by people from the automotive world, so the team must assume not only to deal with engineers, but with an executive representing the various areas of a company, including production, marketing and finance managers. The assessment is focused on the content, organization and illustration of the project, as well as the ability to answer judges' questions, therefore the team that will produce the best presentation, associated with the quality of the vehicle, will win the test. The maximum score for this event is 75 pt.

Engineering Design: the concept of the design event is to evaluate the student's engineering process and effort that went into the design of a vehicle, meeting the intent of the competition. These aspects are evaluated by the judges in conjunction with the team's ability to respond to questions asked and inspection of the machine, which must be presented fully assembled and ready to compete. The maximum score for this event is 150 pt.

1.1 Target setting

A FSS score benchmarking analysis was performed to assess the nature of the gap between two considered top teams and Squadra Corse. Therefore, from this comparison, the weaknesses and strengths of the previous year work were highlighted, in order to define the targets for the new project. Starting with the static events scoring, thanks to the feedback sheets of the judges which were given to us after the competition, it was possible to understand what were our deficiencies.



Graphic 1. *Formula Student Spain 2018 static events scoring.*

The best result of our team was that obtained on the business plan presentation: the score achieved was 69/75 points, 6 points more compared to Zürich and 13 compared to Stuttgart. The aspects to be improved mainly concerned the graphic layout of the presentation, and a little bit detailed financial analysis could be done; in general an excellent result, even more if compared to that obtained by the top teams. On the contrary, many negative feedbacks have been reported regarding the other two static events. Due to an incomplete and superficial cost and benefit analysis, the scoring related to the cost presentation was 55.2/100, disappointing compared to the 76 and 82 points obtained by competitors. But the result that we are most interested in analyzing is that related to the evaluation obtained at the engineering design presentation. In fact this event summarizes all the fundamental aspects of the project, starting with its layout, its development and the result obtained. If we consider the workflow phases of the project, none of them was satisfactory. First of all, the judges saw a total absence of the most critical phase within the development of a project, that of the setting of targets: to define objectives provide a clearer picture of the project's priorities, serve as a basis for budget management and performance evaluation and for this reason the evaluation was not good and the point lost related to this deficiency were 10. Furthermore, going into the details of the choice and design of the components, no innovative and distinctive technical elements within the project were found, which not only did not excite the interest of the judges but it goes against the spirit of competition itself and for this reason 20 points have been lost. Others 25 points were lost due to the lack of validations of the results obtained through the developed models, such as for example the wind tunnel test to assess the aerodynamic drag of the vehicle or the chassis torsion test. This too is a very important phase of development within a team, as it measures the validity of the designed components and the models created, placing a more or less firm foundation for the following year design. Moreover, the absence of ergonomic studies on the cockpit was highlighted and further penalized the team. Finally 15 points were not earned because of the contents that were entered in the design report.

On the basis of these feedbacks, targets for the 2019 project have been set both to define guidelines to be followed to reach a better preparation for next year static events, and to improve certain project aspects.

Work progress reports have been planned every two months in order to keep the state of the works up-to-date and to have already collected useful material when preparing presentations for static events. So as to keep track of all the possibilities that have been considered for each component, and therefore of the reasons and performed analysis for which a certain design choice was made leaving the others. It is therefore possible to have all the intermediate phases of the development of the project neatly documented to avoid, during the preparation of supporting documentation needed to the static events presentations, lack of material in support of certain design choice or material or even processing technique. In this regard and in general to manage the CAD models, a chronology of development of the components was implemented through a new internal method of coding the components.

The coding was planned in this way: XX.YY.WW.ZZ

where:

XX was the code belonging to the division responsible for the component in question (for example 01 aerodynamics, 02 battery pack, 03 chassis and so on);

YY indicates to which sub-assembly of the main assembly XX belongs to (01.01 rear wing, 01.02 front wing etc);

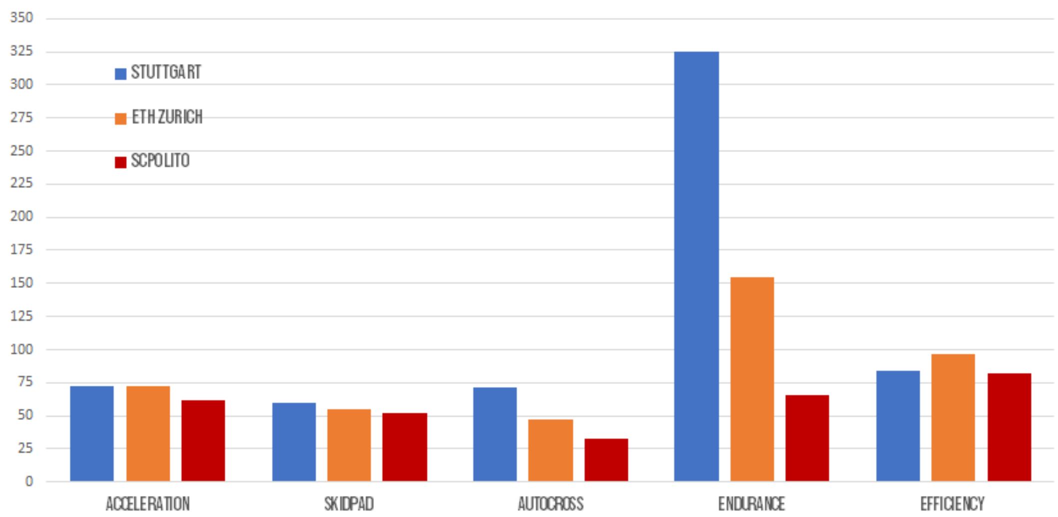
WW code assigned to the component;

ZZ is a number that goes from 00 to grow, indicating which version of the component versions it is, so that in the shared folder the last version of the component is always that of the file at the top or at the bottom, depending on whether the order criterion is increasing or decreasing.

As regards the evaluation of the project, the main negative aspects were the lack of validation tests of the models. This, however, turns out to be very tied to the available budget as necessary tests like the one in the wind tunnel for the validation of the CFD simulations for example, result to be an excessive expense.

Instead regarding the innovative aspects of vehicle design, at the beginning of the season we immediately started with the development of carbon fiber suspension A-arms. The questions concerning these components were related to both the manufacturing and design process, since never before in Squadra Corse's vehicles have been used CFRP A-arms. The prototyping of these was scheduled in the first month of work, so that the production process could be improved before the final version of the arms, and so that they could be tested first on the SC18.

Same analysis has ben performed also for the dynamic events, in order to define the main target aimed to improving the performance of SC19 with respect the previous vehicle and in relation to competitors. Facing these results the main causes have been drawn and the relative influences estimated and here reported.



Graphic 2. *Formula Student Spain 2018 dynamic events scoring.*

The biggest gap that catches immediately the eye is that occurred on the endurance event. In this case we scored only 65.5/325 due to multiple causes and apart from this, the delay that we have marked on the winner of the test is the most disconcerting datum: in fact the German team took 6 minutes less than us to close the 22 km of race. Of these 360 s approximately 300 have been justified and their causes have been identified. First of all a penality equal to 2 min was given since we were not in time at the starting line due to battery pack problem. Furthermore, due to an inefficient battery pack cooling system, the cells overheated and to avoid exceeding the maximum temperature allowed by the regulation of 60° C it was necessary to lower the required currents and perform the endurance with an average speed of about 7 km/h lower that Rennteam Stuttgart. The same overheating problem did not make current regeneration possible, causing an estimated delay equal to 40 s. Moreover, part of our delay on the best is certainly due to the driving skills of our drivers, since in many teams professional drivers are present. Furthermore, shortly after having passed the finish line, at the end of endurance, the transmission broke. Considering now the performance obtained in acceleration, the difference in points between SC and the two teams considered was less than 9 points as they both scored 72 pt. The time taken by the vehicle of the acceleration winner team Elblorace (TU Dresden) was 3.496, 0.3 s less than SC18. This delay was in a third part due to the weight, as our vehicle was about 30 kg heavier than theirs. Another third part has been attributed as a power control not precise which, if set to the limit, risked making the run invalid due to exceeding the 80 kW limit .

Obviously the same problems listed for acceleration and endurance have also influenced the performance in autocross, in which our lap time was 6 s higher than that of the winner, TU München.
Basically the three macro-categories on which it was necessary to act in order to improve the performance of the new vehicle were reliability, efficiency and vehicle dynamics.
Starting from the reliability , concerning the electric and electronic fields first of all the wiring have to be improved and the starting point was that of include also the wires in CAD models so that considering also their size when positioning the powered component. Interference and disturbances problems have been found both in the battery pack and in the inverter and to avoid that a new position of the BMS in the battery case must be found and a new shielding for inverters must be designed. Other problem concerning reliability were encountered during competitions such as water infiltrations in the rear compartment, due to the interface between the two firewall, mobile and fixed , not easily sealable. To improve reliability it is fundamental to test may times the vehicle and all its components. For this reason, a carry-over strategy was made for the new project, so that taking what have been already designed the previous year as a starting point to improve the project, without distorting it with risky technical choices and limiting radical changes that can damage the SC19 reliability. Therefore during the design phase of the SC19 many sessions on track with the SC18 were planned, so as to carry out tests on the battery pack and to collect other data on the behaviour of the cells, to test some prototype components and moreover to improve the control strategies.
Without going into detail, regarding the improvement of vehicle efficiency the main objectives have been identified in the design of a battery pack cooling system with ducts which external manifolds allow a sufficient amount of air to be carried into the battery compartment, so that carrying CFD simulation of the internal air flow the cooling of the modules can be optimized. can intake air into the battery case and focusing on the study of internal flows through cfd models optimizing its cooling. Another important aspect of the vehicle efficiency is that related to the aerodynamics, whose goal for 2019 has been set in achieving an aerodynamic efficiency as close as possible to 4, without exceeding with the drag coefficient a value equal to 1. Furthermore, after the problems obtained during the production of the wings profiles, it was decided to simplify them so that they could be produced with higher precision in order to avoid undesired flows behaviours. Also the structural aspects of the aero package has to be improved. Also the transmission ratio must be optimized, trying to find the best trade-off between performance and energy consumption, obviously considering the feasibility and cost constraints.
Finally, considering the improvements to be made with regard to the dynamics of the vehicle we can list the reduction of the overall weight, of which we will talk more in detail, the optimization of the controls of yaw, power and traction, the need to validate the model of estimate of the center of gravity of the vehicle and the design of innovative CFRP A-arms.
After this quick overview of what were the global objectives set at the beginning of the year regarding the project of the SC19, now we will go more in detail with the target on which much depends on what we're going to talk about in the next chapters, in relation to the vehicle chassis: the target weight of the

SC19.

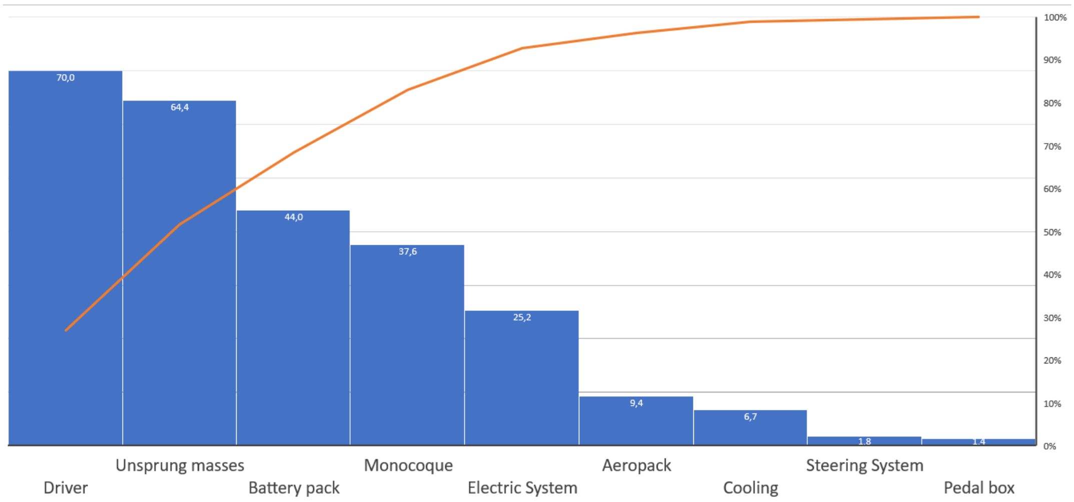
In order to define a value for the weight of the new vehicle so that it could be more competitive, we carried out a benchmarking on the weights of the strongest competitors. The first analysis was made to assess what is the weight gap between us and the top teams; in this regard the vehicle weight of thirteen of the first fifteen classified EV teams at Formula Student Germany 2018 were collected. The table below reports the name of these universities and their placements both in the German and Spanish competition, and the the vehicles recorded weights at these events.

Team	**FSG**	**FSS**	**Weight [kg]**
ETH Zürich	1	7	166
NTNU Trondheim	2	4	183
Running Snail	3	3	202
KIT	4	19	180
TU Eindhoven	5	6	197
Monash	6	-	276
Deggendoorf	7	15	193
UAS Nunberg	8	-	238
TU Delft	9	-	172
TU München	10	12	158
TU Stuttgart	13	1	176
DHBW Stuttgart	14	2	193
Tallin	15	-	184

Table 1. *Weight benchmarking.*

Considering all these values we found out an average vehicle weight equal to 193.7 kg and taking into account that the weight of the SC18 was equal to 203 kg the gap was of about 10 kg.

At this point was important to analyse the weight distribution between SC18 assemblies, in order to define where it is possible to save weight. For this purpose a Pareto diagram was useful: the horizontal axis of the Pareto chart shows the assemblies which determine the overall weight of the SC18. The sequence of those elements is less and less important from left to right. Besides, the value indicated on each bar of the chart represents the weight in kilos of the related assembly, while right vertical axis shows the cumulative percentage. Thus, the height of each bar acts as influencing the degree of each element and the upper line indicates the cumulative frequency line.



Graphic 3. *SC18 weight analysis: Pareto diagram showing the distribution of weights between different assemblies.*

After this weight analysis, estimates of the possible weight savings were performed, trying to find the best trade off between performance, weight and cost, but also reliability (FMEA approach). The lightening process has been focused on the three heavier assemblies, since considering the other not much weight can be saved. As for the unsprung masses, although it represents the heaviest assembly, it is possible to make change of only 40% of this weight since the other 60% is that of purchased components such as electric motors, tires and rims. Squadra Corse is far from the development of custom electric motors, both technically and in terms of instrumentation and budget, but it is not so far from the development and use of smaller and lighter carbon rims. Then the possible weight saving of this assembly was estimated equal to 4.5 kg, considering a new suspensions layout with air springs and CFRP A-arms and performing an optimization of the uprights. For what concerns the monocoque, after a preliminary analysis, the estimated weight saving was of 3 kg; in the next chapters we will go further in detail with both the targets setting and the developments of the SC19 chassis. Others weight that could be reduced were that of the battery pack, for which a target of 42 kg was set, and that of the rear wing of about 1 kilo. Other 2 kg were estimated to be saved thanks to a new inverter packaging leading to a final overall weight of about 191 kg. This value is completely aligned to the average weight of the fifteen top vehicle considered before, so was a good starting point for the design of the new vehicle.
Thanks to a lap simulator implemented by the vehicle dynamics department manager it was possible to evaluate the performance improvement due this weight reduction, both in terms of lap time and energy consumed: considering only this weight reduction, the lap time is improved of 1.2s and 5 Wh of energy can be saved each lap.

Chapter 2

Overview on technical requirements

Before starting to speak about the SC19 monocoque, it is necessary to clarify that there are many rules that the design of a FSAE vehicle must comply. This chapter intends to report the most relevant project constraints and requirements that each team must consider when designing a composite chassis for a Formula Student competition. This will be useful in order to understand in the best way all the design choices that will be explained in the next chapters, leading to know as the SC19's monocoque has come to be designed.

2.1 Definitions

Each part of the chassis has a name and some areas are grouped under a technical term, so below are reported the definitions that it's necessary to have clear in mind.

Chassis – The fabricated structural assembly that supports all functional vehicle systems.This assembly may be a single welded structure, multiple welded structures or a combination of composite and welded structures.

Chassis member – A minimum representative single piece of uncut, continuous tubing or equivalent structure.

Front bulkhead – A planar structure that defines the forward plane of the chassis and provides protection for the driver's feet.

Front bulkhead support – A structure that defines the side of the chassis from front bulkhead back to the top of the upper side impact structure and the front hoop.

Front hoop – A roll bar located above the driver's legs, in proximity to the steering wheel.

Front hoop bracing – The structure from the front hoop forward to the front bulkhead.

Impact Attenuator (IA) – A deformable, energy absorbing device located forward of the front bulkhead.

Main hoop – A roll bar located alongside or just behind the driver's torso.

Monocoque – A chassis made of composite material.

Node-to-node triangulation – An arrangement of chassis members projected onto a plane, where a co-planar load applied in any direction, at any node, results in only tensile or compressive forces in the chassis members.

Primary structure – The primary structure is comprised of the following components:

- Main hoop
- Front hoop
- Roll hoop braces and supports
- Side impact structure
- Front bulkhead
- Front bulkhead support system
- All chassis members, guides and supports that transfer load from the driver's restraint system into the above mentioned components of the primary structure.

Roll hoops – Both the front hoop and the main hoop are classified as "roll hoops"

Roll hoop bracing – The structure from a roll hoop to the roll hoop bracing support.

Roll hoop bracing supports – The structure from the lower end of the roll hoop bracing back to the roll hoop(s).

Rollover protection envelope – Envelope of the primary structure and any additional structures fixed to the primary structure which meet the minimum specification defined in rulebook.

Side impact structure – The area of the side of the chassis between the front hoop and the main hoop and from the chassis floor to the height as required in T3.15 above the lowest inside chassis point between front hoop and main hoop.

Surface envelope – The surface envelope is the surface defined by the top of the roll bar and the outside edges of the four tires.

2.2 Design requirements

Bodywork

In general, the vehicle must have a formula style body: open-wheeled, single seat and open cockpit with four wheels. There must be no openings through the bodywork into the driver compartment other than that required for the cockpit opening. Concerning the external shape of the body, the monocoque in our case, all its edges that could come into contact with a pedestrian must have a minimum radius of 1 mm. The bodywork in front of the front wheels must have a radius of at least 38 mm extending at least 45 deg relative to the forward direction, along the top, sides and bottom of all affected edges.

Chassis design

General requirements It is important to say as first thing that the vehicle's structure must include:
• Two roll hoops that are braced
• A front bulkhead with support system and IA
• Side impact structures

Structural equivalency All teams must submit a Structural Equivalency Spreadsheet (SES) that is a spreadsheet form that can be downloaded from the competition website. This is the tool with which the chassis structure can be verified by judges. Teams, submitting the file, confirm that vehicles have been fabricated in accordance with the materials and processes described in the SES. For teams as Squadra Corse, designing a composite monocoque structure, the SES is both a powerful and difficult to use tool. If composite structures are used in the primary structure or the tractive system accumulator container, the Flexural Rigidity (EI) of that structure must be calculated with the tools and formulas in the SES, that must include: material types, cloth weights, resin type, fiber orientation, number of layers, core material, lay-up technique and required tests that will be explained later.
Alternative materials used on the primary structure must show an equivalen minimum material requirements to that of steel tubing structures and the steel properties used for the calculations in the SES are indicated. Compiling the SES, the actual geometry and curvature of the panel may be taken into account for the main hoop bracing support, the front hoop bracing, the front bulkhead support structure and the shoulder harness bar. For all other areas the EI must be calculated as the EI of a flat panel about its neutral axis.

Laminate testing If composite materials are used for any part of the primary structure or the tractive system accumulator container the team must:
• Build a representative test panel which must measure exactly 275mm×500mm that has the same design, laminate and fabrication method as used for the respective part of the primary structure represented as a flat panel.
• Perform a 3-point bending test on this panel, reporting on the SES data from these tests and pictures of the test samples and test setup. The test results must be used to derive strength and stiffness properties used in the SES formula for all laminate panels. If a panel represents side impact structure it must be proven that it has at least the same properties as two steel tubes meeting the requirements for side impact structure tubes for buckling modulus, yield strength and absorbed energy.

The 3-point bending test must be performed with a distance between supports not lower than 400 mm and the load applicator used to test any panel or tube must be metallic and have a radius of 50 mm. The load applicator must overhang the test piece to prevent edge loading.
•Perimeter shear tests must be completed which measure the force required to push or pull a 25mm diameter flat punch through a flat laminate sample. The sample must be at least 100mm × 100mm. The test fixture must support the entire sample, except for a 32mm hole aligned co-axially with the punch. The sample must not be clamped to the fixture.

Roll hoops The roll hoops must extend from the lowest chassis member on one side of the chassis, up, over and down to the lowest chassis member on the other side. In case of tubular chassis, both roll hoops must be securely integrated to the primary structure using node-to-node triangulation; otherwise, in case of composite monocoque, must be proofed that the structure is equivalent to a node-to-node triangulation, it will be explained how and where these equivalency must be performed. Both roll hoops must be mechanically attached at the top and bottom of both sides of the structure and at intermediate locations if needed to show equivalency.
Our front hoop is fully laminated to the monocoque, that means that the hoop has been encapsulated with laminate around its whole circumference, as said in the rulebook. The main hoop must be supported to the front or the rear by bracing tubes on each side of the main hoop. The braces must be straight and attached to the main hoop no lower than 160mm below the top-most surface of the main hoop. The included angle formed by the main hoop and the main hoop braces must be at least 30 deg. The lower ends of the main hoop braces must be supported back to the upper attachment point of the main hoop to the side impact structure and to the lower attachment point of the main hoop to the side impact structure by a node-to-node triangulated structure or equivalent composite structure. How our bracing structure equivalency wae proofed will be explained in chapter 3.
The picture below summarizes the requirements related to front hoop bracing, main hoop bracing and steering wheel.

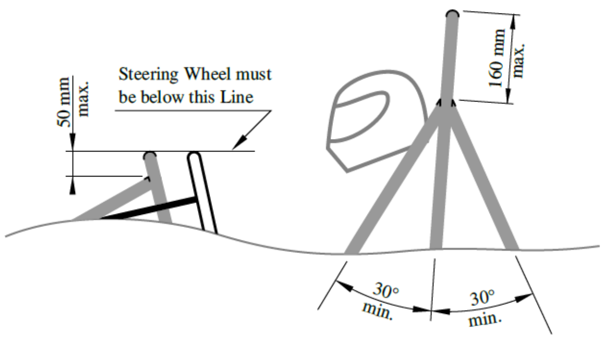


Figure 1. *Front hoop bracing, main hoop bracing and steering wheel requirements*

Front bulkhead and FBH support Any alternative material used for the front bulkhead must have a perimeter shear strength equivalent to a 1.5mm thick steel plate.
The front bulkhead must be supported back to the front hoop by a minimum of three tubes on each side: an upper member, a lower member and diagonal bracing to provide triangulation. Since our front bulkhead support is part of a composite structure, it must have equivalent EI to the sum of the EI of the six baseline steel tubes that it replaces. The perimeter shear strength of the monocoque laminate in the front bulkhead support structure must be at least 4 kN.

Side impact structure The side impact structure must consist of at least three steel tubes, on each side of the cockpit; if the side impact structure is part of a composite structure, the following is required:
• The region that is longitudinally forward of the main hoop and aft of the front hoop and vertical from the bottom surface of the chassis to 320mm above the lowest inside chassis point between the front and main hoop must have an EI equal to the three baseline steel tubes that it replaces, see figure.
• The vertical side impact structure must have an EI equivalent to two baseline steel tubes and half the horizontal floor must have an EI equivalent to one baseline steel tube.
• The vertical side impact structure must have an absorbed energy equivalent to two baseline steel tubes.
• The perimeter shear strength must be at least 7.5 kN.

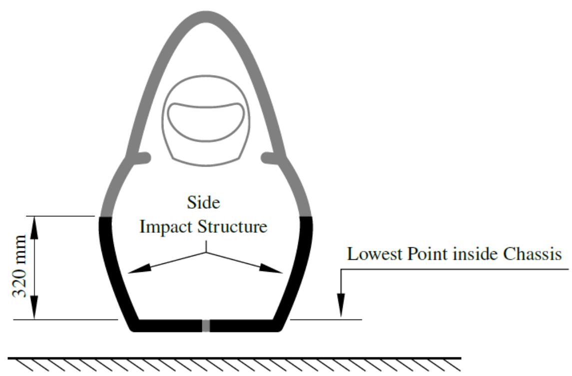


Figure 2. *Side impact structure monocoque*

2.3 Cockpit

Cockpit opening The size of the cockpit opening needs to be sufficient so that the template, that is shown on the left in figure below and must be held horizontally, can pass vertically from the opening until it is 320mm above the lowest inside chassis point.

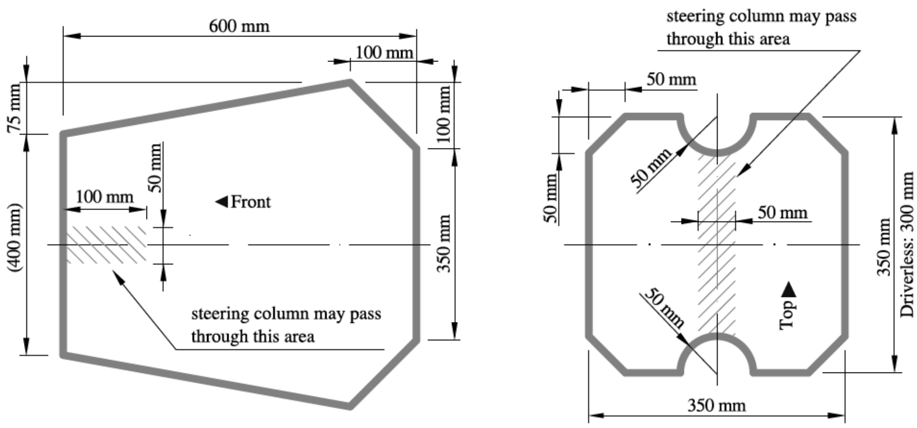


Figure 3. *Cockpit opening template (left) and cockpit internal cross section template (right)*

Cockpit internal cross section The cockpit must provide a free internal cross section sufficient for the template shown on the right in figure above to pass from the cockpit opening to a point 100mm rearwards of the face of the rearmost pedal in an inoperative rearmost position.

