POLITECNICO DI TORINO

Master's Degree in Automotive Engineering

Master's Degree Thesis

Design of a carbon fiber monocoque for high performance car

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Table of Contents

List of Tables

List of Figures

Summary

The 004C from Scuderia Cameron Glickenhaus is the only vehicle in the GT class to be based on a carbon fiber monocoque. This vehicle has been designed to comply with the GT3 regulations that is a category of vehicles derived from road legal versions. The car is created to compete in the most iconic endurance races, like the 24 hours of Nürburgring, requiring a high level of engineering technique and experience. The monocoque together with the roll-cage are responsible for the safety and the dynamic performance of the vehicle, giving their contribution to the overall torsional stiffness. This document will go through the design flow used to design the carbon fiber monocoque explaining the complex mix between costs, weight and performance targets along with regulations and safety constraints. All the information explained in the following pages has been gathered directly from the same study made to develop and produce the real vehicle. Deriving from a three seaters road legal car, with the central driving position, and starting from a blank page, the evaluation of the shape and internal components layout has been performed preliminary. Using structural analysis based on the toughest load cases taken from the previous years track activity, the best layup has been selected between different combinations of carbon fiber plies and core materials. This has been correlated with the design of every single structural attachment insert ensuring the desired strength and stiffness. After that the attention will be focused on the FEM analysis performed for the homologation requirements, from front impact crash test, passing through the safety cage verification up to the lateral crash. In fact, being the 004 project a very exotic and limited batch size production car,the safety of the vehicle is evaluated, in the first stage, only on virtual tests, that had

a very strong correlation with reality. The proof of this interrelationship will be verified accordingly to the US homologation physical tests, performed just before the start of production of the road legal car. The aim of the last part is to describe the manufacturing and assembly phases, which despite all are one of the most important processes that guarantee the success of a project. As a final remark it is important to underline that the entire process from design to track operations has been managed by an Italian company, Podium Engineering, where I'm directly involved.

Here the contents of different chapter in detail:

Chapter 1

The attention is focused on the project in general, starting from what is the Scuderia Cameron Glickenaus, passing through the passion for the races up to the 004C, the last machinery for the Nürburgring.

Chapter 2

The attention is moved on what is needed for competing in a high performance championship, explaining the homologation and safety requirements and which are the guidelines used to design a Green Hell successful car.

Chapter 3

Taking into account the chassis design, the attention is reserved, in particular, to the carbon fiber monocoque. This is a very complex engineering component, because needs to respect safety constraints, habitability and ergonomic requirements and dynamic targets. The chapter will focus in particular on all the design concepts behind the vehicle, adopted to meet all the design and cost constraints

Chapter 4

All the designed components need several verification, in order guarantee the successful behaviour during the normal usage. The finite elements analysis is a required tool that allow a validation process before the production. There will be give a description of the simulations done on all the structural components, allowing to respect homologation, safety and performance targets.

Chapter 5

Being made up by several different parts, before the final assembly, the chassis must be checked, in order to be sure to have a final product that meets the project targets. All the measurements made and assembly processes used to complete the chassis will be described in this chapter.

Acronyms

SCG
: Scudera Cameron Glickenhaus

CFRP
: Carbon Fiber Reinforced Polymer

NLS
: Nürburgring Langstrecken Serie

CFD
: Computational Fluid Dynamics

FIA
: Fédération Internationale de l'Automobile

HIC
: Head Injury Criterion

MDB
: Moving Deformable Barrier

FEA
: Finite Element Analysis

GSM
: Gram square meter

DMSB
: Deutscher Motor Sport Bund e.V.

Chapter 1

The project

1.1 The idea behind the vehicle

The 004 vehicle, is the third vehicle of the Scuderia Cameron Glickhenhaus, a small American company that competes in the most famous endurance races against multinational big manufacturers. This is the basic idea behind all James Glickhenaus cars. The journey has started some years ago with the Ferrari P4/5 competizione, that complete in the 2012 the 24h of Nürburgring using an hybrid powertrain. Some years later in 2015 the same venture has been faced with the newer prototype the SCG 003C. This car, passing through different upgrades and performance improvements in the years, has ended his career in 2019 with a ninth place overall in the Nordschleife endurance race. All what learned in these 8 years of racing, has been used as starting point for the last machinery of the Scuderia Cameron Glickjenhaus: the 004C. The new car has a simple principle: a three seater sport car, designed to be road legal, but having clear in mind to race in most iconic endurance races, just like the 24h of Nürburgring. All the project, from the design and manufacture up to the racing management is followed by an Italian company: Podium Engineering, based in the north of Italy. Thanks to the experience achieved in the last 8 years racing in the Green Hell, the 004C is design to be a very easy to drive car keeping in mind to be accessible to a large customer audience reducing the selling price and giving the possibility to chose between 5 different versions, 2 road legal and 3 track dedicated.