Non-welded driver's harness attachment Any harness attachment to a monocoque must be using one 10 mm metric grade 8.8 bolt or two 8mm metric grade 8.8 bolts (or bolts of an equivalent norm) and steel backing plates with a minimum thickness of 2 mm. If the attachment of the drivers harness is not welded to a steel structure, it must be proven that the attachments for shoulder and lap belts can support a load of 13 kN and the attachment points of the anti-submarine belts can support a load of 6.5 kN.
The strength of lap belt and shoulder belt attachments must be proven by physical testing where the required load is applied to a representative attachment point with the layup and attachment brackets as in the chassis. The rulebook gives indication about how to perform the test.

Driver's seat There The lowest point of the driver's seat must in side view not extend below the upper face of the lowest side impact structure member and an adequate heat insulation must be provided to ensure that the driver is not able to contact any parts of the vehicle with a surface temperature above 60 deg C.

Firewall A firewall must separate the driver compartment from all components of the liquid cooling systems, the low voltage battery and any TS component. The firewall must be a non-permeable surface made from a rigid, fire resistant material, which must be rigidly mounted to the vehicle's structure. Any firewall must seal completely against the passage of fluids, especially at the sides and the floor of the cockpit. For Ev only, the tractive system firewall between driver and tractive system components must be composed of two layers:

- One layer, facing the tractive system side, must be made of aluminum with a thickness of at least

0.5mm. This part of the tractive system firewall must be grounded according to rules.

• The second layer, facing the driver, cannot be made on CFRP but must be made of an electrically insulating and fire retardant material; the thickness of the second layer must be sufficient to prevent penetrating this layer with a 4mm wide screwdriver and 250N of force.

2.4 Driver restraint system

The lap belt, shoulder harness and anti-submarine strap(s) must be securely mounted to the primary structure. This structure and any guide or support for the belts must be equivalent to that made of steel tubes, satisfying equivalency of the minimum material requirements. The tab or bracket to which any harness is attached must have a minimum cross sectional area of 60 mm^2 of steel to be sheared or failed in tension at any point of the tab, and a minimum thickness of 1.6 mm. Where brackets are fastened to the chassis, two fasteners of 6 mm metric grade 8.8 fasteners or stronger must be used.
The attachment of the driver's restraint system to a monocoque structure requires an approved SES.

Shoulder harness The shoulder harness must be mounted behind the driver to a structure that meets the requirements of the primary structure. The shoulder harness mounting points must be between 180mm and 230mm apart. From the driver's shoulders rearwards to the mounting point or structural guide, the shoulder harness must be between 10° above the horizontal and 20° below the horizontal.

Head restraint A padded, vertical head restraint must be provided on the vehicle to limit the rearward motion of the driver's head. It must be located so that for each driver:
- The restraint is no more than 25mm away from the back of the driver's helmet, with the driver in their normal driving position.
- The contact point of the back of the driver's helmet on the head restraint is no less than 50mm from any edge of the head restraint.
-The head restraint, its attachment and its mounting must withstand a force of 890N applied in the rearward direction at any point on its surface.

Chapter 3

Monocoque targets setting

As well as the global objectives have been defined in the preliminary phase of project definition, before starting to design the monocoque it was necessary to set the targets that guide its design process, in relation to what has been said so far, in order to make possible the reaching of the objectives set on a larger scale considering globally the vehicle.

Targets were divided under two categories:

1. Functional targets: they refer to those design solutions aimed at improving the vehicle in terms of "out of track performance". These targets are related to the improvement of the conditions of action on the vehicle, both as regards the actions of the driver himself, both the actions that must be performed externally by team members on the vehicle.

2. Performance targets: just think about what is directly related to lap time. In fact the features of the frame to which we are referring with this type of targets are those that have a direct influence on the performance of the vehicle.

Functional targets

This category of design objectives is aimed at solving the problems, partially discussed in the first chapter, that have occurred in the previous vehicle. In particular we had to deal with issues related to these three macro categories, so an improvement of them were needed.

1. **Mantainability and Accessibility**: a good accessibility to all the "critical" parts of the vehicle is required to ensure short maintenance time, that is a key factor while operating a race car prototype. Maintainability is a function of engineering design: it requires that the installation is serviceable and can be easily repaired and practically kept in or restored to a usable condition in a reasonable time. Designing for maintainability was a key factor in the development of the SC19: were in fact

immediately dictated by the technical director of the project of the guidelines regarding the design of the components, aimed at optimizing the maintenance process such as reduce to minimum the number of required tools to assemble a system or device and avoid requiring special tools for assembly, avoid interference coupling for parts which may require maintenance, optimize shape of parts to simplify assembly and many others "good practices" to follow. But remaining in the monocoque field, the main problem that was identified during the previous season was related to the firewall sealing. In the following pages we will explain how this problem has been solved, adopting a solution that has also allowed us to reduce the weight of this composite structure.

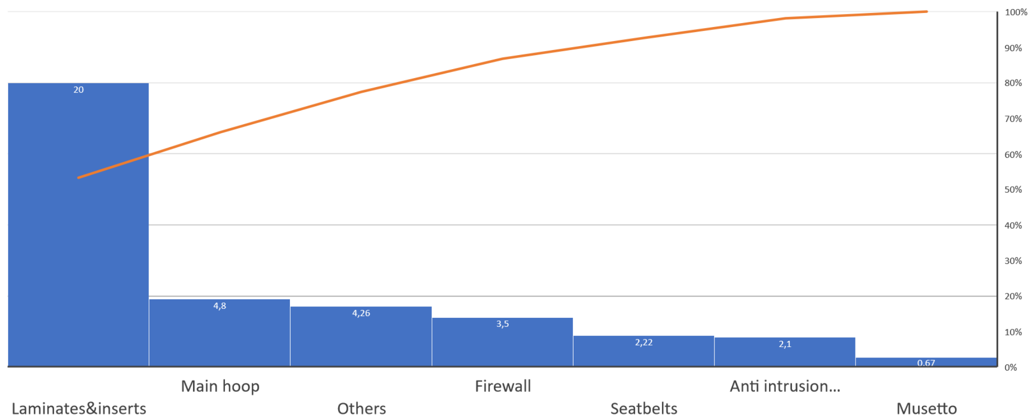
2. **Packaging**: the packaging of the SC19 has been studied in detail. 3D CATIA modeling software has been used and DMU of all components and assemblies presented in the vehicle (including wiring) have been produced. This made it possible, in a first phase, to define the size of the main assemblies, useful to first of all evaluate the more constrained and critical dimensions of the body, and subsequently a detailed elaboration of all the components allowed to define their precise positioning, fixing and assembly techniques to speed up the assembly process. Accessibility is strictly related to this topic, since the positioning of components that are subject to numerous external actions after their assembly, such as that called of 1st line maintenance activities, that can be performed directly on the track and the time requested to perform the must be minimized, must be carefully studied. We are not going to justify all the choices that have been made for each individual component positioned inside the monocoque, but we will analyse how the positioning of the larger assemblies has necessarily influenced the design of the body shape.

3. **Ergonomics**: the study of human-machine interfacing is important to vehicle design because the ultimate control of the vehicle belongs to the driver [6]. Due to the amount of time that drivers remain seated during endurance, sitting comfort level takes a lot of importance. In order to provide a most comfortable position to the driver, this year a seat was designed.

Performance targets

As already said, among the most critical keys to success in the Formula Student competition include the ability to reduce vehicle weight. Overall weight reduction enhances the ability to rapidly change vehicle speed and direction. Concerning monocoque weight reduction instead, pay attention that this, however, must not weaken the stiffness of the frame since it is important that an high chassis rigidity provides a reliable and predictable platform for high performance handling.
The same type of analysis that, reported in chapter 1, allowed to define an overall target weight for the SC19, was also performed between the components designed by the chassis department (reference to the chassis "department" was made since it is misleading to talk about components that are part of the monocoque assembly). We must remember that the Pareto of chapter 1 showed that the monocoque was

the third heavier assembly of the vehicle, but despite its weight was 42% lower than that of the unsprung masses, the heaviest one, the value of weight reduction for the two assemblies estimate was almost the same, since the 30% of the unsprung masses cannot be lowered due to purchased components.
As before, a Pareto diagram is used to show the SC18 chassis weights.



Graphic 4. *SC18 weight analysis: distribution between components of "monocoque assembly".*

At this point, looking to each column and evaluating the possible design choices that can be adopted in the SC19, it is possible to estimate of how each individual component could be lightened and so a more precise contribution in terms of weight saving of the monocoque assembly was fixed.
The greatest weight saving was identified not in a "pure lightening", but in a reduction of the size of the body itself and especially of the width. In fact, this reduction carries with it the consequent reduction of other components of this assembly due to the fact of the lowering of their main dimensions. Therefore narrowing the sections both of the front and of the cockpit, the consequent lightening of the hoops and the AIP was estimated to be of about 1.7 kg. For what concerns the monocoque, its reduction of dimensions and laminates improvement can lead to less than 1 kg of saving. The weight of laminates and inserts in the Pareto is grouped together, since last year we had forgotten to weigh the inserts before they were put into the core of the monocoque so we are not aware of their actual weight. So also in the graphic of estimates they are represented by a unique bar. A different solution instead, should have been adopted for the firewall, aiming for a weight reduction of 1 kilo but, above all, aimed at solving some problems encountered the previous year (later discussed).
Below is a summary of the objectives for the chassis department concerning the SC19 monocoque design.

Graphic 5. *Summary of weight saving prevision for the SC19 monocoque.*

By summing all the contributions, the total weight saving estimate was of 4.1 kg (larger that the one done in the general vehicle analysis, more conservative). If we consider part of this "assembly" also the seat, not present in the previous vehicle, the final target for the monocoque designers was of reduce the weight of 3.4 kg, that means, thanks to the developed simulator, a reduction of 0.34 s per lap (supposed to be an autocross track).

Another important properties of a vehicle chassis, universally recognized as for the mass, is its torsional stiffness. There are several reasons for which high chassis stiffness is preferable: lack of chassis torsional stiffness affects the lateral load transfer distribution, it allows displacements of the suspension attachment points that modify suspension kinematics and it can trigger unwanted dynamic effects like resonance phenomena or vibrations. As Costin and Phipps said [5], "it is difficult to imagine a chassis that has enough torsional stiffness without having ample rigidity in bending" so that "the criterion of chassis design, and in fact the primary function of a high-performance chassis, is torsional rigidity". Despite the relevance of the problem, the literature on the subject is rather scant. Some rules of thumb are diffused in the racing community, which suggest some figures about the minimum chassis torsional that ensures the designer that the above-mentioned problems are avoided. However, they cannot be used for advanced design. It is well known that the ratio of chassis torsional stiffness to suspension roll stiffness is a good indicator of relative chassis stiffness and as a goal, at the beginning of the year the vehicle dynamics division had asked to reach a value for the torsional stiffness of the body equal to three times the roll stiffness of the suspensions (68 kNm/rad). We will find out in the next pages if this goal has been achieved and how.

Chapter 4

Targets-based design

This chapter is the core of the thesis: it will be explained how the monocoque design has developed, in order to reach the targets indicated above. By starting with the functional one, for which it is necessary to immediately set the design of the bodywork so that they can be reached, we will deal with packaging issues and ergonomic evaluations. In the second part, instead, then having explained how the FEM model of the monocoque was obtained, it will be explained how the design has been done. The innovative features of the SC19 monocoque will be explained, with how those of the previous chassis have been improved, so that the targets of torsional stiffness and weight placed for this season were reached.

4.1 Improved accessibility and packaging

A good organization and positioning of the assemblies inside the body of the vehicle allows you to make faster all the actions such as assembly/disassembly or replacement of components, for example, and above all an optimization of the spaces makes possible the design of a body with smaller size, objective of this year. Moreover, the achievable cornering velocity is strongly determined by the C.O.G. height of the vehicle. To this purpose, in this chapter it will discuss how the positions of the two biggest assembly hosted in the monocoque, the battery pack and the inverters, has been determined.

Starting with considering the battery pack and its constraints, due to its dimensions the only possible location of it was the rear compartment of the monocoque.

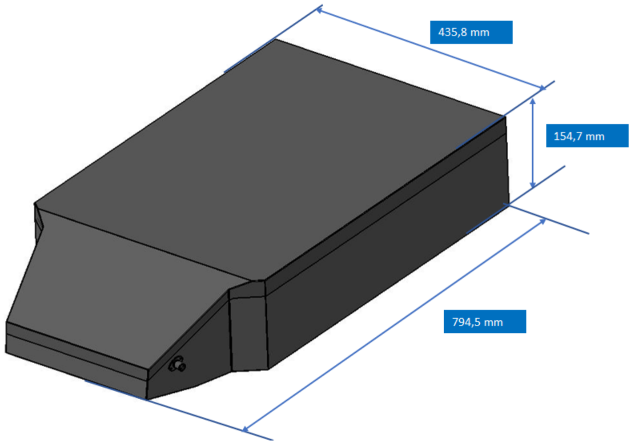


Figure 4. *Battery pack dimensional constraints.*

The size of its case are not the overall dimensions of this assembly, since for example the need of a cooling system therefore the space necessary for manifolds and ducts and all the other components related to it. Above all, the battery pack compartment must be completely separated by the cockpit through a firewall and also the need to remove it from the vehicle for each recharge cycle or for other maintenance actions must be taken into account.

So also all these reasons confirm the need to put the battery pack in the rear part of the monocoque, since it is the only possible positioning as in SC18, with also the low voltage battery and all the components needing to be separated from the cockpit, except the inverter assembly for which different solutions have been evaluated and following explained. However this part of the chassis have other functional requirements previously said such as the suspensions' panels offset and the floor inclination of 7° as aerodynamic request, so the battery pack positioning must be fitted together with these other design aspect of the monocoque.

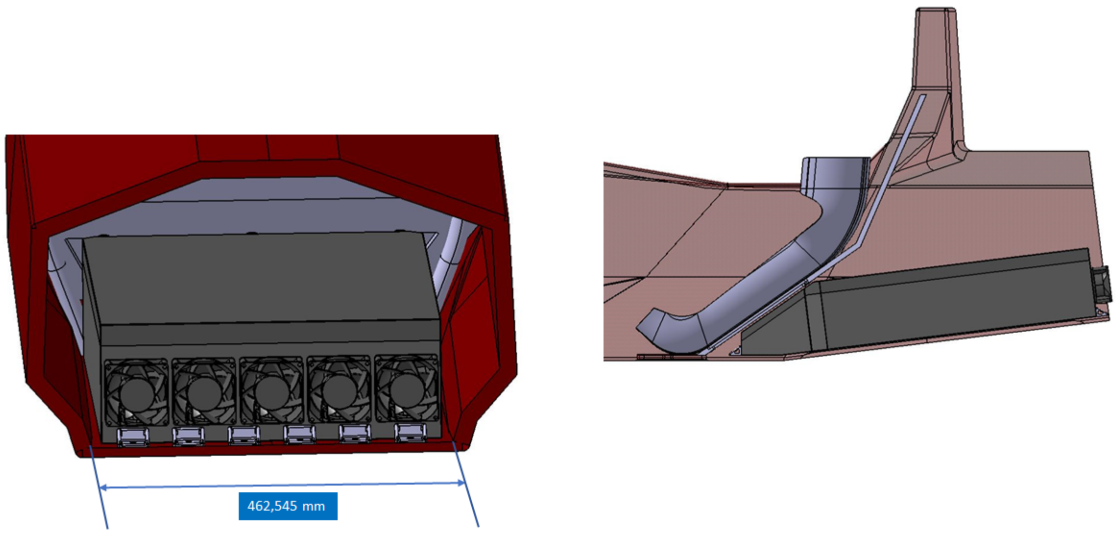


Figure 5. *Left: with dimension of the rear part of the monocoque depended on that of BP. Right:*

forward position of the BP to meet dynamics requirements.

In the figure above it is possible to note how the width of the final section of the body was determined by the size of the battery pack, the same for the length of it: the monocoque body end exactly in correspondence of the BP's fans. In the CAD screenshot reported on the right it is possible to see how the packaging has been optimized by positioning the battery pack immediately behind the firewall, following its inclination in the first part of the case, in which is housed the BMS Master. In this way it was possible to shorten signal wiring and reduce sensitivity to disturbances, that was a problem encountered the previous year, in which it was put above the battery modules.

Unlike the battery pack, for which the possible positioning was, as just said, one only, the situation is a bit different if we consider now the other main assembly mentioned before concerning monocoque's packaging, the inverter. For this assembly the constraints to determine its location were basically the same as the BP, excepts for the accessibility, that is not a request since no frequent operations are performed to it. Given this, the possible locations have been identified in the front part of the frame and in the central part, in the cockpit. In reality due to dimensions and in order to minimize the number of firewalls, a possible solution could be also that of put it on the rear compartment, with the battery pack, but this solution would have involved a further over sizing of the back of the body, and possible electromagnetic interference between the electronic components present and not shielded from each other. So this solution was not considered and the one considered as possible have therefore been front and cockpit.

Since the inverter is a component that is bought from the same supplier of the electric motors and not designed by us, its dimensions of the assebly reduce our field of action concerning the positioning. The image below the main dimensions of the assembly of the boards have been highlighted, so as they are supplied to us at the time of purchase.

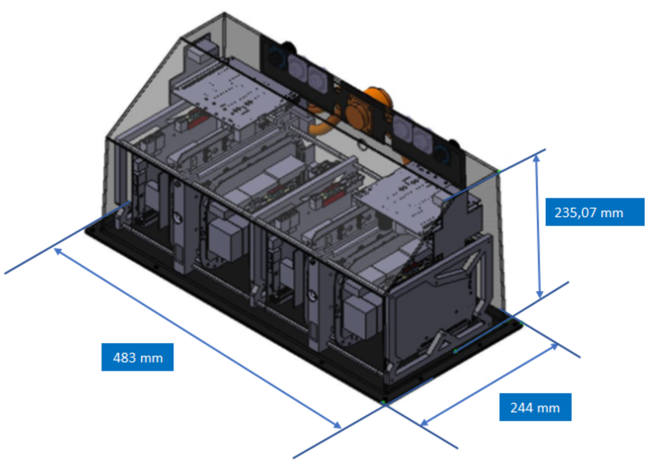


Figure 6. *Size of assembled inverter's boards.*

However, the electronics department has decided, already last year, to dismantle the assembly supplied to us by AMK. This is not a trivial operation for various reasons, including the fact that being fragile components disassembly and re-assembly could cause damage of them, and also the wiring that must be completely re-studied and redone (by us in the laboratory). But doing that give the possibility to design a new layout of the boards that would make it possible to position them in the desired position on the vehicle that as said depends on dimensions, avoiding possible electromagnetic interferences, firewall and moment of inertia of the assembly. The figure below reports all the dimensions of the boards, splitted and not seen as an assembly. Remember that the size of the final assembly in order to design its case must consider also the dimensions of the numerous cables present, not only that of the boards obviously.

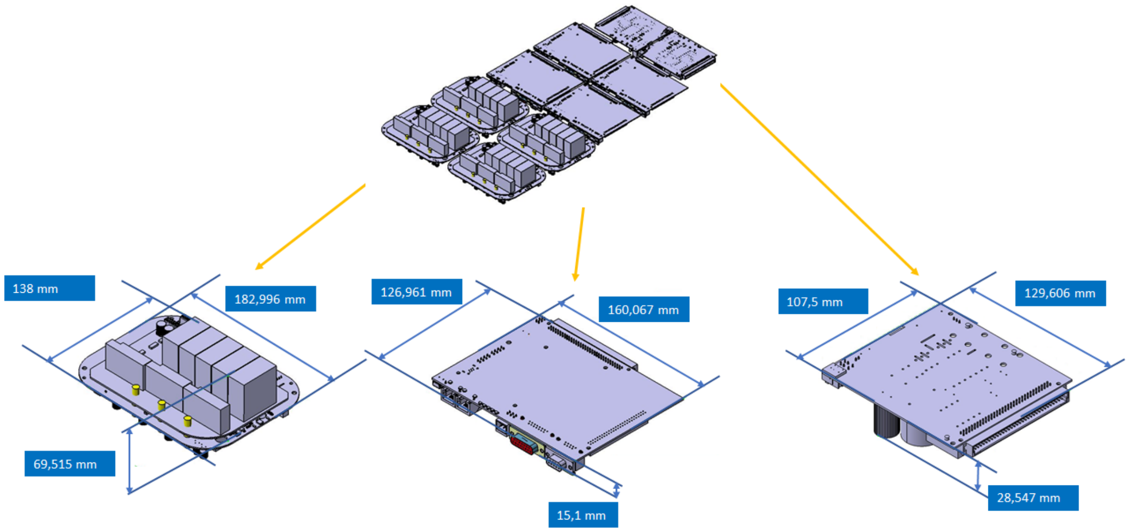


Figure 7. *Size of disassembled inverter's boards.*

Last year the inverter has been disassembled and divided into two separate inverters both put into the cockpit compartment: one for the left side motors and one for the right ones. This layout had led to a considerable enlargement of the cockpit section and to a difficult design regarding the firewall and subsequently problems with its sealing. Having a look on the previous configurations and the new one considered for the SC19.

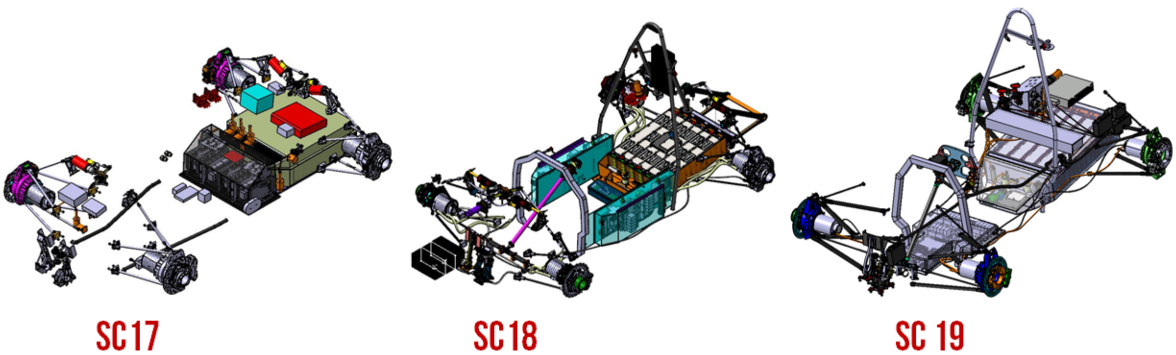


Figure 8. *Inverter positioning evolution.*

Considering the front section of the body, the only possibility is to place the inverter under the driver's legs as, as already mentioned, accessibility is not important in this case, as it is essential to design a non complex firewall and to make sure that its interface with the monocoque internal surfaces will be easy to seal. Another feature that had been requested for the front of the body frame panels, and that will be explained later in more detail, was to arrange the upper and lower attachment's points of each suspension on two different planes, at a given distance between them (along y). This requirement with that of the need to arrange the inverter group on the bottom was satisfied by creating a restriction of the section (z-y plane) of the monocoque, therefore a sort of tunnel was designed in the lower part. In this way the lower A suspension arms were fixed to the side panels of this tunnel, and the inverter can be placed on the bottom panel of the monocoque and, thanks to its firewall, it was possible to create a uniform plane inside the cockpit from the pedals precisely up to the seat, fixed instead together with the seatbelts on the bottom of the body frame. In the following picture we can see how the assembly design of the boards has been redefined so that they could be positioned in the tunnel.

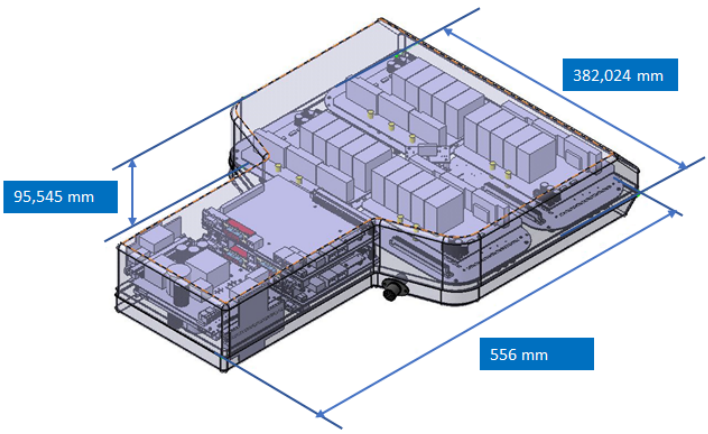


Figure 9. *SC19 inverter assembly.*

The narrower part is obviously the one positioned towards the front of the vehicle, therefore the one housed in the tunnel under the legs, while the enlargement takes place in correspondence of the central part of the body, in which the tunnel is no longer present, also satisfying the need for a wider bottom surface to met aerodynamic issues.

As said before, one of the most important requirement for the inverter positioning was that to minimize its moment of inertia and so, after having described what was the choice for its positioning given the constraints, let's see in the next tabular what were the advantages in terms of moment of inertia reduction with respect the configuration of the previous year.

	I_G	[Kg*m^2]			
Configuration	Component	Mass [kg]	I_{XX}	I_{YY}	I_{ZZ}
2018	Left inverter	3.15	0.62	0.31	0.67
	Right inverter	3.15	0.62	0.31	0.67
	Inverter assembly	6.30	1.24	0.61	1.35
2019	Inverter assembly	6.30	0.17	1.08	0.97
			-1.07	0.47	-0.38
			-86.1%	+76.6%	-27.9%
				(out of interest)	

Table 2. *Inertia comparison between SC18 and SC19 inverter layout and positioning.*

As summary, this picture is reported in order to have a global overview on the packaging of the SC19, which was said by judges to be a strength of our vehicle design.

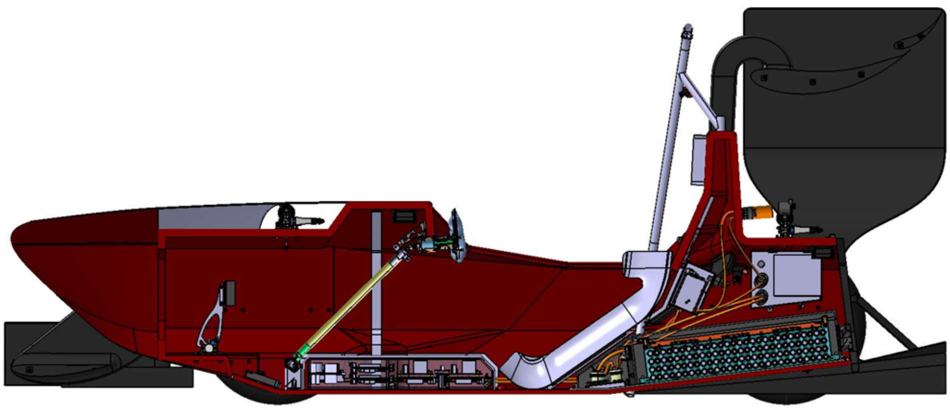


Figure 10. *Free-Size opt setting B: Contour plot of panel thickness obtained.*

As said in section dedicated to the setting of targets, concerning maintainability and accessibility, one of the problems encountered during the previous year and related to the field of action of the monocoque designers was that of the firewall. In the previous vehicle the firewall was composed of three different shells: the first one, the so-called "fixed firewall", which was permanently fixed" to the monocoque and its function was the hosting of the inverter boards' assemblies located on the sides of the cockpit in the SC18 (as said before); fitted to that shield another one was designed, in order to separate the cockpit from the inverters and also with the function of seat. This firewall has been designed separated to the fixed one considering that it had to be removed if external support on inverters is provided; so it can be considered as a "partially fixed" firewall due to the fact actions on inverter are only needed in case of faults. Then a removable firewall cover was present in the middle of the fixed one, rear the backbone of the driver, to allow to allow the frequent operations required on different components in the battery compartment. Just think to whenever the battery pack has to be removed from the vehicle, to recharge or other actions: the connectors must be detached from the front side of the BP to allow its removing and so an opening on the firewall is needed. This solution presented more than one problem. First of all the difficulty of sealing the partially fixed firewall, that was screwed in four points and than around all the perimeter silicone was applied without a great success, due to its dimensions and fitting on the surfaces of the fixed one led to found water in the inverter compartment after the rain test of all the races. The same problem was also found for the removable part. A second problem was related to the driver comfort but the cause of this is not so much the firewall itself, as the decision to put the inverters on the sides of the cockpit. This layout limiting the space available for the movement of the driver's arms, which often knocked the walls with the elbows during rapid manoeuvrers or simply strong lateral accelerations.

The solution adopted this year was allowed by the new location of the inverters inside the vehicle. Thanks to the positioning of the inverter boards in the tunnel on the bottom of the body, under the driver's legs, it was possible to put one fixed firewall covering them (or better called "partially fixed as before"), and another behind the seat to isolate the driver from the battery pack compartment with a much narrower opening panel, to permit all the actions on the battery compartment. In the figure below is possible to see on the left the CAD of the SC18, in which the the fixed firewall is blue, the partially fixed one is orange and the yellow one is what allow you to reach the battery compartment from the front. On the right the SC19 configuration in which the firewall are completely separated and the opening to the rear compartment is much smaller.

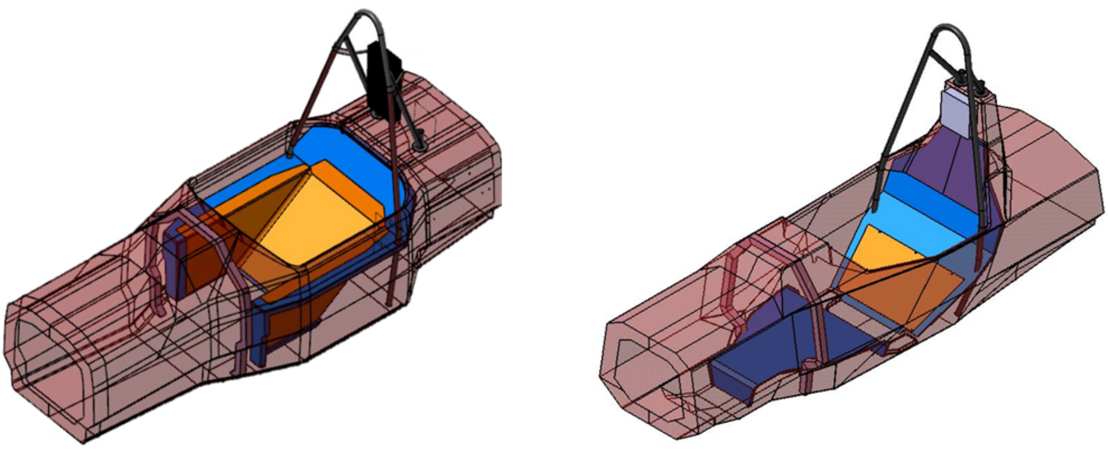


Figure 11. *Fixed and removable firewalls: SC18 (left) layout vs. new SC19 configuration (right)*

4.2 Ergonomics

Design of cockpit is one of the important part of Formula student racing car as it contains several essential components which a driver needs to operate during its operation like steering, buttons, accelerator pedal and brake pedal. It takes even more importance when considering the time that an endurance driver is seated on the car, driving at average of about 60 kph in a very tight circuit. So the vehicle control and the space available for the arms and legs operations have to be optimized so that the driver will be more comfortable and better focused on driving, reaching higher performance.

Competition rules

The main resource to study an ergonomic posture for the driver so that safety aspects are ensured is the FSAE rulebook. So being the constraint part of ergonomics, now we will speak about some necessary rules reported on section T4.3 of the FStudent 2019 rulebook, that the cockpit should meet in order to be suitable for people within the range of 95 percentile male and 5 percentile females. Starting from the positioning of the helmet, when seated normally and restrained by the driver's restraint system, the helmet all of the team's drivers must (see figure below):

- Be a minimum of 50mm away from the straight line drawn from the top of the main hoop to the top of the front hoop.

- Be a minimum of 50mm away from the straight line drawn from the top of the main hoop to the lower end of the main hoop bracing if the bracing extends rearwards.

- Be no further rearwards than the rear surface of the main hoop if the main hoop bracing extends forwards.

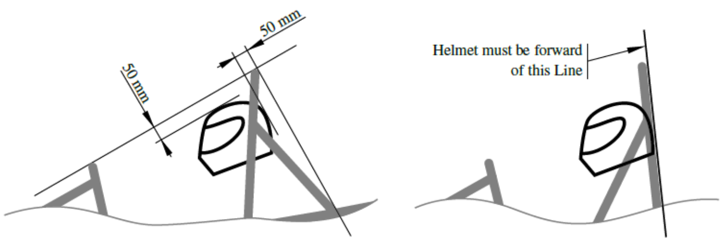


Figure 12. *Minimum helmet clearance.*

It also indicated how the 95^{th} percentile male must be represented with circles and line and how it must be positioned into the cockpit. Follows the template and the rules related to it (T4.3.4).

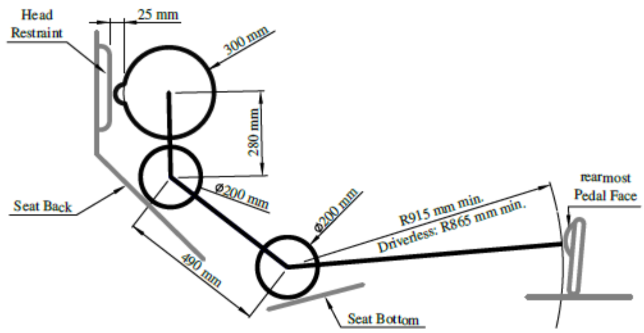


Figure 13. *Percy placement.*

The figure has to be positioned in the vehicle as follows:

- The seat adjusted to the rearmost position The pedals adjusted to the frontmost position
- The bottom 200mm circle placed on the seat bottom. The distance between the center of the circle and the rearmost actuation face of the pedals must be minimum 915mm.
- The middle circle positioned on the seat back
- The upper 300mm circle positioned 25mm away from the head restraint.

For what concerns the steering wheel, the rule that governs its position is reported in section T2.6 and indicates that the steering wheel must be no more than 250mm rearward of the front hoop (horizontally measured). About the shape, it's declared in T2.6.7 that the steering wheel must have a continuous perimeter that is near circular or near oval, and having an outer perimeter profile with some straight sections is admissible but no concave sections. The link between shape and location is the T2.6.8, for which in any angular position, the top of the steering wheel must be no higher than the top-most surface of the front hoop.

Ergonomic design goals

T4.3.4 has supported in defining the location of certain body parts and then an ergonomic design were made while considering all of these dimensions.
In general, the design objectives for race car seating position can be summarized as follows.

-To enable the driver to see clearly ahead.

-To provide a comfortable position for the drivers so they do not become tired.

-Seat thigh angle should be so that facilitates knees according to operation of pedals.

-Steering wheel position should be so that:

-drivers are not too close or too far away from it, finding steering tiring.

- to ensure that in the worst case, the driver's arms will not be straight while steering (that is a situation both uncomfortable and a poor leverage position)

-the drivers can turn the wheel without hitting their legs with the steering wheel or their hands. Note that the steering wheel is not a full circle, so lower portion of it is flat, but must be ensured that also in turning clearance between driver's legs exists

-when turning, one arm will be closer to the driver's body and must be ensured that no interference between the body itself or with the seat or other part of the cockpit occurs

-drivers can operate on pedals without bumping it.

-Steering wheel size is important since determines the amount of motion required by the driver to turn the vehicle. The dimension of our steering were determined on experience and feedback of the drivers of the previous vehicle

-A proper width of the cockpit to accommodate the body and volumes involved in operations.

-Pedals must obviously be reached easily and comfortably by all the drivers, the height of this assembly is important.

-Pedals travel must be setted considering motion fatiguing and control sensitivity: for instance, the travel gas pedal might be longer that the brake one.

-Generally speaking, a starting angle for the legs should be no less than 90 degrees for a normal seating position. In our case, that involves both shorter pedal travels and lower hip point location, angles about 120 degrees or more may be preferable.

Mockup and results

To make sure that the design of the SC19 was set precisely on these ergonomic tips, an ergonomic mockup cockpit was made at the beginning of the season. All the drivers have tested it, adjusting the distances and angles in order to find a comfortable position that meets also the comfort of the other drivers, since the pedals and the seat can be a little bit adjusted, but not in a wide range. The mockup with one of the drivers, that of average height, is pictured below.

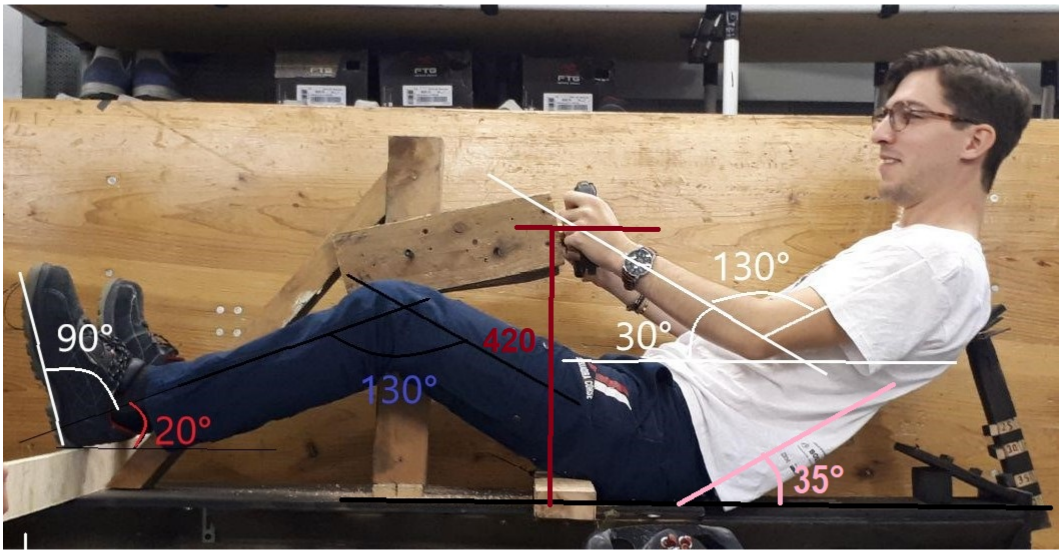


Figure 14. *Ergonomic mockup cockpit with measured distances and angles.*

A board was hinged to a longitudinal beam as a mock of the seat back. It is possible to adjust its angle by blocking it through the different steps on the supporting beam. Another transversal beam was put on the floor in order to set the thigh angle: since the beginning of the project there was the possibility to put the inverter under the leg of the driver so also in this situation, this possible configuration was considered, limiting the thigh angle by positioning this beam. A transversal beam was used as heel support, since the pedals assembly is located higher than the cockpit floor.
Once having collected these data, the design of the cockpit was oriented to these values.
In addition to ergonomics problems, the others issues found by the drivers of the last vehicles were basically two: one problem was due to the fact that inverters were put on both the sides of the cockpit, so that the available space inside it was limited and many times during rapid changes of direction or excessive lateral accelerations drivers ended up bumping with elbows the side walls. In SC19 despite having narrowed the cockpit width, this problem was solved by having the inverters arranged in another area. The other problem was the absence of a seat. This latter must not be considered only an additional comfort for the driver but it is fundamental also in terms of performance, considering that it influences the drivers' readiness, tiredness and sensitivity, and also because it gives stability to the center of gravity of the driver, reducing its moment of inertia of more than 20%. So the below reported, laminated, slightly adjustable seat was added in the SC19 cockpit.

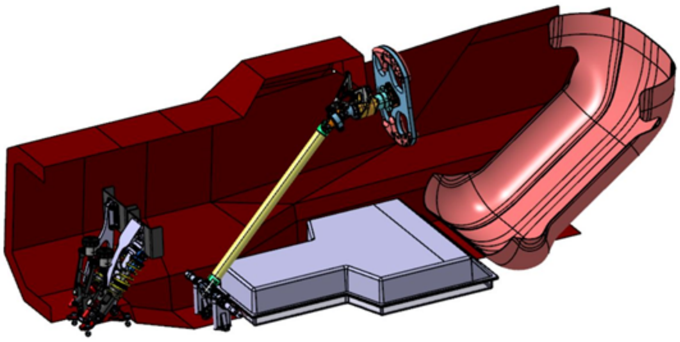


Figure 15. *SC19 cockpit with new designed laminated seat.*

Also the steering wheel has been ergonomically improved, since drivers said that the handles of that of the SC18 were slippery, since they didn't fit with the hand of the drivers causing less grip, despite the using of professional gloves. So a wavy shape has been given to the internal parts of the handles, so that avoiding this problem and improving the moment given on it. This year has also been added on the steering wheel a small display, so that the driver in case of loss on connection with the strategist during an endurance, can continue the race keeping the battery SOC and temperature under control.

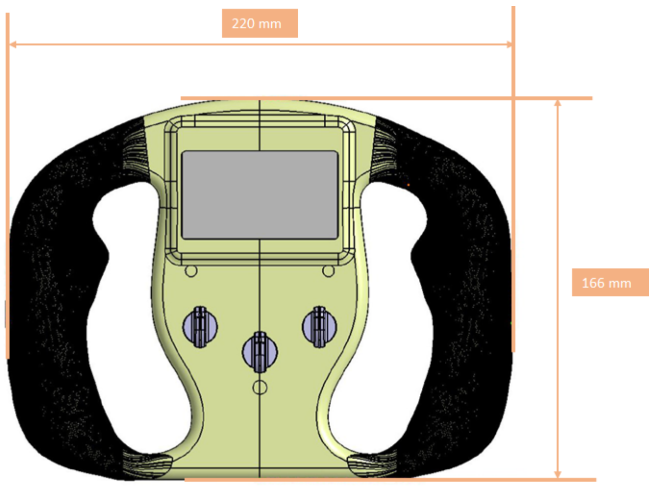


Figure 16. *SC19 steering wheel dimensions.*

To conclude, CAD pictures of the final design of the SC19 monocoque are reported, in order to know if the comfort and ergonomics objectives, set at the beginning of the year as a result of these assessments, have been achieved. The dummy put into the cockpit has the same dimensions of the guy reported in the picture of the mockup, being the driver neither higher nor lower.

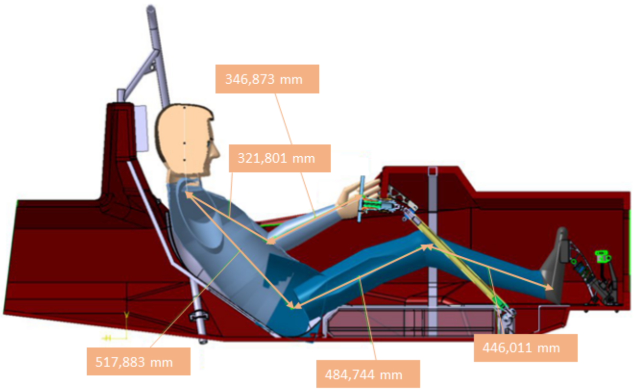


Figure 17.

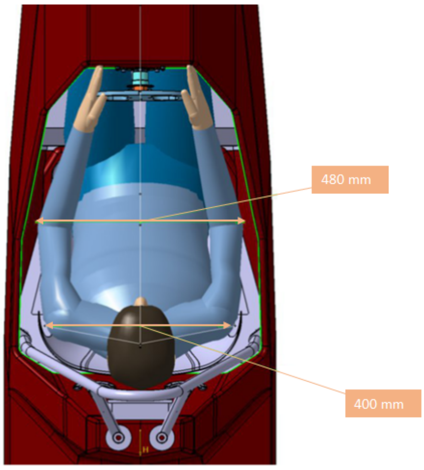


Figure 18.

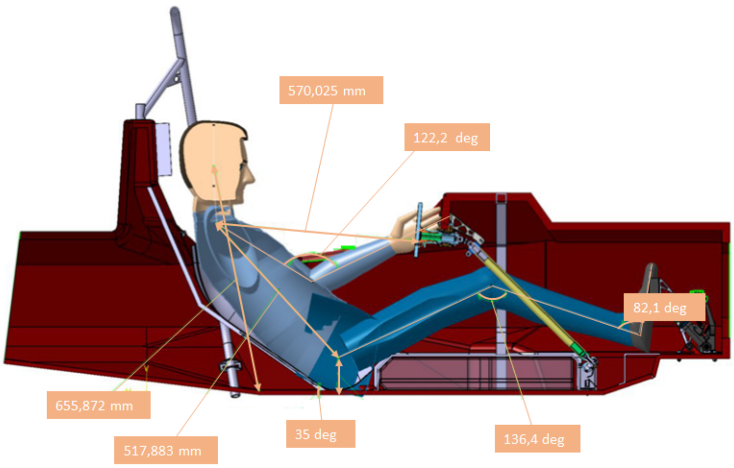


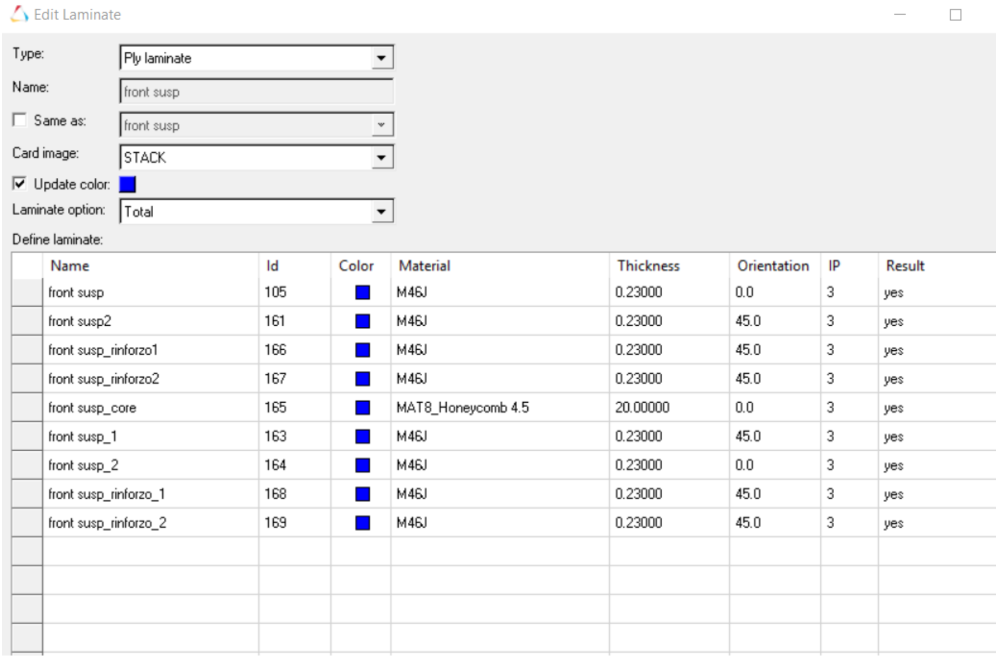
Figure 19. *Ergonomics: dimensions and angles coming from the CAD model of the SC19.*

Having an overview on the resulted design, considering the main angle: that of the leg for which the objective was 30° and after the design a slightly higher value comes out, that between leg and

foot that is lower but acceptable, the angle between upper arm and forearm that was approximately set at 130° and from the CAD model the value of this angle is 122° and finally one of the most important request, that of the back seat angle that was perfectly satisfied.
In conclusion it can be said that drivers have found positive feedback on the entire cockpit design of SC19 both in terms of ergonomics and comfort, which improvements were mainly determined by the presence of a seat.

4.3 FEM model

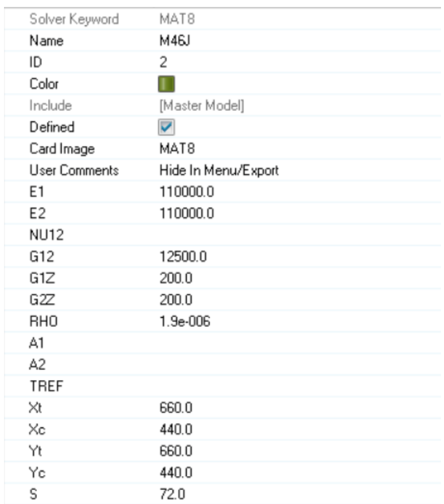
Finete Element Method was used to analyse the structural performance of the monocoque. Linear static analysis of SC19 was performed using the Hypermesh and Hyperview software (v.17) and using the Optistruct solver (both provided by Altair, Troy,MI, USA). To create the monocoque, by exporting the CAD design of the chassis, its shell was meshed using two-dimensional elements, since one dimension is irrelevant with respect to the others, according to the hypothesis that the distribution of stresses along the axis orthogonal to the panel is irrelevant. Both quadrilateral and triangular elements were used as elements in the mesh with a maximum dimension of 2 mm.
To characterize panels materials, MAT8 card was used since defines linear temperature-independent orthotropic materials for two-dimensional elements. For the property of the monocoque, a PCOMPP card was defined. The sandwich panels, made of two skins of CF plies each side of the core material, were defined through stack card: the monocoque was divided into sets, by selecting and so grouping the elements of different panel structures, and then by selecting these sets, the plies were created and so the ply-based composites were defined. Direction must be given to the plies, being highly anisotropic along the two directions; the 0° direction was oriented along the x-axis of the vehicle. So laminates were defined by stacking plies of materials as reported in the example below.



Name	Id	Color	Material	Thickness	Orientation	IP	Result
front susp	105		M46J	0.23000	0.0	3	yes
front susp2	161		M46J	0.23000	45.0	3	yes
front susp_rinforzo1	166		M46J	0.23000	45.0	3	yes
front susp_rinforzo2	167		M46J	0.23000	45.0	3	yes
front susp_core	165		MAT8_Honeycomb 4.5	20.00000	0.0	3	yes
front susp_1	163		M46J	0.23000	45.0	3	yes
front susp_2	164		M46J	0.23000	0.0	3	yes
front susp_rinforzo_1	168		M46J	0.23000	45.0	3	yes
front susp_rinforzo_2	169		M46J	0.23000	45.0	3	yes

Figure 20. *Laminate editing: stack card.*

Material cards used are showed below.