Speaking about the road versions, it is possible to chose between two types:

- 004S
- 004CS

In the first name, the "S" means "stradale", that is for what has been designed, from the bodywork and cockpit features up to the suspensions and wheels. As is possible to understand is the standard version, powered by a V8 supercharged engine with 650 HP and with a 6 speed manual gearbox. This is assembled just behind the engine that has been installed in middle position. In the second name of the list, the "CS" means "Corsa-Strada", giving immediately the idea of what is the purpose behind the car. The aerodynamic has been revised increasing the load on the front, with the wheel louvres and with the blown rear diffuser. The cockpit has been made more race addicted, with the introduction of race digital cockpit, 5 point seat belts and more sporty racing seat. As optional can be ordered the race air-jack lifting system, while the wheels with the quick center-lock are included. This version is powered by a V8 supercharged engine with 850 HP with automatic transmission and steering wheel paddle shift. The 004 has a very singular solution: the driver seat is in the middle of the car, with two passenger seats on the side, slightly behind. The choice has been made to leave enough space for the two passengers, that in this position could stay seated comfortably with straight legs.

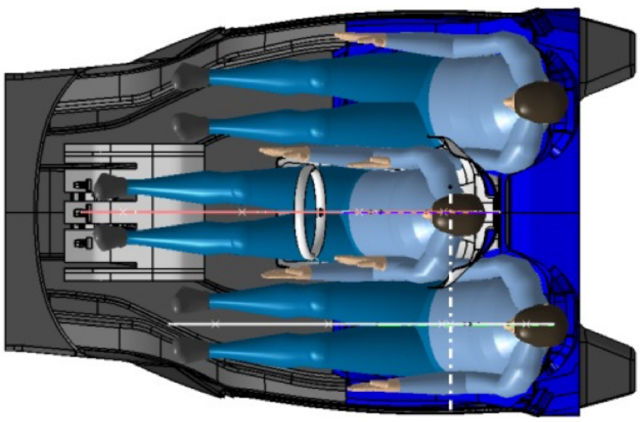

Figure 1.1: Occupants position

Another peculiar solution of the car are the doors. In fact, they have been designed to open vertically, with only one central hinge. On the road car they are completely automatic in opening and closing, thanks to an hydraulic piston, while on the race car there is only a gas spring helping in opening.

Figure 1.2: The 004S presentation at the Nürburgring

As already said, the 004C version is developed starting from the road one, from which has taken the overall vehicle settings. The carbon fiber monocoque and the cockpit dimension are the same, while the rear steel chassis has been revised to increase stiffness. Also the suspension geometry and wheel hub has been redesigned, in order to save weight and improve the dynamic performances. Also in this version, the driver position has been kept in the central place, while the passenger seats has been replaced by the racing fuel tank, that can store up to 120 litres of fuel. The external bodywork has been made always by carbon fiber, but upgraded in the front splitter and rear diffuser; the desired down-force has been reached thank to added 3D printed aerodynamic components and to a big rear wing, allowing to transfer the correct amount of torque to the ground. All the parts of the car have been designed allowing a quick disassemble procedures, that are fundamental in endurance races. All the aerodynamic devices and shapes are developed by an incredible number of CFD simulations. The driving idea was to reduce the drag of the vehicle, by keeping a considerable value of down-force. At 250 km/h the 004C can generate 450 kg of vertical load. The skeleton is a mix of modern and classical engineering: the driver compartment is made by a carbon fiber monocoque, while the rear frame and the front crash structure are made by classical aluminum and high strength steel. Speaking about the former, all is made by aluminum, fixed by screws, welding and rivets. The rear chassis, on the other hand, is made by high strength steel tubes of different dimensions and with a large number of gussets to meet the torsional stiffness required. All these aspects have been decided in parallels with continuous FEA analysis, that define the right direction to keep. In this document, the attention will be focused on the carbon fiber monocoque, explain the major design principle behind her creation.