Solver Keyword	MAT8
Name	M46J
ID	2
Color	
Include	[Master Model]
Defined	
Card Image	MAT8
User Comments	Hide In Menu/Export
E1	110000.0
E2	110000.0
NU12	
G12	12500.0
G1Z	200.0
G2Z	200.0
RHO	1.9e-006
A1	
A2	
TREF	
Xt	660.0
Xc	440.0
Yt	660.0
Yc	440.0
S	72.0

Figure 21. *Materials cards: material of the plies used for all the monocoque.*

Solver Keyword	MAT8	MAT8	MAT8	MAT8	MAT8
Name	MAT8_Honeycomb_6.1	MAT8_Honeycomb_3.1	MAT8_Nomex_2.5	MAT8_Honeycomb 4.5	NOMEX 3.2
ID	39	5	31	33	64
Color					
Include	[Master Model]	[Master Model]	[Master Model]	[Master Model]	[Master Model]
Defined					
Card Image	MAT8	MAT8	MAT8	MAT8	MAT8
User Comments	Hide In Menu/Export	Hide In Menu/Export	Hide In Menu/Export	Hide In Menu/Export	Hide In Menu/Export
E1	5.0	5.0	5.0	10.0	5.0
E2	5.0	5.0	5.0	10.0	5.0
NU12					
G12	3.0	3.0	2.0	3.0	2.0
G1Z	675.7	310.0	29.0	482.0	41.0
G2Z	282.7	151.0	19.0	186.0	24.0
RHO	9.77e-008	5e-008	3.2e-008	7.2e-008	5.1e-008

Figure 22. *Materials cards: core materials used in the monocoque different panels.*

To fix the other components to monocoque, such as hoops and firewall, groups were created and the card contact of "freeze" type used.
The load steps of analysis will be explained in sections where will be treated.

4.4 Mass reduction

A lot of effort was spent to design lightweight components for the SC19. But as regarding to the monocoque, a low weight not always means good performance. The first drawback, for example, can be the loosing in torsional stiffness, leading to a non proper vehicle dynamic behaviour. So trade off must be found however between lightweight design and the cost that is paid to achieve this.

Dimensions reduction

One way to reduce weight is obviously lowering the dimensions of the car. In this part we will see how the dimensions of the SC19 were defined, without considering structural aspects, which will be considered in the next sections. Therefore the aim is that of describing the reasons that led to the final SC19 shape and related dimensions. Moreover I think that is more important to report the evaluations that have been made to make a choice for the project, with respect that the various phases of the evolution of the CAD of these structures, from the beginning up to the final definition.
Starting with the main dimension of the front and of the central part of the monocoque, since they are strictly related to the safety of the driver, that must be able to egress easily, very demanding rules have been stated. These rules are reported in the cockpit section of chapter 2, were is possible to see the di-

mensions that must be satisfied both for the cockpit and leg opening. In the pictures, that report the final shape of th monocoque with the template regulated, is clearly explained how the openings are verified; these checks obviously are actually done by judges during competitions. We can immediately notice how the dimensions of the body are reduced to the minimum imposed by regulation to the minimum imposed by regulation. The tighten clearances, by design, between the template and the final shape of the shell could be a problem after the manufacturing of the monocoque since the thickness of the laminate can vary of a 20% after the hand lay up and the autoclave also.

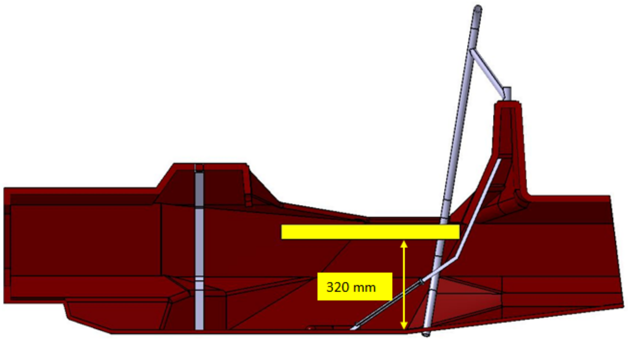


Figure 23. *Side view of the DMU of the monocoque and of the template used to verify the compliance with regulations.*

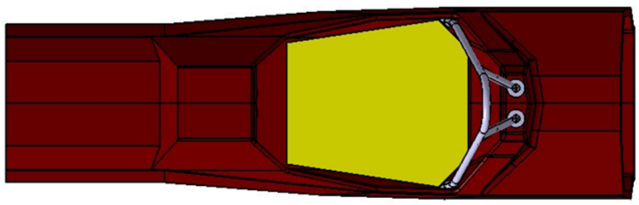


Figure 24. *Top view of the DMU of the monocoque and of the template used to verify the compliance with regulations.*

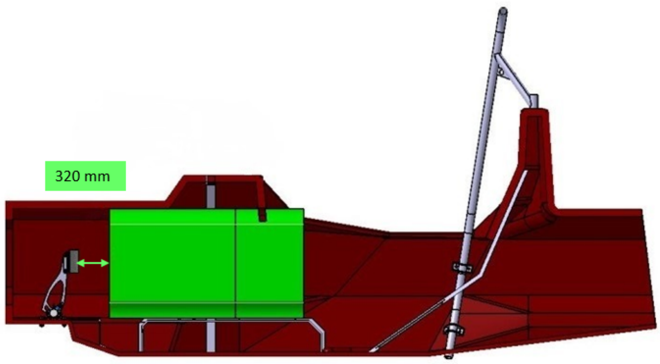


Figure 25. *DMU used to verify that the template can be moved up and down from the opening to a point 100mm rearwards of the face of the rearmost pedal in an inoperative position.*

Finally, a good result was reached for what concern the design and moreover the manufacturing process of the chassis, since also the produced monocoque accomplished these restrictions without need of post processing or modification.

For what concerns the shape and so the dimensions of the body, many other factors have influenced the design. One of these has greatly affected the design of both the front and rear of the car, and it is related to vehicle dynamics: some measures have been adopted in the design of these sections, in order to control the IC migration and reducing the jacking force. The vehicle dynamics division asked us to position the suspension attachments of the upper arms and those of the lower one not on the same plane, but on two surfaces at a given distance on Y- direction. A schematic representation of the request is reported.

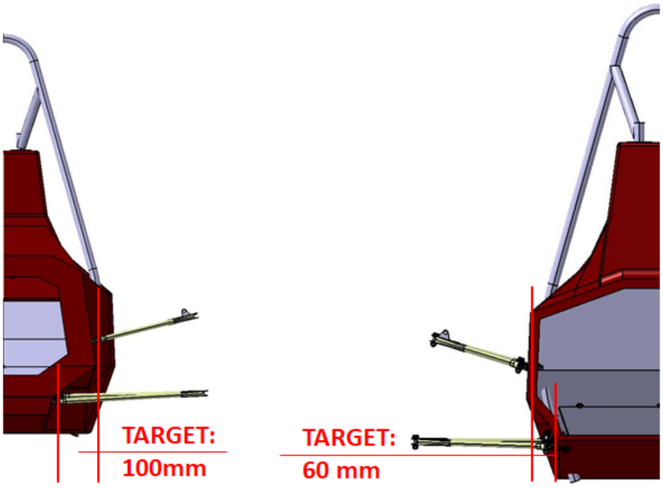


Figure 26. *Requested offsets on Y-direction between attachment suspension points: to the left that of the front suspension, to the right that of the rear.*

The front was more difficult to design, not only for the largest distance requested between attachments, but also because of the correlation of its shape with other constraints, as regulation concerning the dimension of the internal cross section of this part and the aerodynamic need of having a flat floor, for turbulences and downforce reasons. The adopted solution for the first portion of of the monocoque was a sort of tunnel in the lower part of the body. So starting from the upper suspensions' panels, the monocoque sides show a sharp narrowing in order to host the lower attachment in another surface. However this configuration involves another design constraint given by the width of the steering rack, which width and position could not be changed.

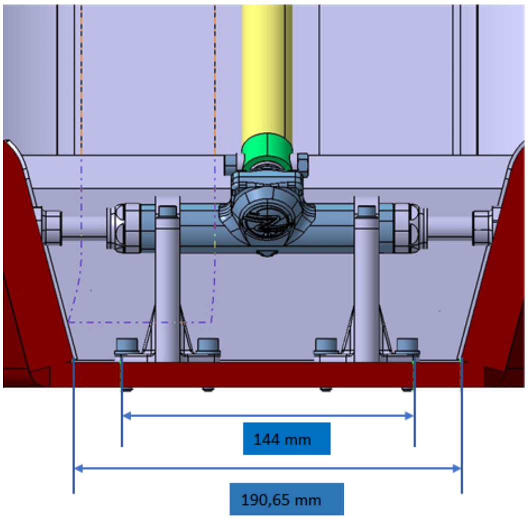


Figure 27. *Constraining value of the width dimension of the steering rack.*

As far as the backside is concerned, the work was simpler as it only influenced the packaging aspects since the rear part of the monocoque hosts the battery pack. To conclude we can therefore say that not without difficulties, this requests were almost accomplished both in the front and in the rear. Precisely, if we consider the following picture of the vehicle highlighting the front suspensions attachment points, the yellow circled one are at a distance along Y equal to 108.53 mm, more than the requested, on the other hand the rear points, that circled on blue, are at distance 3 mm lower than the desired one. Considering the rear suspensions, in which the target offset was 60 mm, we have that the yellow circled points in fig XXX and the blue one are respectively at a distance along Y of 58.45 mm and 59.55 mm.

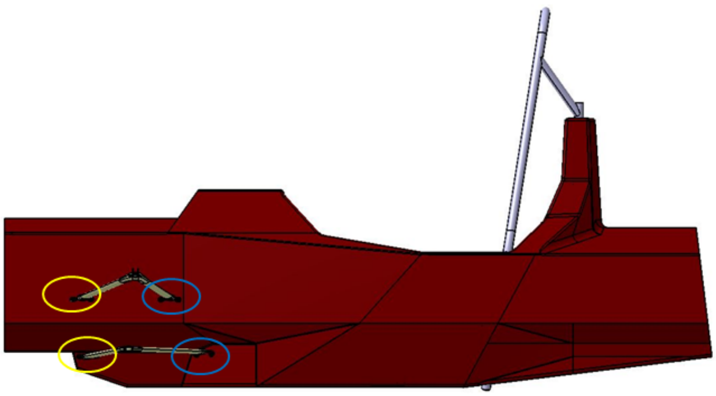


Figure 28. *Front attachment suspensions' points higlighted by colours.*

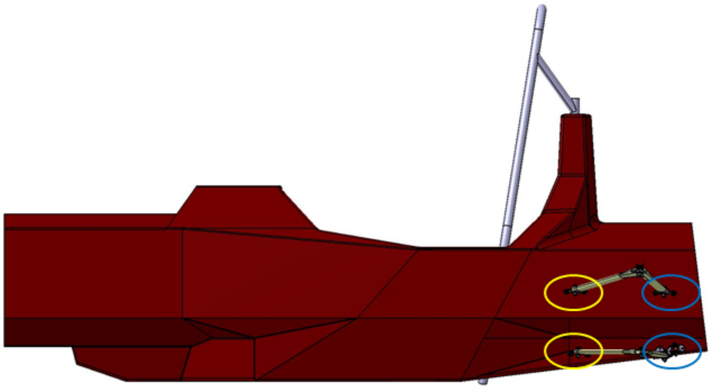


Figure 29. *Rear attachment suspensions' points higlighted by colours.*

As conclusion, a comparison between the dimensions of the SC19 and the SC18 is reported.

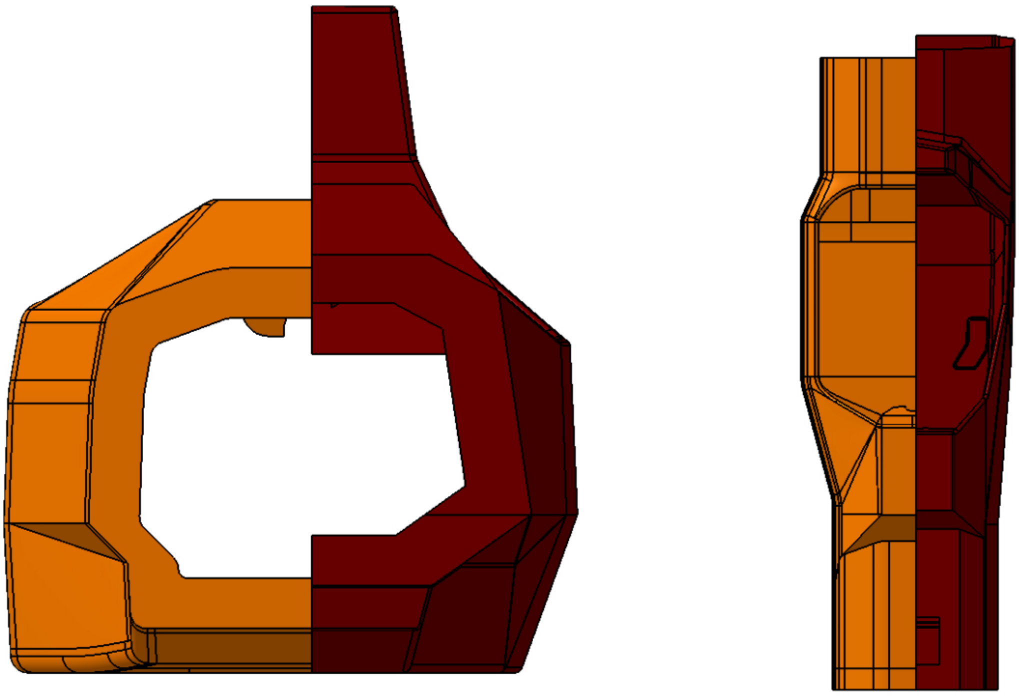


Figure 30. *Main dimensions comparisons: SC18 (orange) vs SC19 (red).*

Main Hoop Bracing Support: new solution

Another solution was found in order to reach our main objective of saving weight. This was an innovation for Squadra Corse, as it is not possible to find this design choice in any other vehicle.
As it is well konwn, in the vehicle structure is mandatory to include two roll hoops that are braced (main and front), a front bulkhead with an impact attenuator, a driver restraint harness and side impact structures. These crash safety features add structural demands to the chassis, increasing its weight.

In this section we will deal with main hoop bracing and more precisely its support structure, since an innovation of this year lies just there, in the main hoop bracing support structure.
Starting from the description of the previous year adopted solution, as showed in figure below, we have basically the MHB tubes directly to the body of the vehicle that, as said before, must be rule compliant, repecting the equivalence of a tubes structure.
This year we have studied the possibility to make a sort of bracing integration with the monocoque, a more complex structure that sustains the MH and its bracing tubes lowering the dimensions of the latter.
The pictures below shows the two solution which are been the object of the analysis: the first one is a possible MH and MHB as the previous year configuration, the new MHB system are reported below.

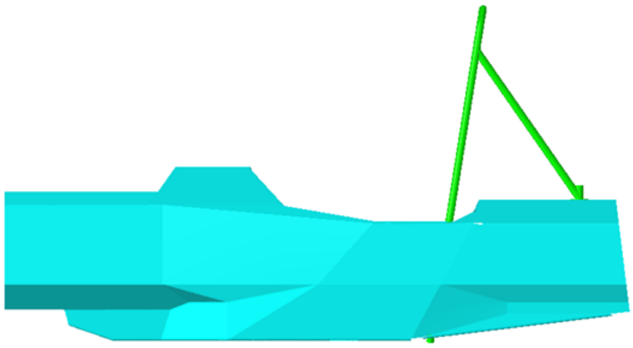


Figure 31. *CAD of the Monocoque including MH and MHB as in the previous year design.*

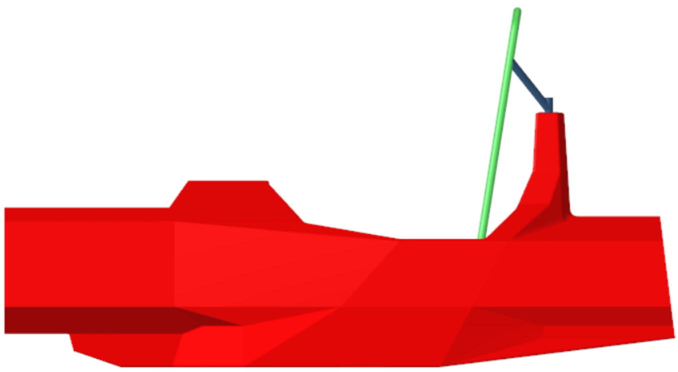


Figure 32. *CAD of the Monocoque including MH and MHB as it was evaluated for the design of the SC19.*

Once the two possible solutions for the main hoop supports have been identified and designed, various comparisons have been made but in order to know if this configuration can be advantageous to reach our objectives, the first evaluation to do, once having defined the geometry was the one concerning the mass. The validity of this comparative analysis stays on the creation of comparable models. What does it means? It means that since the two configurations have two completely different structures for the laminate of the MHBS, we cannot compare the weight of a rule compliant structure and one of a non admissible one. So before making every type of equivalency, we have to defined something to start with this evaluation so the laminate of the panels concerning the "tower" of the monocoque and all around its base. Since no other previous vehicle in SC presented this shape of the monocoque, we had no kind of experience, neither from competitors, so we tried using FEA models to find a laminate for the structure by compare, under same load case, the displacements obtained with this structure and that of the previous year structure, without the tower. By changing different composites stacks for the "tower" we found a possible solution, equivalent to the other concerning compliance. With these "starting laminates" we try to follow the explanation related to the how we defined the composite structures in order to consider our comparison "truthful". Obviously these "starting laminates" then underwent modifications so that structural equivalence was demonstrated. Just to understand the data that will be used during the demonstration below, the equivalent final structure was of 2 plies on external and internal skins of the composite panel, and two different cores, one thicker (20mm) of aluminum on the side walls of the tower and a thinner one (10mm) of nomex on the front and back. Let's starting with the structural equivalency proof.

For what concern the "typical layout" of MH bracing and support, always used in the Squadra Corse vehicles, we have defined the composite structure of the MHBS as has been done in the previous year. So the same laminate and panel's dimensions of the SC18 main hoop bracing support was used, so as to be sure that the structure was rule compliant and effectively able to support the loads in case of roll over.

Not so easy was the definition of the MHBS for the new structure. In one of the final attached sheet of the Structural Equivalence Spreadsheet, some indications about the verification of equivalency for main hoop bracing support composite structures were available, so we have tried to follow them and in order to verifying that dimensions and laminates configuration were compliant with the regulation requirements. These indications were referred to two possible scenarios and for us was not so trivial since our design did not represent none of the two, being an "unconventional" configuration for this structure. In fact in scenario 1 was showed a schematized chassis structure with a square/rectangular structure rearward of the main hoop; this design is fully equivalency as using the flat-panel calculations by entering the panel height as per the image shown. In this case no additional proof is required, only images of the chassis proving the panel height entered must be supplied.

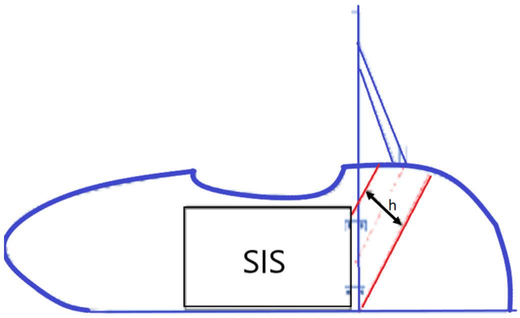


Figure 33. *Attached schematic view on a chassis used to explain how to consider the dimension of the MHBS panel.*

However, the case represented is not the way we wanted to design the frame, but the way it was developed in previous years, to this purpose reported. So our case is not that of scenario 1 but partially was that at point 2, in which is said that if the equivalence is not shown in the flat panel calculation alone, an additional proof of equivalence is required. This can be done using a CAD measure of the cross-section of the MHBS or other appropriate method, provide proof of the second moment of area and area of the monocoque skins. So that multiplying this measured "I" by the "E" derived from the required physical test of your structure, is proved that the buckling modulus is equivalent. The measured "I" must be transposed from the cross-section centroid to a reference coordinate system on the chassis centre-line, and the same completed for the baseline tubes. The used steel tubes configuration used for the equivalency is shown below.

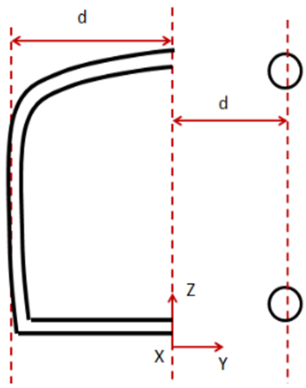


Figure 34. *Chassis steel tubes cross sectional view used for the equivalency.*

$$A = 2 \times \frac{\pi}{4} \times (d_o^2 - d_i^2)$$

$$I_{loc} = 2 \times \frac{\pi}{64} \times (d_o^4 - d_i^4)$$

$$d = \frac{chassis_{width}}{2}$$

For the composite configuration it is indicated to use cut section properties calculated by CAD system and I_{zz} of half car with the reference coordinate system at the centerline of the vehicle. Below the expressions needed to show the rightness of the equivalency test.

$$I_{zz} \geq I_{loc} + A \times d^2$$

$$I_{CFK} \times E_{skinmodulus} \geq I_{STEEL} \times E_{steel}$$

Where:

I_{CFK} is derived from CAD

$E_{skinmodulus}$ is derived by the test of the laminate

I_{steel} as above

E_{steel} 200 GPa as indicated in rule T 3.2.4 of the rulebook (not here reported).

In the third scenario were included all the teams without a square/rectangular structures, that must complete an analysis similar to that required in scenario 2, but at a cross-section through the structure where the equivalent tube offset ("d" in the image below) is 75mm.

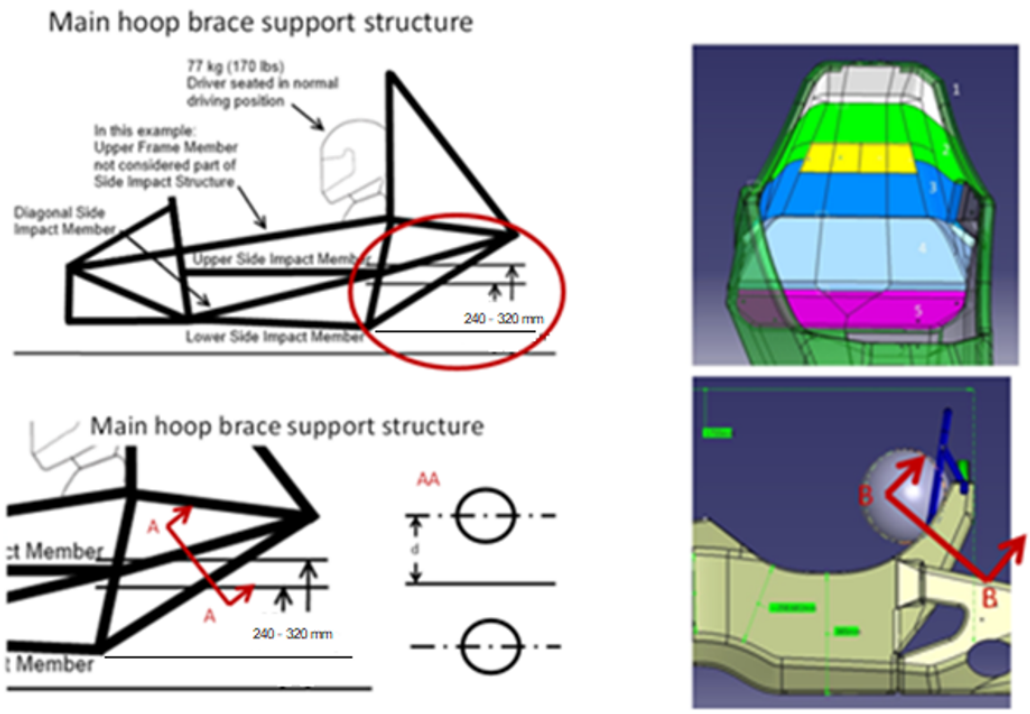


Figure 35. *Schematic explanation give to proof the equivalency of the scenario 3 MHBS.*

Despite these indications, for us the was not so clear which was the right method to deal with our "tower" structure, basically because we had difficulty identifying which was our case between the scenario 2 and 3. So we decided to send a clarification to the Formula Student organization in order to be sure on the proof requested and on the structure feasibility. The answer was that the "tower structure" must be equivalent to two main hoop bracing tubes and then the guidance of point 2 can be followed (indicated immediately upper). The "base of the tower" instead must follow the guidance at point 3 to be proved. Below I report the material and the calculations that have been made to verify the equivalence, accepted since the first review by the organization of all the competitions of the season. Obviously all is reported referred to the final configuration of the laminate in correspondence of the MHBS structure, apart from the evaluation below, other analysis have been performed and I will explain them later, after having concluded with the proof of equivalency that practically is the last stage on design, but in order to be clear I decide to put it as first need.