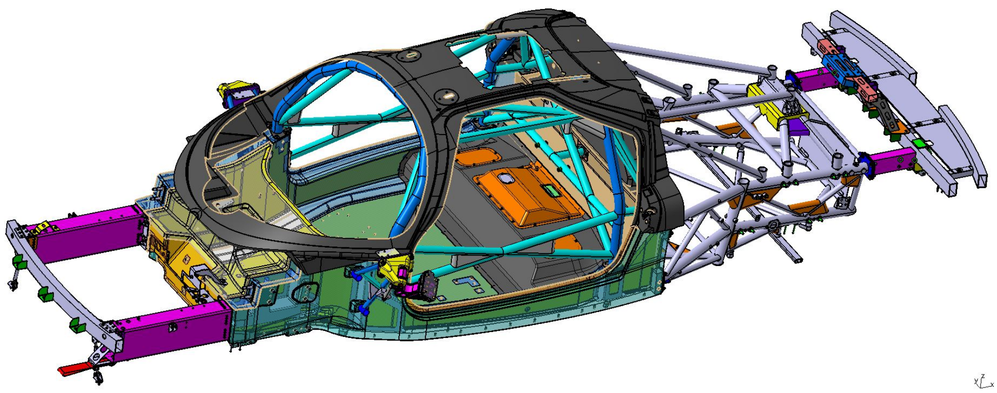

Figure 1.3: Complete chassis of the 004C

Also the 004C is presented in different configurations and price, depending on how the customers want to use it. Starting from the entry level that is a track day car with a fully carbon fiber look, lower performance brakes and simpler dampers and without all the stuff needed of an endurance race, as radio, live telemetry and corner lights. The other version is a sprint race version, with upgraded brakes and dampers and with the radio inside the cockpit. The most performance one, is the endurance spec. 004C. It has fully adjustable front and rear anti-roll bar, endurance oriented brakes, magnesium gearbox case and front corners lights. Inside the cockpit the dashboard is upgraded with a 10 inch screen, with a remotely sliding pedal-box, drink system, radio , data acquisition and telemetry system. Around the car any fluid pipe connection is made with quick disconnect components, in order to save time during pit-stop or after a crash. The car is proposed together with a wrapping of the preferred color.

Figure 1.4: The 004C during the 24h of Nürburgring

1.2 Racing category

The SCG 004C has been designed following the FIA GT3 rules and running under BOP restrictions. The basic requirement to be part of this category is to sell a minimum of 10 car within 12 months from the homologation date and 20 units within the following 24 months. Being brand new project and being in the prototype testing phase of the road car, the already presented 004S, the race version will run for the next years under the SPX category. This is reserved for the special vehicle that didn't get the FIA homologations. Respecting all the rules and having chassis and powertrain able to compete with the SP9 FIA GT3 class, the 004C is subjected to the same balance of performance limitations. In fact the BOP restrictions allow to balance the performances of the car, making the competition more challenging. The changes consist in increasing the car weight and reduce the engine power, allowing a well balanced starting grid. The opponents are well developed cars, that reach the top performance level in year. For example, on the starting grid there are more than 35 cars as Audi R8 LMS GT3, Mercedes-AMG GT3, Ferrari 488 GT3, Porsche 991.2 GT3R and Lamborghini Huracán GT3 Evo. As anticipated in the previous section, the target that has been taken in account during the designing phase was to race against the top teams in one of the most famous endurance race in the world : the 24 hours of the Nürburgring. Probably starting from 2021 due to regulation changes, being the car developed following the FIA GT3 rules, it could be possible not only to compete in that class, but also in all the new ones based on GT regulations. Today the new DTM, WEC and IMSA could find a meeting point creating a derived GT3 class, the GT Pro. For the SCG 004C could be very easy to respect these new rules, made possible by little tuning on the engine that can easily reach up 650 HP or with some aerodynamic adjustments to meet the requests of every organizations. Waiting for some more precise details, the current competition that the car can take part are the NLS and the 24 hours races. In fact, this is only the most important event of a more large racing season, the NLS, composed by 8 races of 4 and 6 hours, used to define the participants of famous final longer endurance race. The track is one of the most complete in the world, the iconic Nordschleife, 25 kilometers around the Nurburg Castle. The circuit is very complicated, combining a low speed part in the GP track, passing through the high speed cornering section in the middle part of the Nordschleife and arriving the long straight the Döttinger Höhe, just before the finish line. Due to this very complex and variable racing ground combined with the length of the races, the vehicle and all the parts must be designed taking in account above all the reliability beside the performance.

As usual the 24 hours race is held between Saturday and Sunday, but the race week starts early. In fact, free practice sessions are made during the previous days, testing the car in light condition, but also during the nights. After the free practices, two qualifying sessions are taken, always in the two possible light conditions. The best 30 cars, will take part to the TOP 30 qualifying, were the best cars give battle each others to catch the first place on the starting grid. Then basing on these results, at 15:00 of Saturday, the race starts, continuing without interruptions up to Sunday at the same time. Due to the high competitiveness of the SP9/SPX class, the requirements to obtain a good result are to not only to have a fast car,

Figure 1.5: Circuit of Nürburgring, 25 kms

but above all a reliable one, with a very good team strategy behind. This goes from the tyre chose and preparation, passing through the good fuel consumption management up to the right pit-stop organization, all mixed with a good quantity of luck, in order to don't make mistakes.