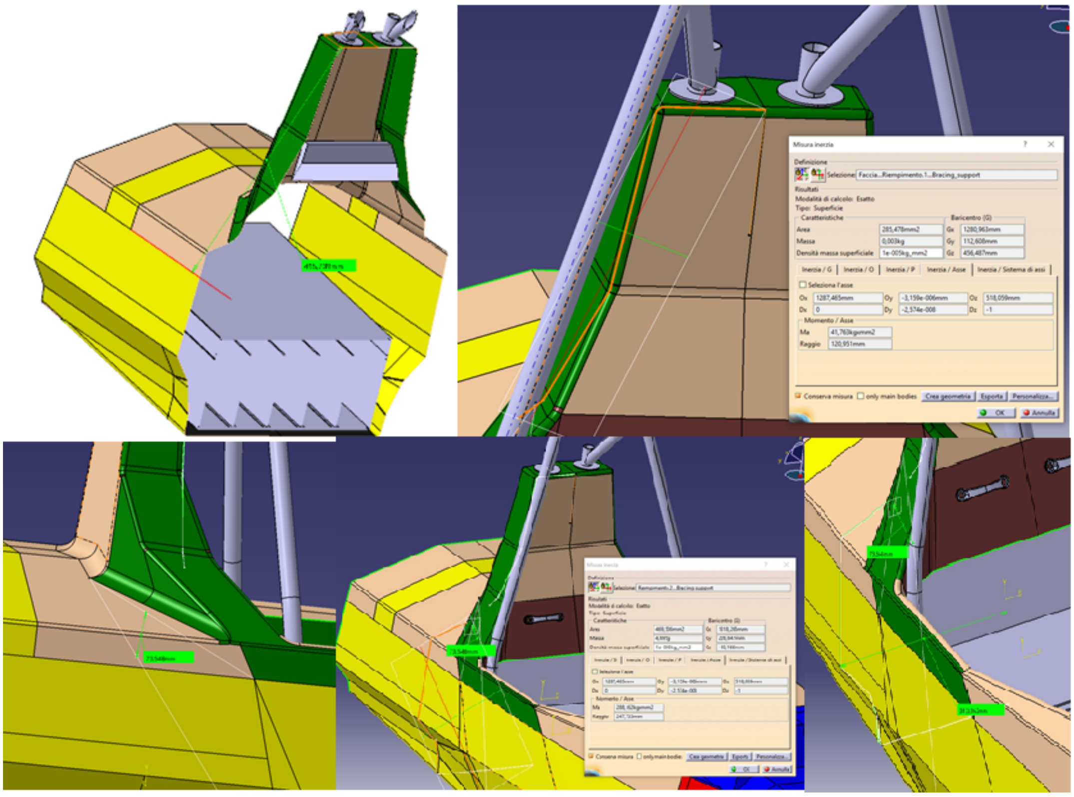


Figure 36. *All the screenshots attached as supporting material to proof the equivalency of the MHBS.*

Calculations requested at point 2:

d_{Otube}	25,4	mm
d_{Itube}	23	mm
n of tubes	2	
d	123	mm
A_{tube}	182,3712	mm^2
$I_{locMHBtube}$	13383,31051	mm^4
I_{steel}	43823,68171	mm^4

Table 3. *Steel tubes used values for the comparison of point 2.*

Ma tower only ply	4,18E+01	$kg * mm^2$
Density	1,00E-05	kg/mm^2
I_{CFK}	4,18E+06	mm^4

Table 4. *Laminate used values for the comparison of point 2, where Ma tower only plies means moment of inertia of external plies around z-axis.*

The following table shows that the inequality of point 2 is verified.

EI_{tower}	1,87E+18
EI_{steel}	8,76E+15

Table 5. *First demonstration for the proof of equivalency.*

Calculations requested at point 3:

d_{Otube}	25,4	mm
d_{Itube}	23	mm
n of tubes	2	
d	313	mm
A_{tube}	182,3712	mm^2
$I_{locMHBtube}$	13383,31051	mm^4
I_{steel}	209503,6817	mm^4

Table 6. *Steel tubes used values for the comparison of point 3.*

Ma support only ply	2,88E+02	$kg * mm^2$
Density	1,00E-05	kg/mm^2
I_{CFK}	2,88E+07	$mm^4$4

Table 7. *Laminate used values for the comparison of point 3.*

EI_{tower}	1,29E+19
EI_{steel}	4,19E+16

Table 8. *Second demonstration for the proof of equivalency.*

As final results, the two structures that we have declared as "comparable", relying on experience, simulations and rule compliance, are the two laminates highlighted below.

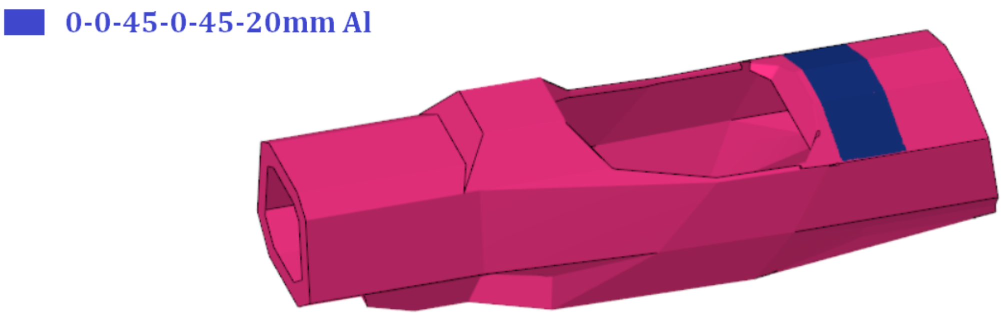


Figure 37. *Monocoque with MHBS laminate highlighted: plies and core as designed for the SC18.*

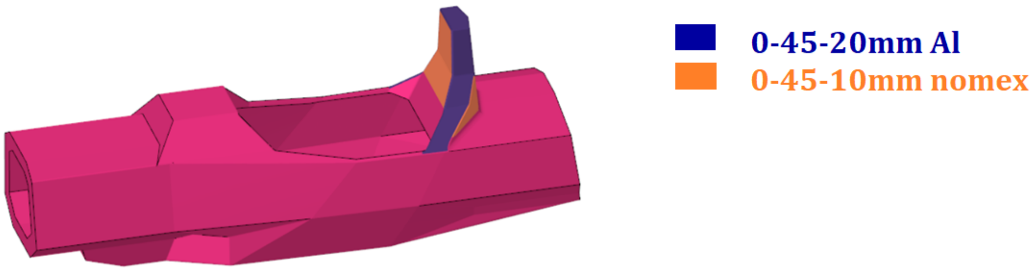


Figure 38. *Monocoque with MHBS laminate highlighted: plies and cores as defined for the SC19.*

Finally this weight comparison could be done and the results was amazing. In the table below is possible to see the evaluated weight of each part, considering the steel tubes and the laminates with number of plies and type and thickness of core as just showed on the figure above.

Configuration		Mass $[kg]$	Total Mass $[kg]$
Previous year configuration	Main Hoop	3.35	
	MHB	1.238	5.024
	MHBS (composite)	0.436	
Innovative configuration	Main Hoop	3.35	
	MHB	0.452	4.115
	MHBS (composite)	0.313	

Table 9. *Weight comparison between the previous year layout and that innovative considered for the SC19.*

From the table clearly comes out that the innovative structure integrated on the monocoque can lead to a weight saving of about 1 kg (0.909 kg) compared to maintaining the solution adopted in previous years (concerning longer and weighter main hoop bracing) . Moreover, an aesthetic advantage can be also associated to this solution: the head rest can be directly applied on the front surface of the coposite MHBS structure (obviously by paying attention on rule conserning its positioning), so as to be more "integrated" with the vehicle and not placed on between the tubes of the roll hoop and bracing as in previous years.

In addition to structural equivalence it has been verified that in the event of a roll over the structure does not yield. The simulation was made using the Hypermesh model of the monocoque and constraints and force were set as follows: a SPC on the nodes of a generic cross section in the middle part of the monocoque was create and all the DOFs of it locked; a force along y equal to the weight of the whole vehicle with the driver considering a lateral acceleration equal to 5g was applied on the top of the main hoop. Below firstly the model then the results.

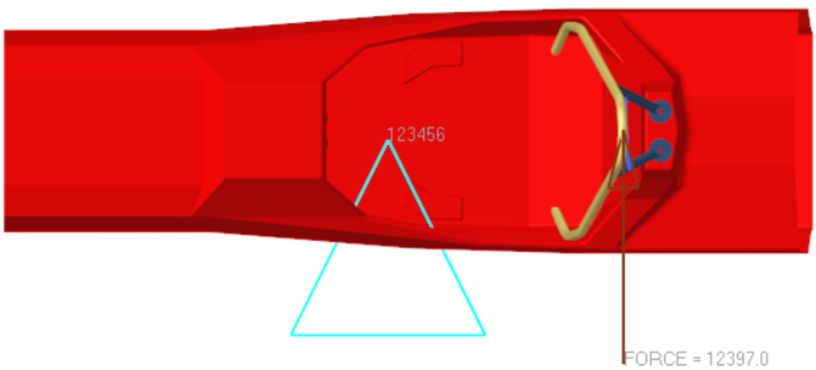


Figure 39. *MHBS verification under roll over load condition: constraint and force showed.*

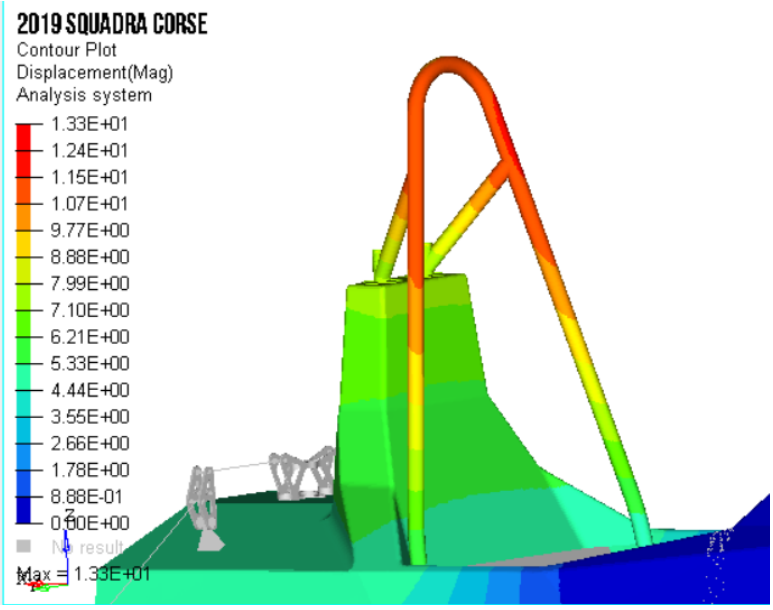


Figure 40. *MHBS verification under roll over load condition: displacements contour plot.*

The contour plot of the composite failure index shows that none region of the MHBS reach a value equal to 1, that means failure of the composites.

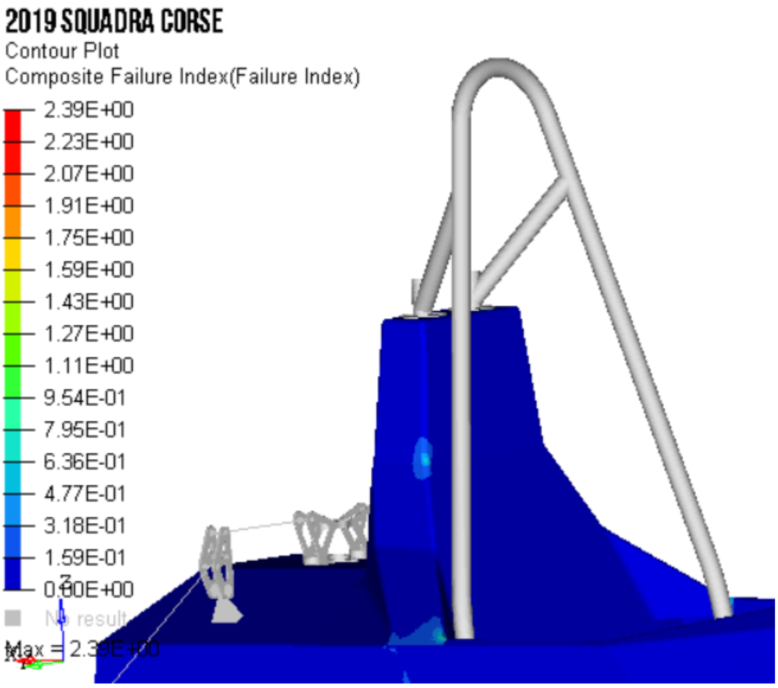


Figure 41. *MHBS verification under roll over load condition: composite failure index contour plot.*

The figure below shows that composite failure indexes larger than 1 are not real, but only located in correspondence to the rigids used to fix the MH to the monocoque

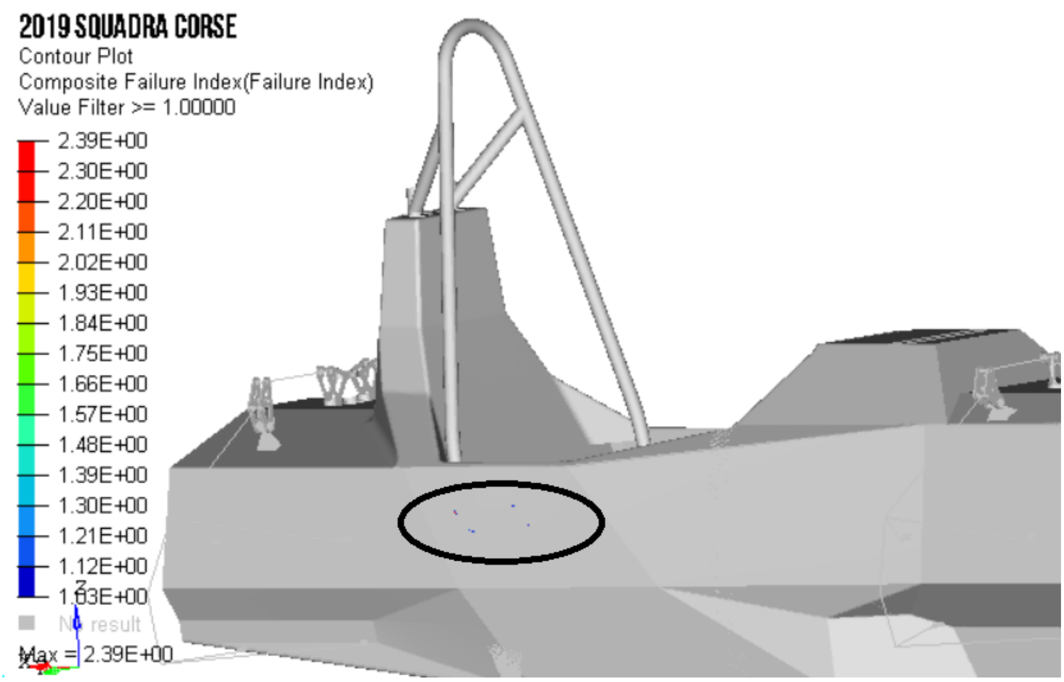


Figure 42. *MHBS verification under roll over load condition: composite failure index contour plot.*

Going beyond the benefits, however, even an evaluation of the possible disadvantages must be done before proceeding with the definition of the final project. In fact this type of choice certainly represents a disadvantage from the aerodynamic point of view. It was therefore necessary to evaluate its influence on the aerodynamics of the entire body, in order to measure its percentage of influence on it, and then decide whether to give precedence: to the best choice for reducing the weight of the body or, if the influence on the aerodynamics is to be considered greater than the advantage of the weight saving, to desert on this project line, remaining on a MHB flat panel support as in previous cars.
The aerodynamics department was therefore in charge of evaluate these two different configurations and their different influences. Since talking about the aerodynamics of the bodywork taken individually it does not make any sense, the CFD simulations (done with STAR-CCM+ software) have been done on a model complete with driver, aerodynamic package, body shell, wheels and suspension. In the image below the two models on analysis are reported.

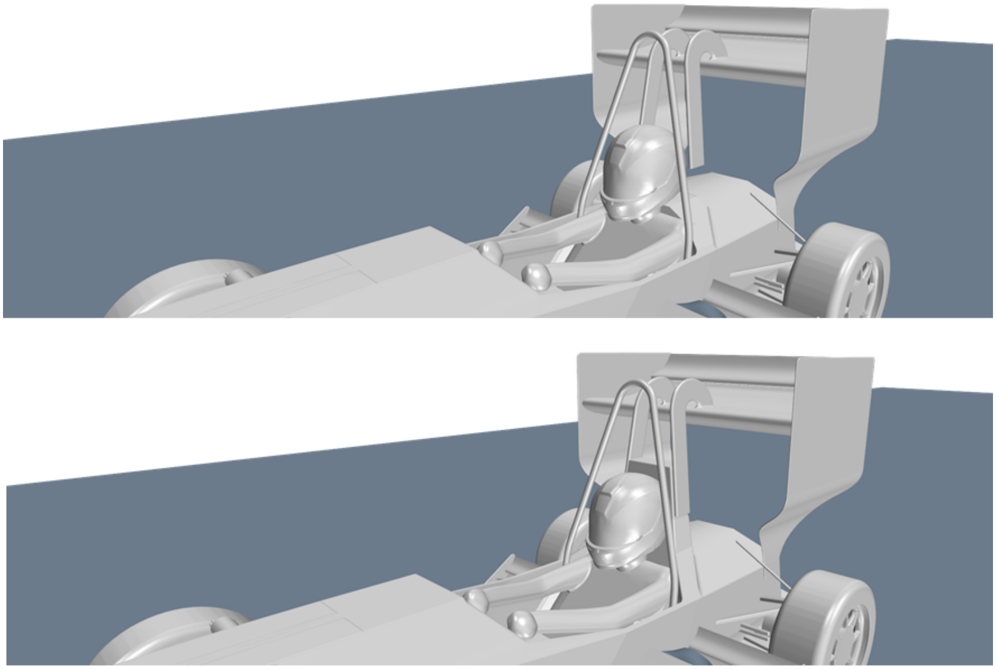


Figure 43. *Screnshoots made on STAR-CCM+ models analysed: upper picture reports the configuration without the tower, as in the SC18; picture below shows the evaluated configuration for the SC19.*

The boundary conditions for the simulation were set as follow, being obviously the same for the two models:

-headwind = 60 kph;

-tunnel outlet pressure = 0 Pa;

-symmetry plane in the middle of the vehicle to halve the number of cells;

-ground moving at 60 kph downstream (to have relative zero motion with air);

- surfaces of the wheels in rotation with respect to an axis centered with the wheel axis (to consider also the influences on flux due to wheel rolling as in the real case).

In order to quickly comment on the results of the simulations, two scenes of the most interesting variable for this type of evaluation are shown below.

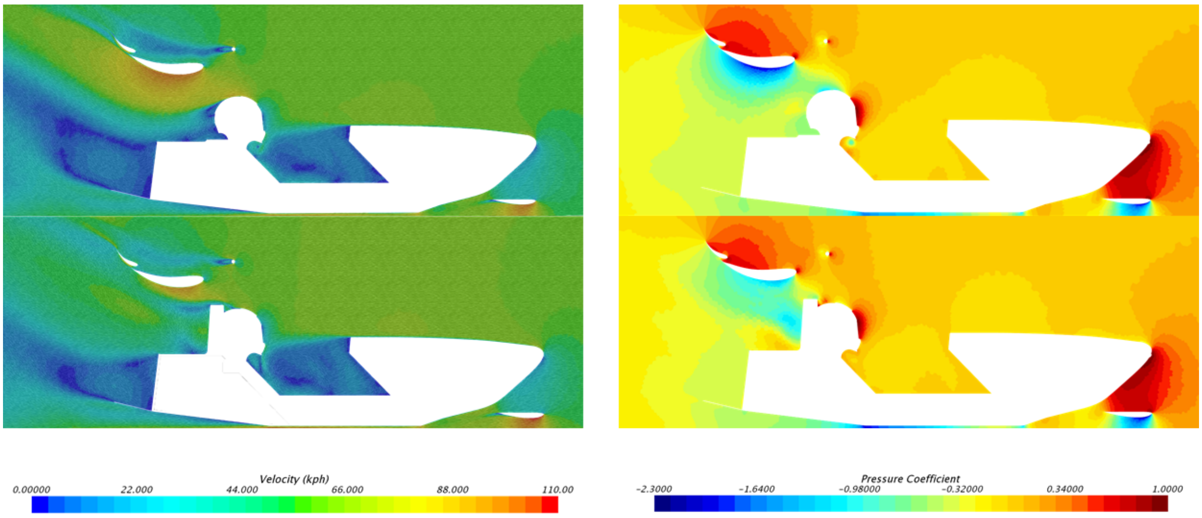


Figure 44. *Left scene: flux air velocities; Right scene: pressure coefficient.*

CFD results			
	Monocoque w/ "tower"	Monocoque w/o "tower	
$C_{DRearWing}$	0.361	0.310	-14.12%
C_{Dtot}	0.777	0.833	+7.2%

Table 10.

A value has been purposely omitted from this table because it requires an additional explanation. What we call C_Dbody is the contribution of only monocoque to the total drag of the vehicle. The simulations show an increase of the drag coefficient C_Dbody equal to 44.8 % for the body that presents the tower compared with respect the other with only tubes. This result, which we expected as obviously the tower represents an additional resistance to motion and so additional drag, is very negative but it is almost totally balanced by another factor. In fact, is possible to note on the table that the drag of the whole assembly of the vehicle in case of the new possible configuration is only 7% higher than the other. How it is possible considering the previous said 44.8% increase in the body drag? The answer comes out from above reported scenes. Without going into details of fluid dynamics theory, that is not the purpose of this section, it can be seen that the air flows subsequently to the bracing support structures have very different behaviours in the two simulations. This difference is highlighted in the first row of the table, where the drag coefficient of the only rear wing is reported. This reduction on drag concerning this wing means that in the case of the tower, where the drag of the only body is much more relevant in percentage above the total drag, the functioning of the rear wing is a little bit limited due to the obstruction of the structure, which in this way is true that it loads less, but at the same time makes less drag. Additionally, since the depression of the wing is lacking, the wake of the car is also limited, limiting its drag. These results, although not totally positive, led us to choose the configuration leading to a greater reduction in terms of weight, being a priority for this year's objectives, compared to that involving a reduction of aerodynamic resistance.

The above explained considerations in terms of torsional stiffness of the monocoque, transfer and support of loads in case of rollover and the final considerations on aerodynamics, have led to the implementation of this new design choice concerning, a sort of integration of part of the bracing tubes in the monocoque composite structure. Moreover the composite "tower" structure allowed to fix the intake manifold of the battery pack cooling system on its side wall.
Concluding, this new configuration allowed to save 0.909 kg considering the MH, the bracing and the support structure.

Laminates optimization

Improving laminates is the fist step to save weight and improve torsional performance of the monocoque but before analyse how the laminates have been improved, by describing their design and tests performed, a brief introduction on the material that will be discussed.
For all the monocoque the same material selected the previous year has been used. A MJ type high modulus fiber with enhanced tensile and compressive strength was selected after having tested also textreme and unidirectional carbon fiber types. For completeness the results table of the tested specimens is shown below.

Specimen Material		Width	Thick.	Area	$F_{max.}$	Strenght R_m	Elongation.	Elastic Modulus
	N°	mm	mm	mm^2	N	MPa	%	GPa
Textreme 45°	1	25,28	1,10	27,81	4.933	177,4	23,0	11,1
	2	25,20	1,05	26,46	4.933	186,4	26,0	11,6
	3	25,61	1,09	27,91	4.790	171,6	26,0	11,1
M46J 45° modulus	4	25,39	1,89	47,99	8.048	167,7	13,0	12,5
	5	25,38	1,92	48,73	7.859	161,3	15,4	1,4
	6	25,59	1,92	49,13	8.080	164,5	17,2	12,7
	7	25,81	1,93	49,81	8.002	160,6	16,4	11,8
	8	25,58	1,89	48,35	7.918	163,8	16,9	12,4
	9	26,41	1,92	50,71	8.191	161,5	14,2	12,9
Textreme 0°	10	13,77	0,72	9,91	8.533	860,7	/	52,1
	11	13,32	0,74	9,86	8.988	911,9	1,6	57,3
	12	13,45	0,66	8,88	9.144	1.030,1	1,5	68,5
	13	13,26	0,64	8,49	7.721	909,8	1,2	71,4
	14	13,88	0,64	8,88	10.033	1.129,4	1,6	70,4
	15	13,06	0,70	9,14	8.708	952,5	1,6	63,6
	16	13,13	0,71	9,32	8.689	932,1	1,5	59,8
M46J 0°	17	13,09	1,32	17,28	10.955	634,0	0,6	110,7
	18	13,20	1,34	17,69	11.364	642,5	0,5	113,3
	19	13,20	1,30	17,16	11.676	680,4	0,7	93,9
UD K63712 0°	20	12,97	0,67	8,69	9.377	1.079,1	0,3	336,7
	21	13,46	0,65	8,75	11.442	1.307,8	0,3	398,6

Figure 45. *Specimens tensile test results.*

So M46J 0/90° woven fabric has been used, since different fiber orientations are needed on the chassis.

For the panels honeycomb cores both aluminium and nomex were used. Aluminium honeycomb represents one of the highest strength/weight ratio with respect other structural materials. Different thickness and cell size can be chosen in order to vary the properties of the core material, but in our case all the aluminium honeycomb cores have the same foil thickness equal to 20mm. Nomex cores were used for their lower densities in panels in which lower mechanical properties with respect aluminium were sufficient.

This year a great deal of research was carried out not only to lower the weight of the car but mainly to give a technical and scientific value to the laminates definition. In fact, one of the objectives of the Chassis Department of the SC19 team was the creation of a model to optimize the laminates of the monocoque to achieve a composite structure that is highly differentiated, stronger and lighter.
This work lays its foundations on a targeted analysis of the previous year's laminates. Starting from there and taking into account the structural equivalence of the composite materials required in T3.4, we tried to identify which were the SC18 monocoque panels that had been oversized, thus presenting a greater margin of lightening while remaining compliant with the rules.
To this purpose I report the laminates configuration of the SC18.

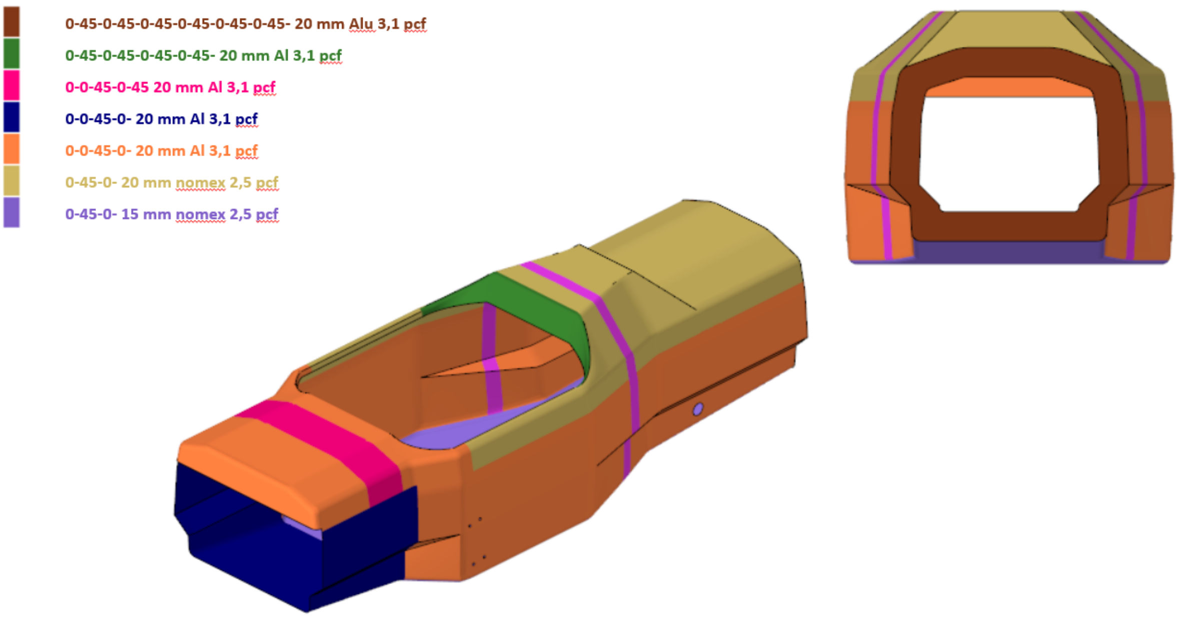


Figure 46. *SC18 Laminates' configuration.*

Proceeding with a schematic analysis of the laminates of the last year monocoque, we will start speeking about which are the one in which modification are possible or needed, afterwards it will be explained which analyses have been carried out on these to then arrive at the final definition of the configuration of the laminates in the SC19 monocoque.
First of all, looking at the previous figure, we can focus our attention on laminates subject to the re-

quirements of the rules and introduce some points from which we started for the design of the SC19 laminates.

1. Front Bulkhead: this laminate cannot be more lightened since it is already to the limit imposed by rules.
2. Front Bulkhead Support: these panels can be strongly improved, in the following pages it will be explained how this has been done.
3. Front Hoop Bracing: its layup is as the yellow configured one in the figure, something can be changed by selecting for example another core material for this panel.
4. Side Impact Structure vertical: this solution is already good as regards the weight, considerations and evaluations relating to the contribution of this panel on the torsional stiffness of the chassis have been done and consequently also this laminate has been modified.
5. Tractive System: same consideration of SIS vertical.
6. Side Impact Structure horizontal: (basically the floor of our monocoque) not only stiffness and weigth had a role on the design of this laminate but this year also packaging constraint showed up.
7. Main Hoop Bracing Support: this composite structure has already been discussed in the previous paragraph.
8. Shoulder Harness Bar: some considerations about the location of the belts attachment points.

At this point, the laminates mentioned above will be discussed one by one, justifying the choice of their configuration, whether it is a carry over of the previous year laminate or an improvement.
To understand well what we will talk about, it will be necessary to consult the definitions and the constraints imposed by the regulation reported in chapter 2. The stress-strain curves of requested tests of each laminate are reported.

1. **FBH**. The final bulkhead design consisted of an anti-intrusion plate bolted with 8 M8 grade 8.8 bolts to the chassis, a composite sandwich laminate with 16 plies of carbon fiber and a 20 mm aluminum honeycomb core with external dimensions bigger than the front bulkhead cutout. The latter was a 122 mm wide sandwich frame of 12 carbon fiber plies each side (woven directions alternately 0-45°) and a core of aluminum honeycomb (selected density 4.5 pcf). Dimensions showed in figure.

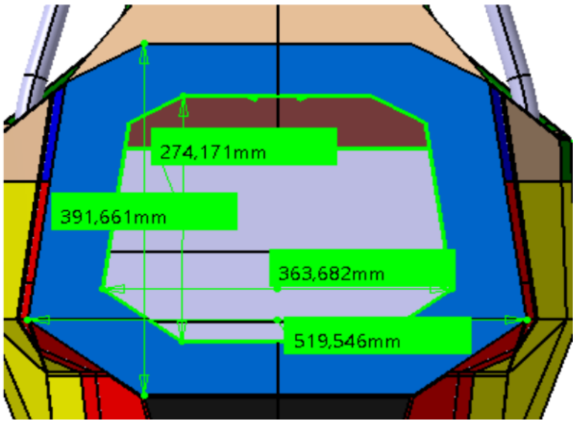


Figure 47. *SC19 front bulkhead structure dimensions.*

Note that the frame members have to be not so thick to permit maximum access to the front of the vehicle for servicing vehicles components such as the brake and throttle pedal assembly.

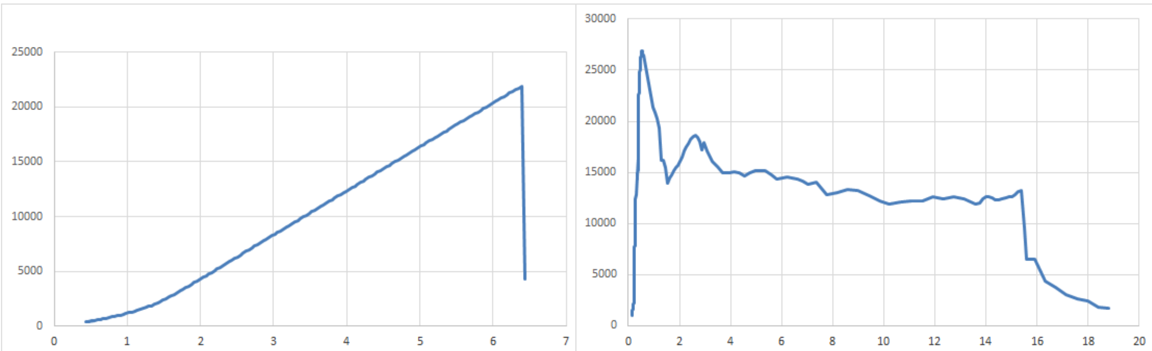


Figure 48. *Stress [N]- strain [mm] curves: 3-points bending (left) and shear test (right).*

2. **FBHS**. Immediately at the beginning of the season this laminate has been subject of study for many weeks. This panel is in fact not only subjected to stringent regulation constraints, but above all its rigidity is fundamental for the vehicle dynamics performance: the suspension attachment points are located on it, therefore it is necessary that its rigidity is such as to avoid the altering of kinematics of the suspension under some loading conditions. Indeed a torsionally non-stiff region of a chassis close to the front or rear suspension can effectively reduce the roll stiffness of that suspension.

   For its importance, this laminate was immediately treated at the beginning of the year, as it has just been said, so that the analysis and considerations that will be explained below, will show the use of the SC18 suspension panel, since the SC19 body shell had not yet been defined.

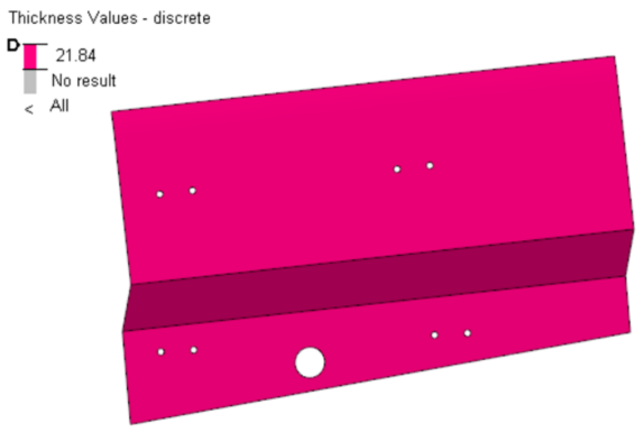


Figure 49. *SC18 suspensions' panel thickness.*

So starting from the examination of the SC18 suspesions' panel, its sandwich panel was made of four CFRP plies each side, and a honeycomb core of aluminium. Its weight was 0.7068 kg. Since the purpose of this work was that of choosing a new composite structure improved with respect the previous one, a comparative analysis on compliance and weight of different laminate configurations has been done. So in our evaluations we had only included the panel, also because it could not be done otherwise having not yet available the entire body shape.
In this study, Finite Element Analysis (FEA) is used to optimize the SC18 panel, analysing its mass and compliance under a particular load case, finding a new improved solution for the SC19. The analysis is performed in two stages. The first stage consists on found some values needed to the second stage, in which a Free-size optimization is performed in order to determine material thickness distribution of the examined panel.
Have a look now on the model involved in the first stage of the analysis. Pay attention that due to the fact that it includes only the panel, displacement or stress values that resulted from simulations must not therefore be interpreted as a real displacement of the panel subjected to that type of load or real stress state of the material, but rather will be considered only as a comparison, as an index of improvement or worsening of the analysed laminate.
To have a model that can also be used in the second stage, we have defined the sandwich panel differently than we usually do for the whole monocoque, explained in the dedicated section. In this case we have defined with two PCOMPP cards the two carbon panel skins, the external one and the internal one, separately as stacks of carbon fiber plies (MAT 8). A different card has been adopted in this case for the aluminium core, to which the MAT9ORT card has been attributed since it was implemented as solid. In the table below are summarized the settings about the performed simulation and then that of values concerning the load case studied is reported.

Analysis type: Linear static			
Load type	**Magnitude**	**Direction**	**Note**
Brake In Turn	given by Adams Car model	given by Adams Car model	load transferred to the panel by means of RBE3
Constraint	fixed		SPC on the perimeter of the panel

Table 11. *Stage 1: linear static analysis of the SC18 panel under BIT load condition.*

Load case (the worst): Brake In Turn					
	UCAR			**UCAF**	
x	**y**	**z**	**x**	**y**	**z**
-264.5	1579	427	-264.5	1365	303
	LCAR			**LCAF**	
x	**y**	**z**	**x**	**y**	**z**
964	-3536	-361	964	2528	329

Table 12. *Load case BIT: values obtained from the suspensions' model on Adams Carn.*

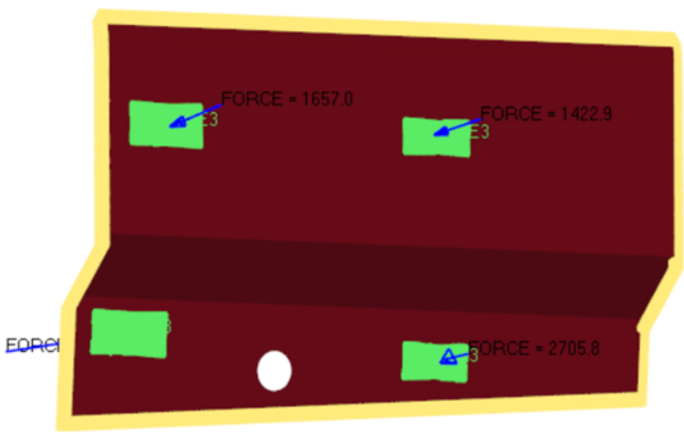


Figure 50. *Load case BIT on SC18 suspension panel.*

The results are showed after the second stage since used as comparison. So the purpose of the stage 1 was that of finding values that will be used as constraints in the next stage in which a free-size optimization was performed.

Free-size optimization in OptiStruct optimizes the thickness of every element, starting from a so called "super laminate" as design space to generate an optimized thickness distribution in the structure, for the given objective under given constraints. Free-size optimization of the suspension panel is done for the same load cases discussed earlier, being the worst one for this part. In order to perform an optimization, define a DESVAR card is needed. Design variable entities are used to define and store design variables for optimization problems. The design variable for free-size optimization is the thickness of the shell elements on the surfaces that for us were two: the inner layers and the outer one. Constraints and objective are than defined performing two different optimizations, setted as schematically show in table below.

Analysis	**type:**	**Free-Size**	**Optimization**		
		setting A		**setting B**	
DESVAR	Entity type	Constraints	Objective	Constraints	Objective
Thickness	Stack:	Max Displacements	Minimize mass	Mass= 0.414 kg	Minimize
	2 laminates	-inner panel= 0.23 mm			compliance
		-outer panel= 0.25 mm			
		-along Y on attachment:			
		UCAF= 0.3 mm			
		LCAF= 0.5 mm			
		UCAR= 0.3 mm			
		LCAR= 0.6 mm			

Table 13. *Stage 2: Free-Size optimization under same load condition.*

The lower bound for the thickness was given as 0.23 mm, which is the thickness of one ply only, while the upper one as 0.92 mm, the thickness of a stack of 4 plies, as in the actual panel of SC18. The other variables of this study were: displacements and mass. So in a first simulation (setting A) the compliance of the panel and so its displacements were put as constraints: the numerical value used for these bounds came out from the linear static analysis of stage 1. In this way we will minimized the mass of our panel without exceeding the maximum displacements obtained with the previous explained configuration, bounding both the less stressed areas putting a limit on the overall displacements of the panel, and also that which are the most stressed, the one hosting the suspensions' attachments, by putting there a bound equal to the y-component of the maximum displacement obtained previously. Setting B presents the reverse situation: the mass was used as constraint, putting an upper value equal to that of 3 plies (one less than the starting panel) each side of the sandwich composite.

In the following two figures the results obtained are showed.

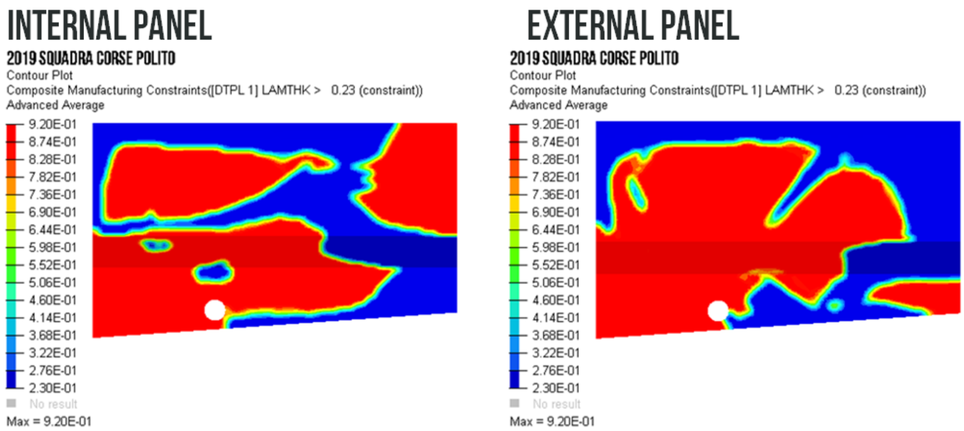


Figure 51. *Free-Size opt setting A: Contour plot of panel thickness obtained.*

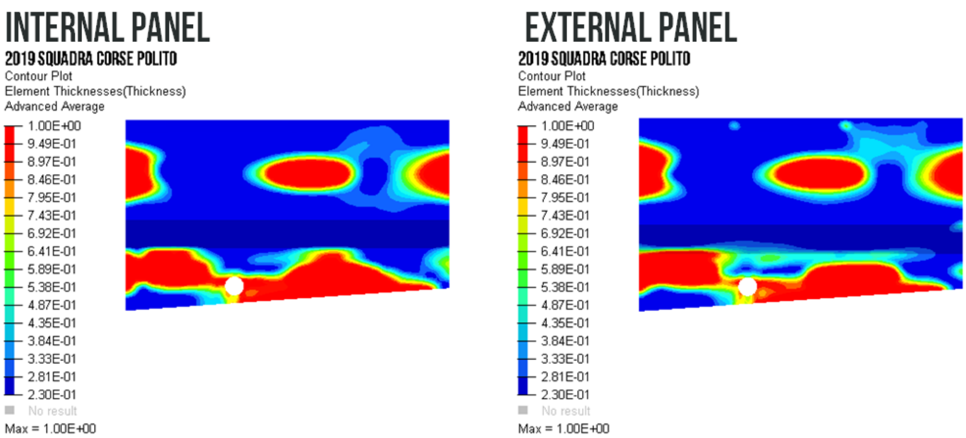


Figure 52. *Free-Size opt setting B: Contour plot of panel thickness obtained.*

Obviously this type of optimization found a random discrete (0.23 mm stepped as thickness of one ply) distribution of thickness so starting from these result we had to evaluate a manufacturable configuration for the new panel. Looking to the plies distribution of setting A, it is not possible to identify a geometry that can be easily implemented with different patches of CF. On the other hand in setting B results, two thicker rectangular zones, obviously in correspondence of the attachments of suspension's arms, came out. So in this case we were able to identify a manufacturable configuration with bands.

Therefore the proposed new solution was the following

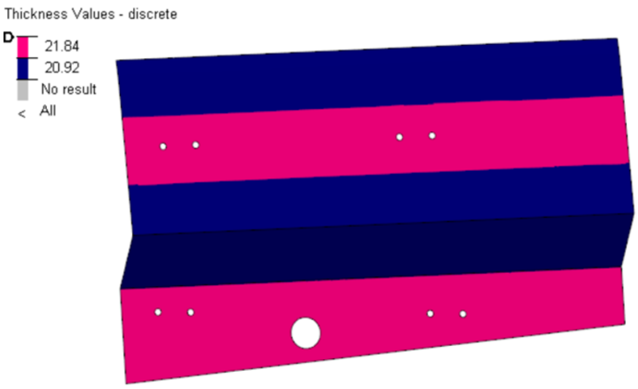


Figure 53. *New reinforced bands suspensions' panel.*

Looking to the thickness scale of this capture that represents the new solution derived from the optimization's results. It was created a panel with two global plies covering all the surface of the panel, and then four reinforcement bands (two in correspondence of the upper suspension attachments and two on the lower one) were put. Now a compliance comparison must be performed, in order to decide if this configuration was acceptable or not. A linear static analysis of the new panel, which weights 0.5538 kg (21.65% less than the previous), as done in stage 1 for the SC18 panel, was performed, with the same load and constraints (look back at the table). The obtained displacements are compared below.

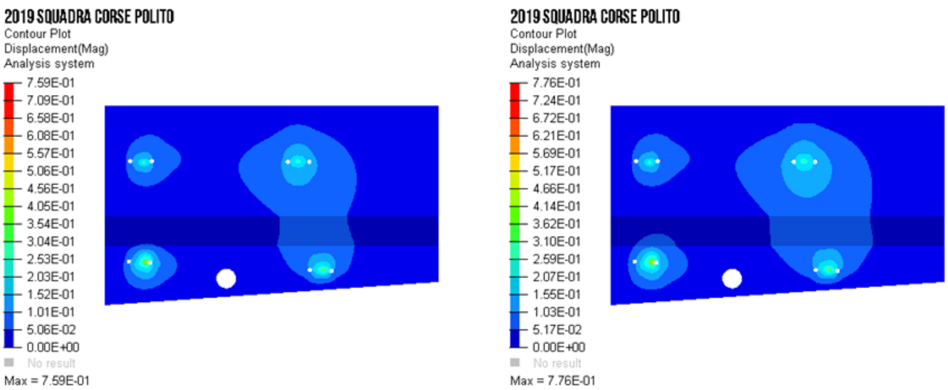


Figure 54. *Displacements comparison between the 4 plies each side SC18 panel (left) and the new panel with 2 plies and reinforced with 2 bands each attachment (right).*

As can be seen from the contour plot the distribution of the displacements are almost the same: the difference on the maximum displacements (in magnitude) referred to the LCAR can be accepted since it is minimal. The influence of this difference was then evaluated as negligible by simulating the load case on the whole body with the suspension system included.

Once having decided the layout, simulations were performed in order to decide the best plies

orientations to reach the best result in terms of stiffness of the panel. By evaluating also other solutions for the aluminium honeycomb core, a different density was selected.
In conclusion this study was performed in the same way also for the rear panels and at the end this band layout was adopted for all the SC19 suspensions' panel, leading to a weight saving of more than 20% with respect the previous configuration.

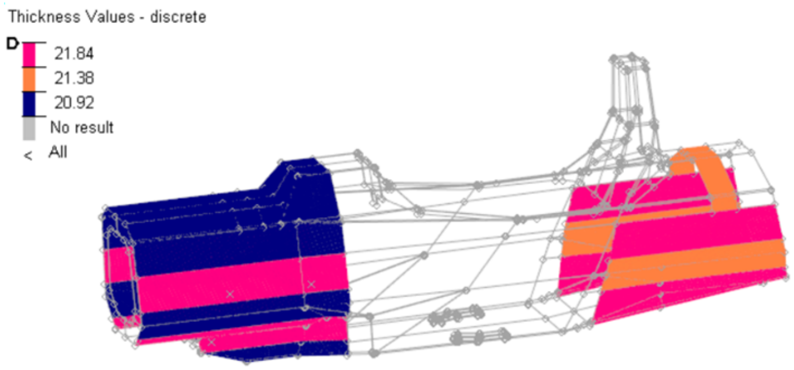


Figure 55. *Band Layouts. Front panel plies' directions: global plies 0-45 + band plies 45-45. Rear panel plies' directions: global plies 0-45-0 + band ply 45.*

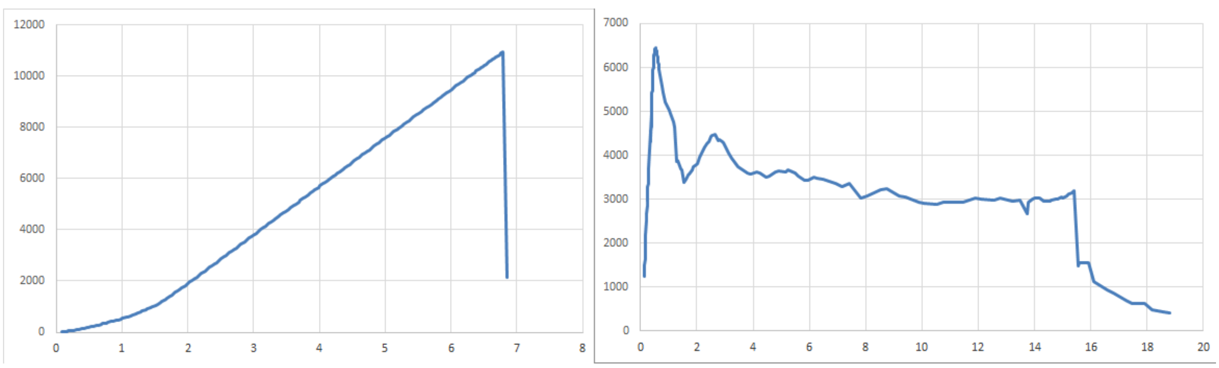


Figure 56. *Stress [N]- strain [mm] curves: 3-points bending (left) and shear test (right).*

3. **FHB**. This laminate in correspondence of the roof of the front part of the monocoque was basically chosen to make the manufacturing easier, by using the same laminate as the adjacent suspension panel (without the reinforcements bands obviously). The dimension used in the SES to proof equivalency is showed in the figure below.

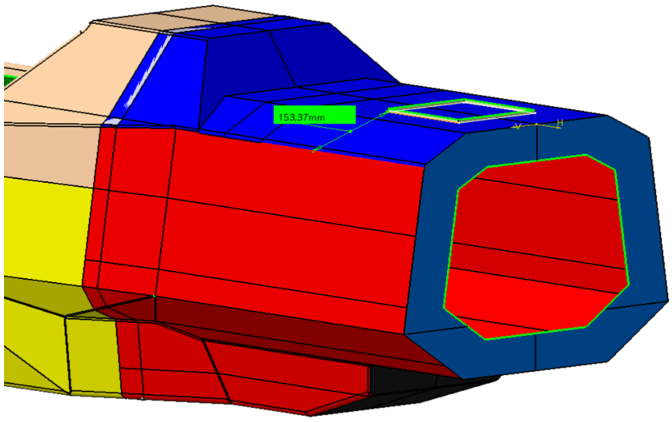


Figure 57. *Front Hoop Bracing dimensions.*

This chose for the core material with respect the nomex used the previous year for this panel has enhanced the stiffness of the chassis.

4. **SIS vertical**. The vehicle cockpit sidewalls were designed to be 0.396 m tall and the side impact zone corresponds to a 0.346m tall section of the side wall considering that 0.32 m tall section of the sidewall by definition in the rules is required as impact structure. In order to improve the previous laminate stiffness by reducing its weight, a new core was evaluated, permitting to reduce the laminate of both the skins of one ply. Two different cores both in aluminium were considered with higher density with respect that used on SC18 (3.1 pcf): 5.3 and 6.1 pcf (also this panel has a thickness of 20mmm). The choice was made comparing both the torsional stiffness of the monocoque and the weight obtained with the two panel. The difference in weight was of about 1% as almost the same was found for the torsional stiffness. However, in order to be more conservative in the equivalency the 6.1 pcf aluminium honeycomb core was used, with a skin layout of 0/45/0.

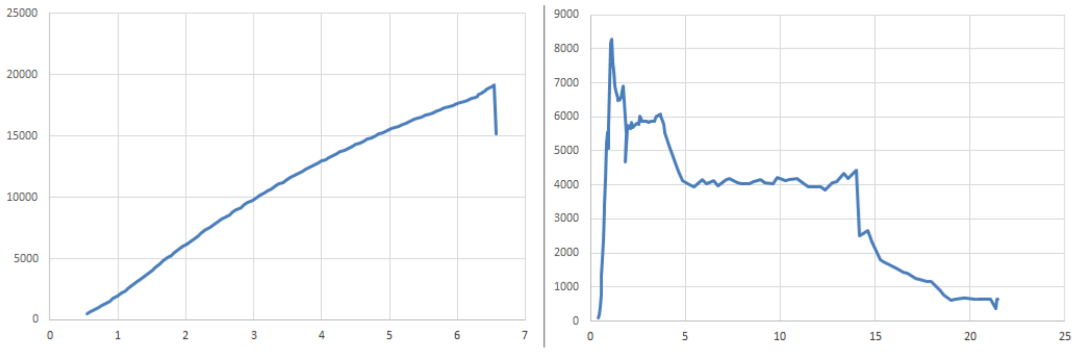


Figure 58. *Stress [N]- strain [mm] curves: 3-points bending (left) and shear test (right).*

5. **TS**. This panel was radically changed with respect the previous year. Same analysis and simulations as for the FBHS (point 2) were performed leading to the application of a similar solution. It was proved that also for the rear suspensions' panel the band reinforced was advantageous in terms of weight and stiffness but some other constrains must be taken into account in this case. As said in T3.4 (summary of rules of interest on chapter 2), if composite materials are used in the tractive system accumulator container the flexural rigidity (EI) of that structure must be calculated with the tools and formulas in the SES. Considering the dimensions of our panel, in order to proof the equivalency one global ply was added and another density of the core material was changed.
The obtained configuration for the panel was 0-45-0 CF global plies and two reinforcing bands one for the upper attachments and one for the lower one at 45 deg. To improve its torsional performance a 6.1 pcf Al honeycomb core was selected.