Chapter 2

Technical specification

2.1 Regulations

The car has been designed respecting the FIA GT3 regulations that are adopted in all the events that take place at the Nürburgring. The first requirement to take part to this category is to have a car directly derived from a homologated road vehicle produced in series. Starting from this version, the vehicle must be modified and upgraded following the rules listed in the FIA appendix J of the article 257-A, named "Technical Regulations for Grand Touring Cars (Group GT3)". This rules book give indications about every aspect of the car: general dimensions of the car and of all the aerodynamic devices, components constraints, indications about homologated fuel-cell and a description of all the safety components need to make a car eligible to race. The bodywork is the first element that is taken in consideration. In particular the bonnet and the rear hood must be fixed with at least two safety fasteners, allowing their removal without any tools. Also the side windows need to be secured with quick fasteners. The aerodynamic is influenced by the external bodywork, in fact the rules allow changes in the rear wings in any moments to balance the performance of the vehicle. Another element that influences the competitiveness of the car is the weight. In fact there is a minimum allowable weight that can be passed. In this case and to meet the BOP restriction, a handicap ballast must be mounted. A box with the right dimensions and adequate fixing points near the seat position must be designed. The power generated by the engine must be controlled by homologated and dimensional checked air restrictors. The chosen ones are defined by the organization basing the decision on the previous races and on the car dyno bench test. Also the noise generated by the car is regulated: it must no be higher than 110 dB. On the other hand, the elements allowed in the cockpit and the electronic devices that can be used are listed in the rules-book. For example mandatory lights, wiper, engine starter and battery types. In order to run on the Nürburgring, the vehicle must full-fill also all the requirements explained in the official 24h rules-book, that has a lot of connection with the official GT3 regulations.

2.2 Safety constraint

The aspect of the safety during the races is becoming more and more important in the world of international competitions. Before being admitted to a race, the FIA scrutineers have to check the presence, the correct installation and the working of all the safety components. Starting from the cockpit exiting in case of crash, every car must be designed with a roof hatch and with a quick release door mechanism. The former must be of defined dimensions and closed with a cap using quick fasteners. The latter must ensure a quick door removal in case of crash or overturning. To avoid possible fires in these situations, every car must be equipped with a homologated fire extinguisher system compliant with FIA standards 8865-2015. This needs to be installed with a sprier in the cockpit and three in the engine compartment. The system can be activated from outside the vehicle by moving a switch. Other requested items are a racing seat combined with a six-points safety belts and lateral racing nets chosen accordingly with the FIA rules. They must be also installed in compliance with specified installation drawing and with defined anchor points. As said, being an endurance race up to 24h without interruptions, the cars must be equipped with a rubber bladder fuel tank conforming or exceeding the specification of FT3-1999 and with homologated fuel pipe lines and ventilation systems. Regarding the safety of the driver, and in the case of the road vehicle of all the occupants, the car must full-fill different requirements: respect defined deceleration and damage for the front impact, side impact and rollover structure static load test. Being part of a small batch production car, to be admitted in the SPX class (that on the Nordschleife runs under the same BOP restrictions of the GT3 category), no physical tests need to be done on a real vehicle. The racing homologation can be requested on the basis of certified virtual tests. In side impact crash, the race car must comply to the same US regulations of the road one. Being the two monocoque different only from the point of view of pick-up point, the validation of the latter is valid also for the former. In fact, being the carbon fiber tub the core of the chassis it need to be already homologated, regardless of the race approval. The guidelines and the requirements are described in the Code of Federal Regulations (Title 49, Subtitle B, Chapter V, Part 571, Subpart B, §571.214) which the purpose is to define standards in order to avoid serious and fatal injuries to occupants of passenger cars. An accelerometer must be positioned in center of gravity of the dummy head to measure the resultant head acceleration a used in the following formula:

$$HIC = \left[\frac{1}{(t_2 - t_1)} \int_{t1}^{t2} adt \right]^{2.5} (t_2 - t_1) \tag{2.1}$$

where a is multiple of g and the value of t_1, t_2 define a time interval of minimum of 36 milliseconds. The value of HIC must be measured during a 53 $\pm$1.0 km/h impact in which the vehicle is struck on either side by a MDB and must not overpass the value of 1000. No other evaluations about the protection guarantee by doors or other side impact protection must be done, because the monocoque of the 004 has the lower lateral pillar, that is designed to be structural and stiff, higher than the H point of the occupants' seats.