6. **SIS horizontal**. This laminate have been changed due to packaging requests, in order to make possible the new positioning of the inverter's boards that, as it will be explained, have been put in the tunnel below the driver's leg. So in order have enough space along z axis for boards, case and finally creating a uniform internal body floor having the firewall covering the inverter on the same plane of the pedals, a 10 mm thinner core has been selected. So the final layup of this panel was made of 4 plies (one more than the previous year) each side of the panel and inside a honeycomb Nomex core material 10 mm thick (with higher density, the choosed one was in fact 3.2 pcf).
Remember that the main reason to design this narrowing of the body section in the lower part, called "tunnel" due to its shape, was dictated by the request to have the lower front suspension points, which fall on the vertical panel tunnel's side, more internal than the upper ones. This feature of the monocoque was then also used to improve the packaging by create a new possible solution to host inverter.

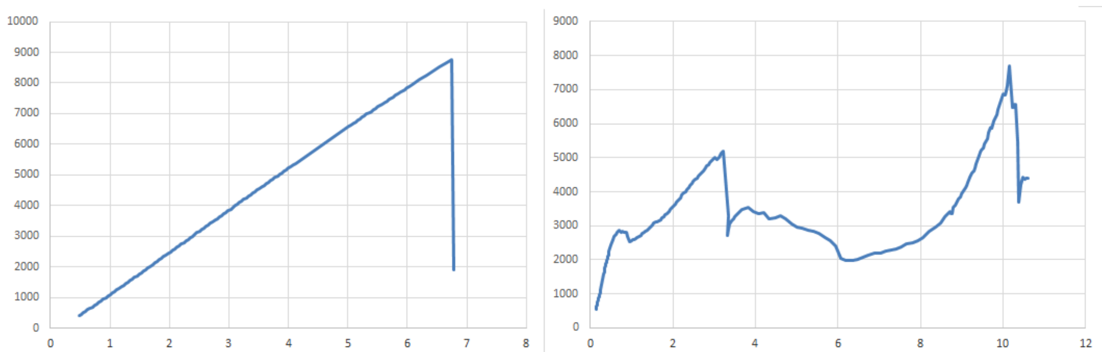


Figure 59. *Stress [N]- strain [mm] curves: 3-points bending (left) and shear test (right).*

7. **MHBS**. This laminate has been already treated in the previous section concerning the possibility to reduce weight changing part of the bracing of the main hoop with a composite structure. The final structure has been defined as previously said.

8. **SHB**. The proposed safety harness design included lap belts attached to bracket mounted to the

monocoque frame, as showed in the picture below, that were required to meet equivalency requirements of 13.0 kN.

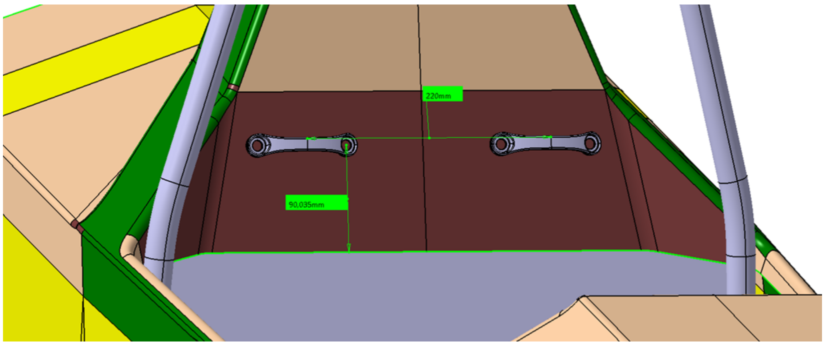


Figure 60. *Shoulder harness attachments.*

The composite structure configuration to proof the steel tubing equivalency for the shoulder harness bar was made on 8 plies (alternately 0-45 ° oriented) each side of an aluminum core 20 mm thick (density equal to 4.5 pcf). This was the layup used along all the opening perimeter of the cockpit, the most critical section concerning torsional stiffness of the monocoque. These attachments are fixed to the panel passing through carbon fiber inserts embedded in a honeycomb sandwich and a backing plate placed above the inner skin of the structure and was held in place by a nut. Harness mount tensile results the through bolt method proved capable of meeting the test. In addition, this year's design has also improved the positioning of the belt points. In fact last year they had been positioned on a horizontal surface of the body, behind the cockpit before the bracing attacks. This caused the insert to bend on the composite, the exact opposite of the function that it should have for which excessive loads could damage the panel and endanger the driver's safety. A diagram below is given to show how the belts, and therefore the direction of the applied force, were oriented with respect to the insert, going to subject it to a bending load rather than compression and traction as in the new configuration as can be seen in the previous picture reporting the attach

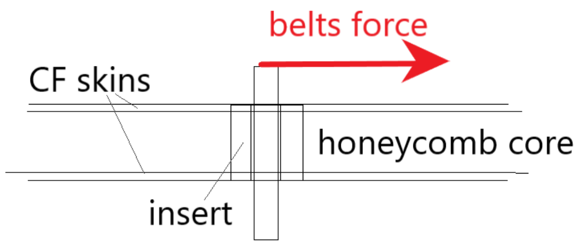


Figure 61. *SC18 shoulder harness attachments scheme.*

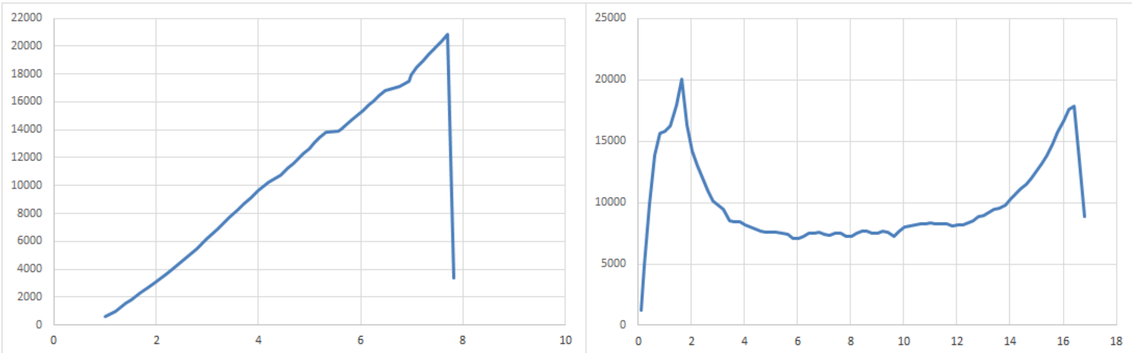


Figure 62. *Stress [N]- strain [mm] curves: 3-points bending (left) and shear test (right).*

The final configuration of the SC19 monocoque panels is reported below: nine different types of laminates were used, compared the seven of the previous monocoque, involving a more difficult manufacturing process. The Al core used on almost all the SC18 was not used for this monocoque. More research on core materials has been done, considering various possibilities leading to the usage of four different types of core considering both material, thickness and cell size.

Figure 63. *Final SC19 laminates configuration.*

Carbon fiber inserts

Laminated inserts are present in every attachment points of the monocoque and their design is here mentioned since the new solution has made a great contribution to reducing the weight of the monocoque.

They are used in order to reduce stress in composite skin, avoid collapsing of the core due to tightening of bolts and improve friction and radial transfer load on CF laminate. Due to the fact that different thickness of sandwich panel are presents, different heights of inserts have been designed, with different optimized shape and obviously for different screw diameter.

Dimensioning of inserts was performed by verifying that the maximum sear stress equal to the force applied to the insert over a surface evaluated as the perimeter of the inserts multiplied by the thickness of plies (0.23 mm times the number of plies) was less than the maximum admissible shear stress of the

CFRP (assumed 45 MPa).

Two possible materials was considered this year to make the inserts: aluminum as the SC18's inserts, and carbon fiber. The latter was chosen since mechanical properties are sufficient and weight saving could be so high. Having a look on the following table, we can see how many inserts are present in the monocoque and the weight savings that led to the use of this material.

Insert		**n°**	**Aluminum [kg]**	**Carbon fiber [kg]**
Shoulder harn.	attach.	2	0.089	0.053
Sub-marine	attach.	2	0.014	0.008
Suspension	attach.	14	0.037	0.022
Suspension	LCAR rear	2	0.042	0.025
Front rocker	attach.	2	0.019	0.011
Rear rocker	attach.	2	0.023	0.014
Circular att.	5x20	36	0.01	0.006
Circular att.	8x20	8	0.011	0.007
Circular att.	10x20	4	0.008	0.005
Circular att.	5x10	4	0.011	0.007
Circular att.	6x10	2	0.013	0.008
Total		**82**	**1.442 [kg]**	**0.866 [kg]**

Table 14. *Weight comparison between aluminum and carbon fiber inserts.*

The total weight reduction was 0.576 kg, equal to saving 40% of the previous solution weight.

In conclusion, a small summary of what has been said. The weight-oriented design was thus developed: first of all we tried to reduce the size of the central section, which was possible thanks to a new layout for positioning the inverters. This new packaging of the assemblies on the monocoque led also to a re-design of firewall, that was splitted in two parts with a final weight lower than the SC18 configuration. Some constraints have limited the restriction of the body sections and have therefore defined their geometry. A new main hoop bracing structure has contributed to save weight. Free-size size optimizations have been performed to re-design the layout of suspensions panels; all the laminates were evaluated booth in terms of weight, rule compliance and torsional stiffness of the monocoque. Finally, carbon fiber was used for the production of inserts previously produced in aluminium.

The same bar chart, that in target setting chapter reported the estimates of components weights, is here reported with also the actual weights measured after the manufacturing of components. The green boxes report the percentage of weight saving with respect the SC18.

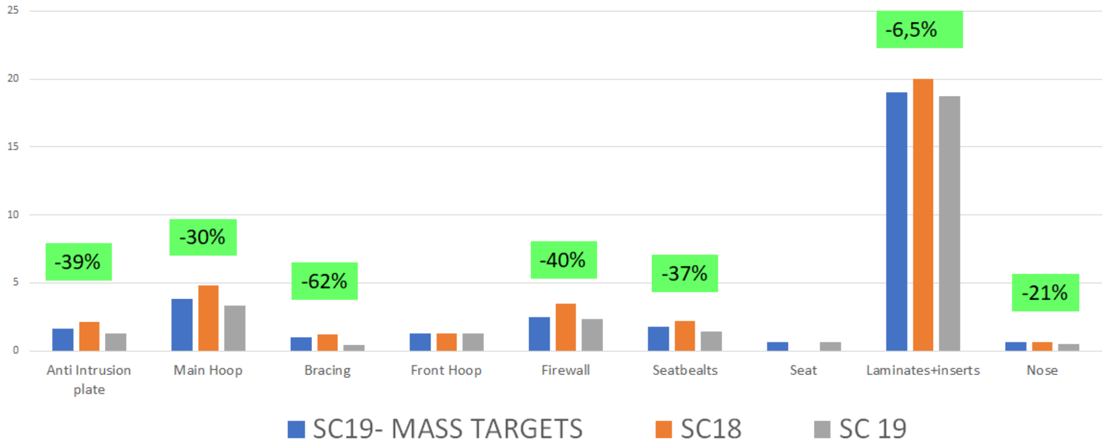


Figure 64. *Weight reduction: final results.*

The actual weight of the monocoque was 19.96 kg, considering also inserts and front hoop. This means that 1.3 kg was saved with respect the previous year. But considering that in the new monocoque it is as if part of the bracing are integrated to it, if we consider the weight of laminates, inserts, front hoop and also bracing the difference between SC18 and SC19 monocoque weight is equal to 2.05 kg.

4.5 Torsional stiffness

FEM Model

The resistance to torsional deformation is generally thought, with the weight, to be the primary determinant of frame performance for a FSAE racecar: low chassis torsional stiffness leads to a modified kinematics of suspensions, due to the displacements of their attachments points, affects the distribution of lateral load transfer, resulting on unwanted vehicle dynamic behaviour.

This chapter presents the monocoque finite element model, that constituted an efficient tool during laminates design and at the end as evaluation of the chassis torsional stiffness. How the monocoque was meshed and defined in the Hypermesh model has been already explained at the beginning of the chapter, so only the load and constrain conditions will be described.

The first setup of the model, was not representing a real torsion condition of the monocoque, but was made for the purpose of evaluating the most critical sections of the monocoque due to a torsion load applied on it. So in this case a sort of "inspection moment" was applied, since we were interested to only the qualitative distribution of the stresses. So the condition tested was a monocoque made by a uniform laminate (regardless of its configuration that was 0/45/0/ 20mm honeycomb Al 3.1pcf/0/45/0), clamped at the rear by an SPC on all the nodes of the section in correspondence of the front points of the rear suspension, and applying a moment of 1000Nmm by rigid members to all the monocoque nodes of the section correspondent to the front points of the front suspensions (linear static analysis). The results are showed below, remember that this simulation has been made only to qualitative purpose.

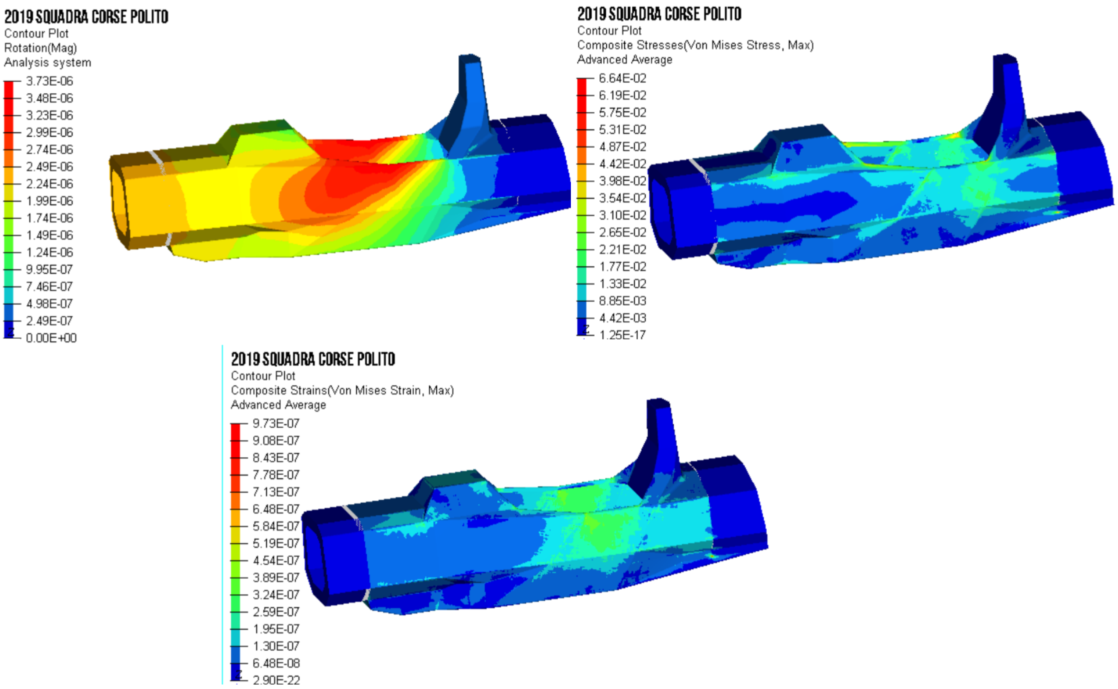


Figure 65. *Preliminary torsional analysis: evaluation of the most stressed sections.*

As we expected, the most stressed areas were that near to the cockpit opening; also the side panels can be considered critical areas with respect the other one. We made a big error by "searching" the most stressed areas in this way, since the most involved areas in actual torsion of the monocoque, so that on which suspensions are attached, mainly that panel where lies the rocker, are different from this foregone result.

Since it is not a small effort create a complete model of monocoque and suspension also, during the design phase this "qualitative" model was used to compare all laminate configurations: basically in order to chose a laminate considering its contribution to the monocoque torsional stiffness, two simulation varying only that laminate was performed and then compared so that the differences in weight and the stiffness contribution can be evaluated and a trade-off can be found. Obviously all these simulations was firstly made with the SC18 laminate configuration in order to have a term of comparison and values to be improved.

During the monocoque design a model to obtain meaningful values of chassis stiffness had been studied. Firstly the need was to consider how to load and constrain the frame for an accurate analysis. We decide to study the stiffness of the monocoque by loading and constraining it in the most easier way, without evaluating actual load case but create a model that can be also validate in future. So the load as been put in as vertical load to one of the front wheel, and the other wheels have been constrained

in such a way that the whole structure was minimally constrained. Once having defined the load and constraining conditions, the real problem was to model the entire suspensions system.
The idea of adding to the model all the suspension components as solid meshed elements was immediately abandoned both for computing power required, since to have good results the mesh of the elements have to be done very carefully with element dimensions at least one order of magnitude lower that that of the monocoque. Another reason what the connection between all of them can be difficult to model, for example using contact freeze to model the fixing of suspension brackets to the monocoque is not properly correct, since in case of load the two undergo to different deformation and so the node cannot be freezed together. So avoiding to create a model that require days to give not reliable results, the suspension system was simplified by using 1D elements for the majority of its components.
There are many types of elements possible for representing suspensions and every choice makes can affect the results. So the real problem of this FE analysis was how to model the various suspension components. By analysing the nature of how the a-arms and pull-links work, they transmit tensile and compressive forces but no bending. So these are modeled in Hypermesh as 1D rod element members.
tubes and engine mounts discussed earlier.
The hardest modeling considerations were the rockers and their connections to the monocoque (same as for the A-arms brackets); so the rockers were imported as solid in the model (so the related property was a PSOLID card in which the properties of material, M46J, same carbon fiber used for the monocoque are defined by a MAT1 card). The SC19 rocker is showed below. Rigid elements have been created at the bearings connection with the push rods and a RBE3 was made on its base both to model ist joint and bracket. The locked DOFs of the dependents nodes were 1,2,3,5,6, since a rocker resists translating in all three directions, and resists rotation in two directions.

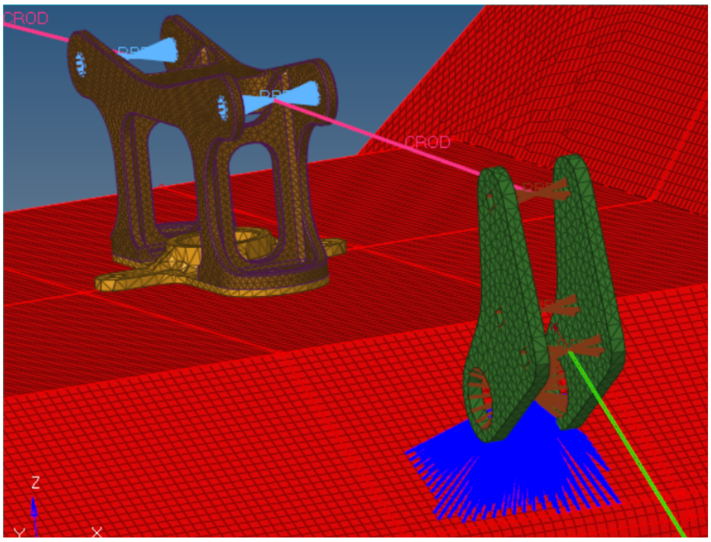


Figure 66. *Rocker modeling.*

From this picture it can bee seen also a rod element in substitution to the air spring and damper, that for the purpose of evaluating the torsional stiffness of the monocoque, and not of the suspensions must be removed since at least one order of magnitude less stiffer.

A different method was used to simplify the uprights. Since we had no idea if and how they can be modeled as 1D elements, we perform a simulation in which the four upright were present. The need of simplify the model comes from the fact that, for example, this simulation took about 8 hours on a laptop with a good processor. The torsional stiffness of the system was evaluated and then other simulations were performed in order to find the element that represent an upright at best. At the end of these comparisons the element with which we substituted the solid upright was a 1D-bar element.

The model il here reported, the load applied was 10N, in order to remain on the field of small displacements end evaluating the stiffness as:

$$K_T = \frac{F \times t}{arctan(\frac{z}{t})}$$

. where:

F is the load applied;

t is the front track;

z is the displacement at the wheel center, on which load is applied.

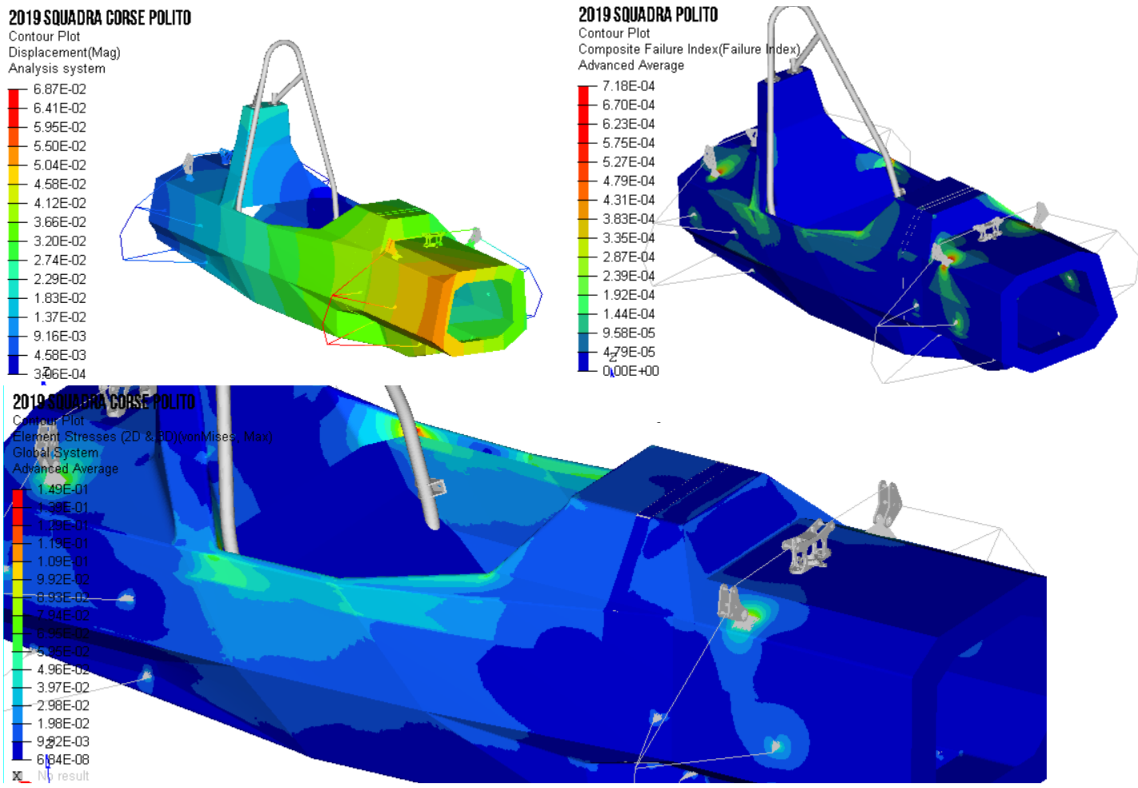


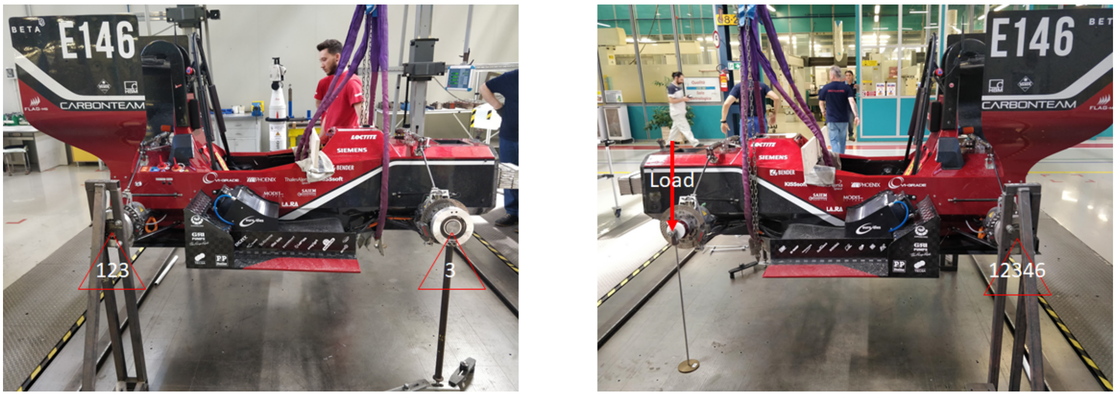
Figure 67. *Torsional stiffness results.*

So the result coming from this model was 209606 Nm/rad, that is 14% higher than the SC18 value, and also higher than the 2019 target of 204 kNm/rad (equal to 3 times the suspensions roll rate).

A kind of validation has been made, but both the model than the validation test have to be improved in next year.