Speaking about the front impact crash, being the 004C a race version, it must comply with a different regulation than the road legal one, that is defined in the FIA appendix J article 259, point 16.3. The front safety structure must be approved in accordance with the approval procedure of safety structures for sports cars (available from the FIA Technical Department on request, for manufacturers only). The procedure requests two different type of successively tests for the production sport car:

- Static side load test
- Impact test

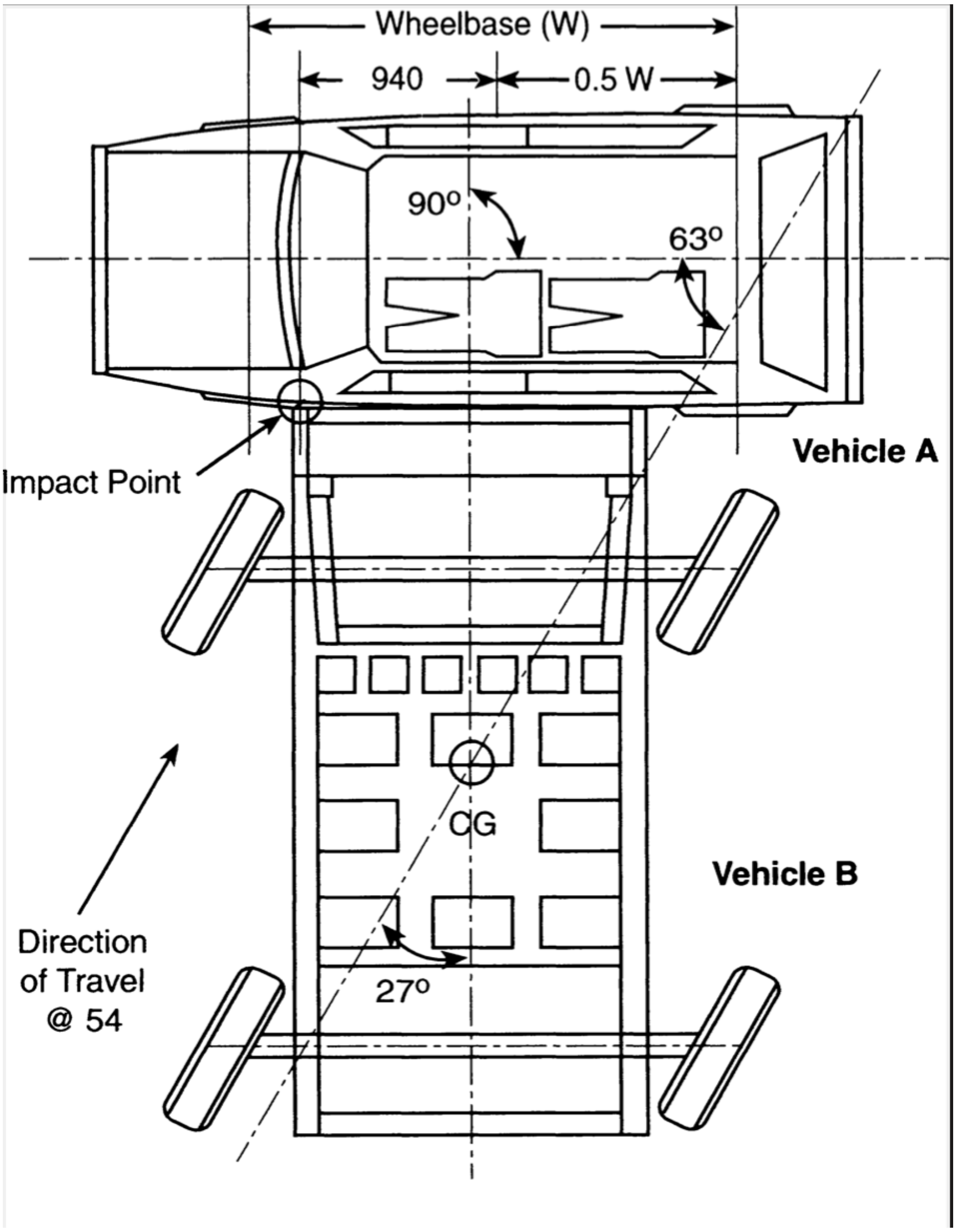

Figure 2.1: Lateral crash: test setup

In the former test a load of 20 kN is applied in a plane passing through a vertical plane situated a 500 mm from the front axle and through a pad to a side of the frontal absorbing structure. The acceptance criteria is that the structure must be able to be normally dismounted and mounted back after the test. In the latter the test require an impact at 12 m/s, with the car in the minimum allowed weight plus 75 kg against a vertical barrier placed at right angles to the longitudinal axis of the car. The acceptance criteria are being under the 25 g and the final deformation must be contained in the zone of 100 mm ahead of the driver's feet.