Full monocoque torsion test

The torsional test of the SC19 monocoque was performed, in order to evaluate the actual stiffness of the monocoque, to try to validate the FE model, and also obtain an higher score on Engineering Design Event.
This test was not performed on a torsion test bench due to budget problem, but we made it on our workshop. The structure was placed on a calibrated bench and displacements measured with a three-dimensional measuring machine. This structure was designed to constraint the monocoque almost in the same way. In the actual case more degrees of freedom were constrained, due to the fact that we werw not able to lock the two translations 2,3 with a structure as in the model. So thanks to bearing and beams we create the wheel hub supports. The load was applied by adding weights, trying to avoid oscillation of the rod supporting these disks. Below pictures about the constraining structure and load application are reported. The FASCE servono soltanto a sostenere la macchina in caso di cedimento della struttura, si vede infatti nella foto che non sono in tensione.



Graphic 6. *Torsional stiffness test.*

Figure 68. *Three-dimension measuring machine was used to measure displacements.*

The loading cycle was performed starting from 0 kg and adding one weight each time, up to 600N and then the same was done to remove them. Each step the displacement of the point of application of the load was measured, and also that of the constrained on the other side in order to take into account of the compliance of the structure.

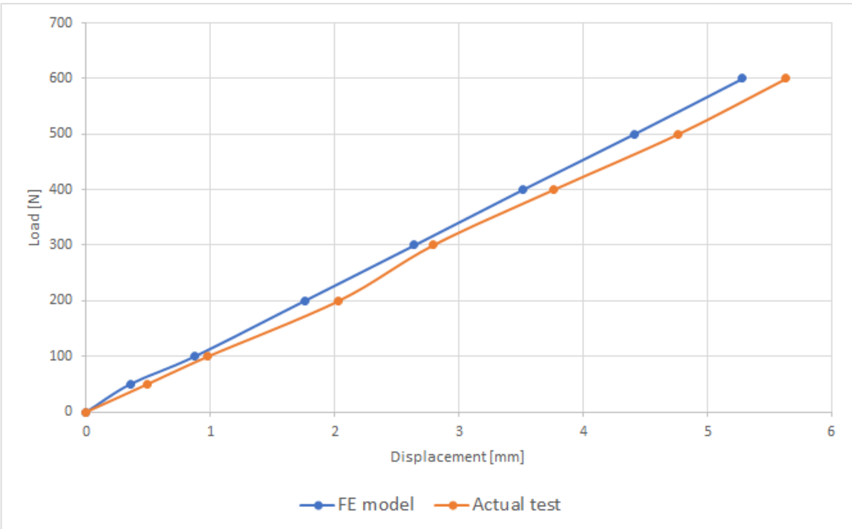
Load [N]	**Displacement along Z [mm]**	
	Application point	**Constrained point**
0	0	0
50	0.49	0
100	0.98	0
200	2.13	0.1
300	2.89	0.1
400	3.96	0.2
500	4.96	0.2
600	5.93	0.3
500	5.13	0.2
400	4.23	0.2
300	2.95	0.2
200	2.24	0.1
100	1.12	0.1
50	0.51	0.1

Table 15. *Test results.*

The same both for loads and constrains was simulated using the model of the monocoque with the suspensions as described before and the has resulted as follows.

Load [N]	Displacement along Z
	Application point
0	0
50	0.39
100	0.79
200	1.59
300	2.39
400	3.18
500	3.99
600	4.78

Table 16. *FEM model results.*



Graphic 7. *Comparison between results.*

Chapter 5

Manufacturing processes

For the season 2012/2013 Squadra Corse designed for the first time a carbon fiber monocoque. Composite frames were designed for all the subsequent vehicles, improving the knowledge about both the design and the production process. Sharing the know how year by year had lead to great improvement on monocoque performance such as weight and torsional stiffness reached but also to a complete independence also as regards the production process. In fact this year for the first we produced the monocoque in total independence starting from the design and processing of the molds up to the lamination of the body itself and the necessary post-processing procedures to prepare it for the painting. In the next pages after giving some information about the hand-layup process, I will describe what we have done to produce our monocoque.

5.1 General overview on hand-layup process

The manufacturing process known as "hand layup" involves manually laying down individual layers or "plies". These plies can be "dry" or "wet".
A dry carbon fiber sheet is laid over the part or mold and resin is applied by hand. The resin provides the stiffness for the dry sheet, and it is the bonding agent for a carbon fiber wrap. With this process, resin mixing, laminate resin content and laminate quality are very dependent on the skills of laminators. Low resin content laminates cannot usually be achieved without the incorporation of excessive quantity of voids. Without going too much deep on details, the most positive aspect of this technique is the low cost tooling if room-temperature cure resins are used but due to the fact that resins need to be low in viscosity to be workable by hand, their mechanical properties are compromised due to the need for high diluent or styrene levels.
"Wet" carbon fiber ply is known as "prepreg". This consists of thousands of fibers, which are pre-impregnated with resin and bundled into tows and arranged either in a single unidirectional ply or woven together.The pre-impregnated roll is frozen by the vendor prior to delivery to prevent the resin

from curing. Pre-preg provides much better penetration of the resin and more uniform resin thickness than the wet lay-up process. So resin content in the fiber is accurately set by the materials manufacturer and high fibre contents can be safely achieved with low void contents. The extended working times permits that structurally optimised, complex lay-ups can readily achieved. Materials cost is obviously higher also because of the expensive advanced resins that are often required for these applications.

The layup process involves manipulating each ply into shape by hand and then firmly stuck to the previous layer or mold surface leaving no air pocket between plies. Different techniques can be followed by the laminators in order to achieve the required shapes but it was not considered relevant to report them in this document.

This process can produce high-quality complex features, has relatively low start-up costs, and is highly adaptable to new parts and design changes. However, it is far from perfect, as production rates can be low and the costs of both materials and labor are sometimes high. As with other manual processes, there is also potential for discrepancies between parts caused by human variation. Despite these disadvantages, the adaptability and quality provided by hand layup means it remains a key part of the composite industry, providing the main manufacturing method for many manufacturing facilities. The fiber is thawed at the lay-up site and hand laid over the part or mold. Typically, it is then vacuum compacted and baked in an autoclave at 120 to 180° C for a prescribed amount of time that depends on the used resin.

5.2 SC19: completely designed and produced by us

As said in the introduction of the chapter, this year the monocoque was entirely produced by our own. In this section I will describe the process trying to be as detailed as possible.

Once the design has been completed, as soon as it was possible, we started with the production of the monocoque's molds, since it's fundamental having the monocoque ready as soon as possible whereas all the other assemblies must be fitted and fixed to it.

Blocks of epoxy resin RAKU-TOOL were used to realize two male molds of the monocoque, one for the upper part and one for the lower. Firstly the blocks were glued together to create a single block of blank that was CNC milled using a CATIA drawing of the monocoque. Then the milled model was sanded and coated firstly with three layer of Chem-Trend®'s mold coating, designed to help seal the mold and fill in imperfections to improve its surface quality, which results in better release of the part, and then 3 layers of Chemlease®'s mold primer to help improve process efficiency and part quality by enhancing the mold surface. The surface finishing of the molds is not a process to overlook, since it take very long time to be concluded both for the precision in which the surface must be sanded but also for the time that must be waited between the application of the different layers of of coating products. Next a wooden divider panel was made to match the upper and lower centerline of the monocoque.

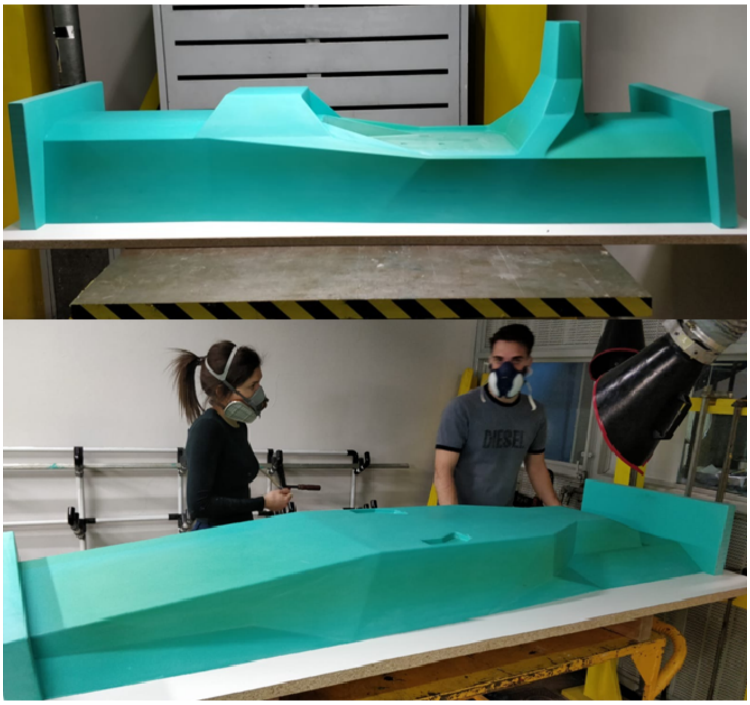


Figure 69. *Upper and lower resin molds of the monocoque.*

Using this divider to create a flange area, two female carbon fiber mold halves were laid up and cured. As first two layers T200 carbon fiber was used (twill, 200g/m ^{2}) since the mold cavity will determine the surface quality of the monocoque. A pre-compression in vacuum bag was performed in order to have more adherence between plies and resin mold. Then other 10 layers of carbon fibers were added the autoclave cycle used lasted 12 h, at 70°C and 5 bar. Also a post-curing process was performed (1h 40 min at 130 °C).

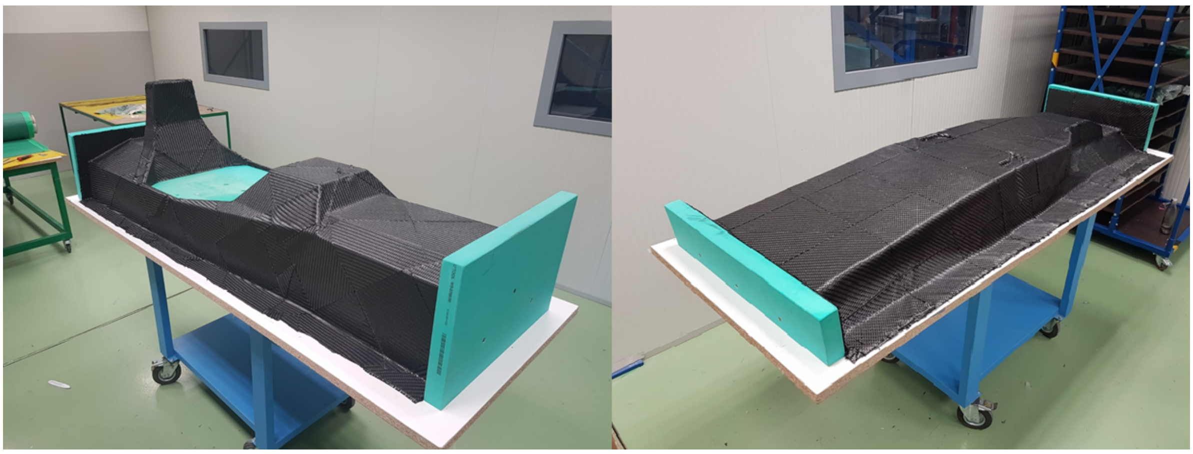


Figure 70. *Female carbon fiber laid up molds.*

Figure 71. *Left: vacuum bag preparation. Right: coupled cured molds.*

So these female molds had a wide flange with several holes for easy assembly and disassembly and from the picture above on the right we can see the perfect coupling reached. Then they were also drilled using a CATIA model of all the holes needed in correspondence of the inserts for hosting their teflon centering pins. Also in this case surface finishing processed were performed as said before for the resin molds.

Before starting the layup process of the monocoque, Laminate Tools software was used to create ply-books. Laminate Tools is a powerful application focused on the composite material features. Importing surface models from CAD system, we had created our model by defining composite materials, plies and layup of the whole monocoque. Ply producibility can be evaluated immediately using proven draping simulation algorithms to identify potential manufacturing difficulties, meaning fewer change orders downstream. Finally flat patterns (considering the proper over-sizing of the plies) for the laser cutting of the plies and ply-books for the manufacturing process were been produced in order to ensure a more correct and efficient procedure.

The layup process was completed in three separate steps; outer skin layup and inserts positioning, core insertion and finally inner skin layup. The description of the laminates of the monocoque is missed since already explained in the previous chapters. After having positioned the teflon pins, some layers of plies laid up yet on the two separated molds, pre-compression in vacuum bag was performed for both the molds, in order to improve the adherence of the plies to the shape of the molds and release air bubbles absorbed during the manufacturing of the laminate. Mechanical properties of the composite are strictly dependant on inter laminar adhesion. After that the two halves of the monocoque have been laid up together using plies overlap between the two. Once all the plies were laid up, inserts were added and in correspondence of them, rectangular reinforcements patches are applied. Moreover all around their surfaces structural adhesive (REDUX 312UL)and carbon fiber strips were putted. The result of the outer skin after the curing cycle (1.40 h, 130°C 3 bar) is reported in the right picture below.

Figure 72. *Left: lay up on the first layers on the two halves; note the presence of pins used for the positioning of the inserts. Right: outer skin cured with inserts.*

The core positioning is a not trivial procedure also due to the number of different core materials used and the difficulty to bend them in order to reach the correct position inside the molds. Theirs shape was previously water-cut using the Laminate Tools flat pattern in order to improve fitting precision. Their sides were glued to the internal and external skins with the same structural adhesive used for inserts. In gaps coming out between different core panels or between inserts and the around honeycomb material a foaming splice adhesive was put. After the core positioning, inner skin was laid up on them, following the order of the ply book, that was reverse with respect the process for the outer skin: as first small patches and ply panels are laid up and as last layers the global, bigger one. In order to avoid the collapse of core materials, the second curing cycle was done at maximum of 1 bar. After the body was released from the mold, defects were covered with carbon putty and then all the surface were sanded to be prepared for the painting process that was not performed by us.

Figure 73. *Left: cores positioning on the outer monocoque cured skin. Right: post processing of the manufactured monocoque.*

Chapter 6

Results and conclusions

In this conclusive chapter, I want to make a final overview on the level reached by the team with this year's vehicle. Therefore it will be discovered if the target set before starting the SC19 design, not only in terms of vehicle weight, has been reached; how is the level of the weight improvement of the monocoque compared to one of the competitors, and finally will be made a quick summary of the results obtained on the competitions we have taken part.

Once the car has been assembled and weighed the result was well beyond the initial target: we designed and built a vehicle by weight of 183kg, 20kg lower of that of the SC18.
Having reached a weight 10kg lower than the average top vehicles weight, although our weight targets have been fully achieved for all the components, we are still far from being among the lightest vehicles in the competitions. To the purpose of showing the nature of the still present, but lower, weight gap, a comparison between the weights of assemblies, and not only of the overall vehicle weight, is reported, considering the weight of the SC19 components and that of a top team vehicle. There was therefore the need to consider a top vehicle with similar setting to that of the SC19, so our research was directed to the AMZ racing vehicle, the first team in the world ranking, having features similar to that of the SC19 such as for example 4 in-wheel motors and CFRP monocoque.
Look to the results below.

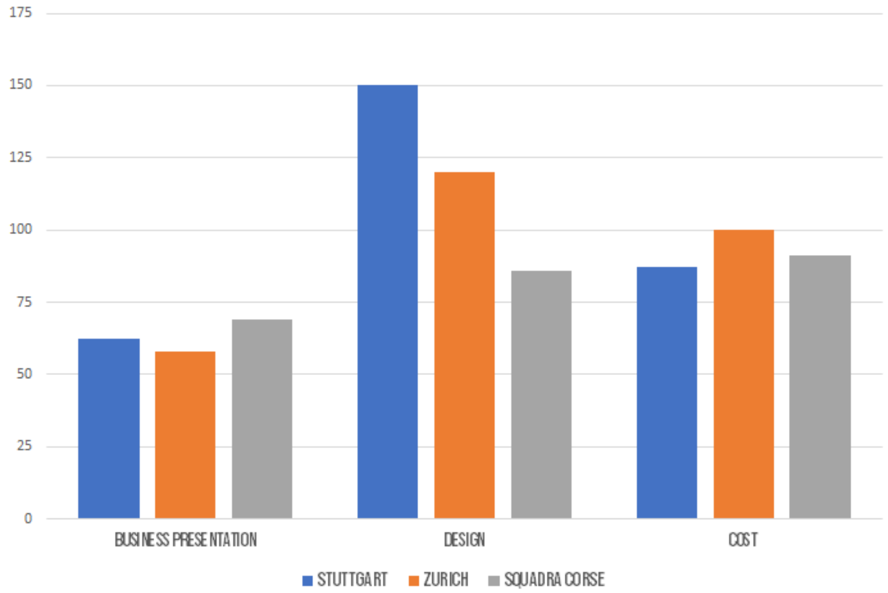
	SC19[kg]	**AMZ [kg]**	**Difference [kg]**
Battery pack	39	35.6	+3.4
Monocoque	20	22.3	-2.3
Powertrain	21.8	16.7	+5.1
Uprights	3.4	2.4	+1
Wheel rims	14.8	8	+6.8
		Tot	+14
Overall vehicle weigth	183	166	+17

Table 17. *Weight benchmarking: SC19 vs. AMZ.*

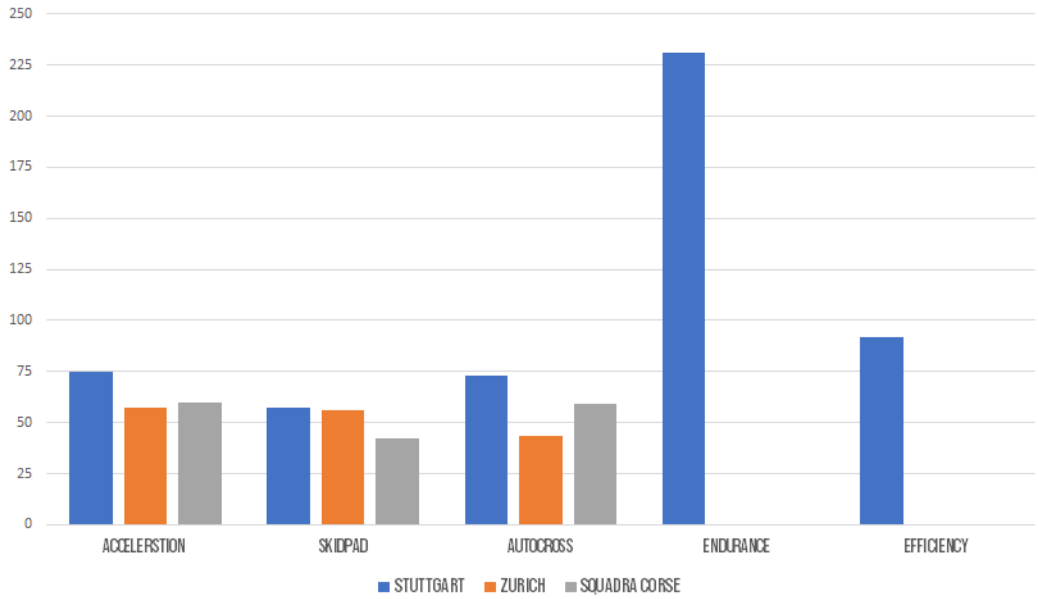
In the penultimate line of the table, the difference in weight between the above listed components or assemblies of the two vehicle is shown, while the last one indicates the total vehicle weights and therefore the difference between them. It can be noted that the overall difference of 17 kg has been almost totally identified and comes from the listed components (less than 3 kg due to data not found).
Considering the battery pack weight gap, it must be said that the technology used and so level of innovation is the same, but due to lower nominal voltage needed (400V sv 518V) the number of cells per series is lower so the weight is lower.
Considering 5 kg of the actual gap, the nature is that AMZ uses completely custom inverter and motors powertrain with respect the AMK set purchased by SC, due to lack of technology, develop time and know how to design a custom electric motor. Concerning inverter, instead, in a very near future there is the possibility that a custom one will be used.
The same applies to the wheel rims, considering the commercial magnesium rims of the SC19 with respect the AMZ CF custom one, causing a higher weight of about 7kg. Since many years, AMZ uses and develops these rims, having reached higher level of reliability, that is the real problem and gap between the teams that already have custom rims and us, since the technology and development could be within the reach of Squadra Corse. The objective is to develop CF in next years.
Considering the monocoque, instead, we are very pleased to note that we got a lower weight compared to that of the monocoque of this top level vehicle.
So, as said also in chapter 1, our limitation in weight reduction is that related to the powertrain and the impossibility, at least at the moment, to develop a custom one with a lower weight. Instead, as far as the wheel rims is concerned, it is necessary to start development and fill that gap between competitors.
Concluding, compared to the strongest team in the world, we can therefore consider these to be excellent results.

In the same way in which in chapter 1 has been said that the score analysis made on the results of the previous year was used to set targets to the SC19 project, now scores and placements obtained in competitions will be used to know if the SC19 vehicle, project and team were be improved.
The competitions we took part this year were three: Formula ATA played at the Riccardo Paletti racetrack, at Varano de' Melegari, Formula Student Czech Republic in Most and Formula Student Spain in Circuit de Catalunya in Montmelò.
The season started in the best way, getting a first place (third in 2018) in the home race in Varano and, moreover, obtaining the Engineering Design finals, that had never happened in the Squadra Corse story, ranking in second place as well as in the Cost Event. This race was won thanks to the endurance, the first endurance of the SC19, played from the first to the 22nd lap under the rain, which stopped the Tallin team but not the SC19.
Same placements concerning Cost and Design events were reached in Most, where a problem on the

control strategy during the endurance has stopped the SC19 immediately after the starting line, thus making us slip from head to head battle for the first place, to a not poor sixth place.
The season ended with the Spanish race, where again the endurance was not concluded but excellent results were obtained in the other tests. As in chapter 1, it will be reported the scoring of SC compared to that of the same two top teams.



Graphic 8. *FSS 2019 static events scoring.*



Graphic 9. *FSS 2019 dynamic events scoring.*

In general the team has shown a great growth in the preparation of the static events, in which in Spain it has obtained 245.9 points compared to the 216.2 obtained the previous year. The same cannot be said for what concerns the dynamic one, as the endurance test has not been concluded twice, demonstrating a poor reliability and management of the vehicle, which has been completed too late penalizing the testing phase, required to debug it. However, if the endurance scoring is not considered, the results obtained in the other three dynamic tests remain higher of 15 points with respect that of SC18, showing that a good job has been done by the whole team.

At the end of my experience in Squadra Corse, I am satisfied and proud to have been part of this team and have contributed to the realization of the SC19, a vehicle that still has ample room for improvement, but that has led the Politecnico to be considered an equal competitor of the best universities in Europe.
I want to make a huge good luck to the SC20 team, that I'm sure will do a great job.

Bibliography

[1] M. Elkington, D. Bloom, C. Ward, A. Chatzimichali and K. Potter, *Hand layup: understanding the manual process*, 2015, Published by Taylor & Francis.

[2] No authors, *Formula Student Rules 2019*, 2015, V 1.

[3] L. Hamilton, P. Joyce, C. Forero, M. McDonaldn, *Production of a Composite Monocoque Frame for a Formula SAE Racecar*, 2013, SAE International.

[4] W. B. Riley, A. R. George, *Design, Analysis and Testing of a Formula SAE Car Chassis*, 2002, SAE International.

[5] M. Costin, D. Phipps, *Racing and Sports Car Chassis Design*, 1974, Batsford.

[6] A. Deakin, D. Crolla, J. P. Ramirez, R. Hanley, *The Effect of Chassis Stiffness on Race Car Handling Balance*, 200, SAE International.

[7] A. Ahmad, S. A. Zaheen, I. Ahmad, F. Talib, *Cockpit Design of a Formula Student Race Car: An Ergonomics study for the Cockpit*, 2017, ResearchGate pubblications.

[8] A. Messana, L. Sisca, A. Ferraris, A. G. Airale, H. d. C. Pinheiro, P. Sanfilippo, M. Carello, *From Design to Manufacture of a Carbon Fiber Monocoque for a Three-Wheeler Vehicle Prototype*, 2019, MDPI Materials publication.

[9] *Guide to composite*, www.gurit.coom.

[10] W. F. Milliken, D. L. Milliken, *Race car vehicle dynamics*, 1995, SAE International.

Acknowledgements

Coming to the conclusion of this work, and of this year in Squadra Corse, I would like to acknowledge Prof. Tonoli, who gave me primarily the chance to be part of a team like this, where there is a lot to learn and that provides to actively participate in a world as fascinating as that of motorsport; then for giving me the opportunity to write my thesis on the project to which I worked so much and I dedicated time and passion throughout the year. I would like also to thank those who have been taught me, in particular thanks to Edoardo and Pier especially for the things learned in the workshop, and to my designer colleagues Simone and Antonio, and congratulate them for the excellent work we have done together.

Having been this not the only experience of these university years for me within a student team, I also want to thank Prof. Massimiliana Carello and Team H2politO for giving me the opportunity to both study the strategy and race on track with a winning prototype.

These five years I can't say they were easy, so I really want to thank all the people who helped me, supported me, and were present starting from my course mates, in particular Umberto, Alberto and Valentina, all the guys of Squadra Corse and H2politO; my "Latte" girls and Victoria, that despite my frequent absence, are still there. I want to thank Francesca, who was both a roommate and an hostess excellent. During these years I also known people that I hope I will not lose since this cycle of my life is about to end, "Meritevoli" I'm talking about you.

I wish to express my sincere thanks to my family without which support I could not have done any of this, and in particular to my grandfather Evasio, who is the person who was most interested in my university career, who always spurred me on, showing me to be proud.

In conclusion I want to dedicate a thought to the best person I know, that I have the fortune to have next, that has always supported me and from which I never tired of learning, every day... thank you Dieghi!