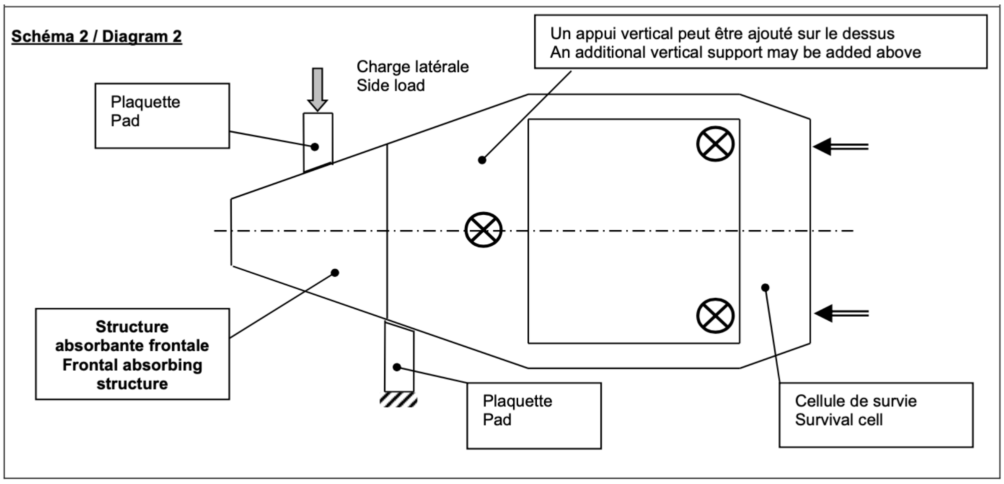

Figure 2.2: Front crash: test setup

Moving to the rollover structure, the compliance of a defined roll-cage is defined in the FIA appendix J, Article 253. The position of the main, front e lateral tube are defined, as their minimum dimensions and material properties. All the possible reinforcements and their positions and combinations are also defined, clarifying that all the safety cage must be ASN of FIA homologated. Each of them must be subjected to three different load cases:

- Front structure, with a lateral combined load applied downward, $60kN$
- Rear structure, vertical load applied behind the driver $130kN$

In both cases the load must be applied in a plane passing through the center-line of the driver seat. In all tests, the deformation measured in the roll-cage must be less than 50 mm measured in the direction of the load and any structural failure must be limited to 100 mm below the top of the rollover structure when measured vertically.

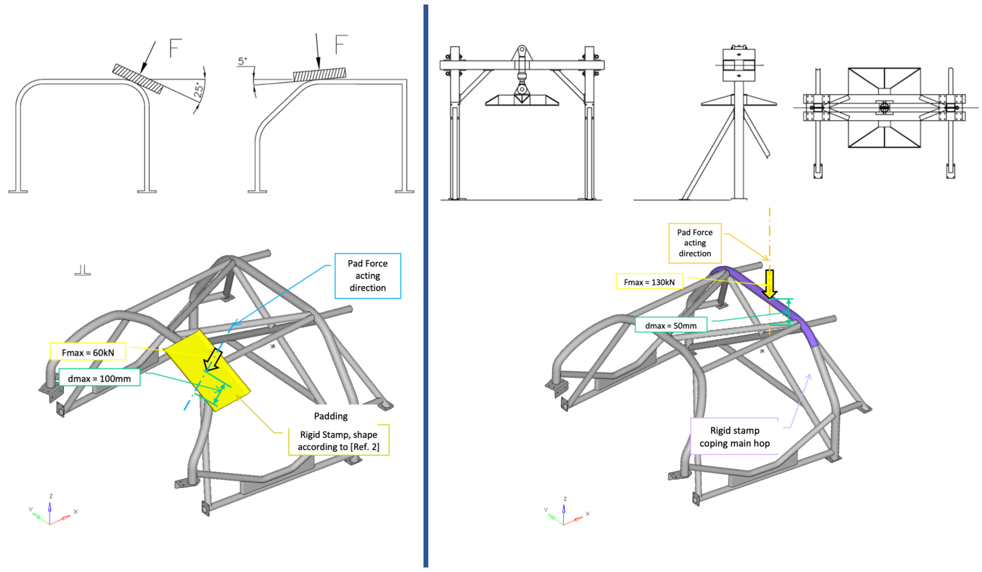

Figure 2.3: Front hoop and main hoop test rigs

2.3 Target setting and load cases

Starting the design of a new vehicle from a blank sheet a big attention to the target evaluation must be reserved. In fact this is only the first step of the entire project, but can decide already a the beginning the right or the wrong direction to keep. Another factor that influence these aspects is the available time, that usually is very limited and doesn't allow bigger changes in a already started project. The driving conditions that have been selected before the design of the SCG 004C monocoque were:

- Cost target
- Weight target
- Reliability target
- Torsional stiffness target

The fist one has been selected because the 004 vehicle, in particular the road one, has been thought to be affordable for a larger population batch respect to the previous cars. In fact the monocoque is one of the most costly components of the entire vehicle, due to its complexity, innovative materials, production techniques and homologation processes. This target has been reached first of all by sharing the monocoque with the road legal versions, ensuring the possibility to create a small batch production series and when necessary build a race version car with any major changes. On the other hand the cost of the entire chassis has been reduced by dividing the chassis in four parts and use other solutions and materials for the remaining structural parts. In fact, only the lower part of the driver survival cell has been made in carbon fiber sandwiches while for the upper section high strength steel has been used. The same material has been selected for the rear chassis frame. In fact the welding technique and the material itself has a lower price compared to the carbon fiber, but can ensure the desired stiffness using the right geometry. On other parts, as the front and rear crash structure, the aluminum 6060 T6 has been selected. Being above all a race car, the weight control has played a fundamental role. Try to keep that value as low as possible has been always been a researched target, also for the 004C. This is important also for the dynamic behaviour being responsible for the static weight distribution and for the load transfer during motion. The target for the only monocoque was settled at 85 kg, while for the entire chassis the prefixed weight was 200 kg. The final obtained results were very near to the estimated, having the monocoque weight at 89 kg and the entire chassis at 215 kg. These errors have been created by the difficulties in welding process controls on the steel parts. The reliability in the endurance races is a fundamental aspect, above all for an important structural components as a monocoque. For this reason during the structural simulation of the attachment points all the aspect from the laminate shear strength around the insert up to the thread pull-out admitted forces. A particular attention has been also reserved to the stresses on the bonding surfaces between the different parts of the monocoque. Having a great number of races at the Nürburgring with the previous car, the 003C, a high number of data has been recorded. Being the two car similar in weight and behaviour, the possibility to consider valid the registered data has been accepted. Simulations for every load case experienced on the rack have been made, highlighting the expected behaviour of the chassis also under the highest load conditions. The analysis gave always a positive value of the reserve factor in every load case, where a safety factor of 1,5 has been used.

Load Case ID		Min RF [-]	
		Front Side	Rear Side
301	Hard braking	3.2	70.4
302	Brake-in-turn	3.3	21.1
303	Cornering	2.2	10.2
304	Acceleration-in-turn	4.7	7.4
305	Full acceleration	34.2	8.9
306	Obstacle Front Axle	3.1	15.6
307	Obstacle Rear Axle	19.5	9.8
308	Obstacle CG	5.7	19.8
309	Braking + Kerb FL	2.5	16.3
310	Acceleration + Kerb RL	25.5	5.6
311	Cornering + Kerb FL	2.2	13.9
312	Cornering + Kerb RL	3.5	4.7

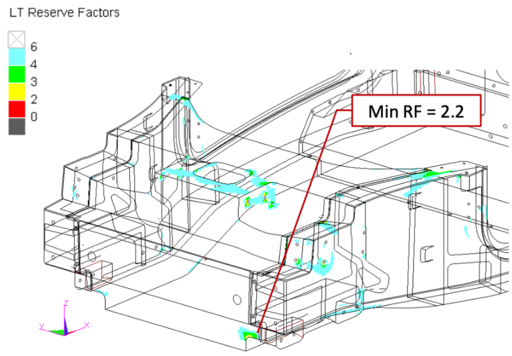

Figure 2.4: Load case for the chassis design

The torsional stiffness of the chassis is a basic requirement for a high performance vehicle as the 004C. This parameter influences massively the dynamic behaviour of the car, ensuring the right position of the suspension geometry during the loads application. The suspension roll stiffness of the car has been computed as 9 $\frac{kN*m}{deg}$ and to not have problems during load distributions and in suspension points variation, the target for the torsional stiffness of the chassis needs to be set in the range of 3-8 times the roll rate. Basing on that the value of 35 $\frac{kN*m}{deg}$ has been set. From the last simulations made for the torsional stiffness, where all the upgrade and lamination optimizations, a result of 32.3 $\frac{kN*m}{deg}$. The final value of the torsional stiffness of the chassis is the result between the stiffness of the monocoque and that of the rear chassis. In fact in the total assembly of the car that connects the front and rear ground contact the chassis works as a spring in series with the suspension stiffness and cornering stiffness of the wheels. Individually the monocoque and the rear frame has a higher value of stiffness, but working in series reduces the overall stiffness, following the Hook law:

$$K_\theta = \frac{(K_m * K_rc)}{(K_m + K_rc)} \tag{2.2}$$

where

K_θ = overall torsional stiffness K_m = monocoque torsional stiffness K_rc = rear chassis stiffness

The torsional stiffness doesn't work alone, but influences the behaviour of the vehicle in combination with the roll stiffness distribution between the front and rear axle, together with roll axis position. If the chassis torsional stiffness is not negligible respect to the axles ones, the chassis must be considered during the evaluation of the set-up of the vehicle, making the decisions more complicated.

Chapter 3

Design

3.1 Shape evaluation

The first stage in the design of a carbon fiber monocoque is the evaluation of the shape. First of all the the packaging constraint must be considered. In the case of the 004 car the central driving position and the other two passenger seats positioned on his side, have represented a very huge problem to be faced. The essence of a sport car must be kept, but leaving much space as possible to the occupants. In the race version this is reflected in a lot of space in the cockpit, being the same CFRP tub of the road one. As a matter of fact from the top view, is possible to see the large width of the cockpit, that in the case of the race version leaves a lot of space for the fuel tank. Setting the position of the latter is a fundamental decision. Two different configurations have been evaluated:

- Formula configuration
- Gran Turismo configuration

The formula option the uniform structural entity is the core. In fact no bonded components are present between the front crash structure and the rear attachment frame, reducing the number of assembled parts during the production . A seat insulation panel is needed to divide the driver space from the fuel tank compartment. This division is not structural and allows a good maintenance of the unit. One drawback of this method is that the mould needed for the manufacturing are more complex and more costly, due to the complexity of the part. Another is that from one hand the integrity of the part is a structural advantage, but on the other hand may cause problems in case of crashes, needing a complete replacement of the tub. The Gran Turismo option is more simple than the previous one. The main tub is smaller and is completed by bonded panels that support the rear frame. This guarantees a more freedom if some changes are needed. In this case the driver compartment is directly divided from the fuel tank by the monocoque. His cover is externally screwed to principal chassis. Due to the fact that in this solution more parts are assembled together, there is more freedom in component changes in case of impact.

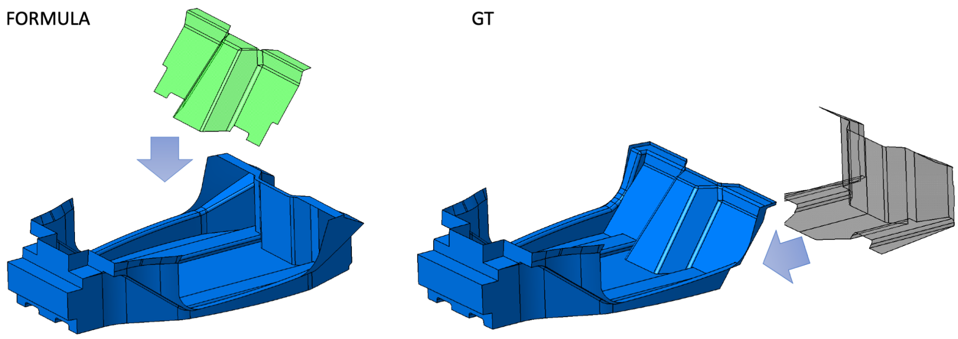

Figure 3.1: Formula vs GT configurations

For of the 004C monocoque a middle solution has been adopted. Since the aesthetic aspect inside a road legal car is important, a male mould has been used for the internal tub. Externally to this part, two structural door sill, created with a female mould, have been bonded with a structural adhesive to it creating a indivisible monocoque. This process allows to have a very stiff component with a good surface internally and externally, but using more easier and less costly tooling, leaving a good degree of freedom in case of shape changes. Being composed by different glued part, the final monocoques may have small differences from each other. To reduce this difference, the insert fixing points and their support surface have been machined after the gluing process. Every structural components, for example suspension brackets, roll-cage and rear frame attachments, are screwed on perfectly planar machined surface. This was made possible by leaving locally some extra millimeters of carbon plies, that will be machined to ensure to have the tub perfectly center respect to the suspension points. This technique is explained in the following image.

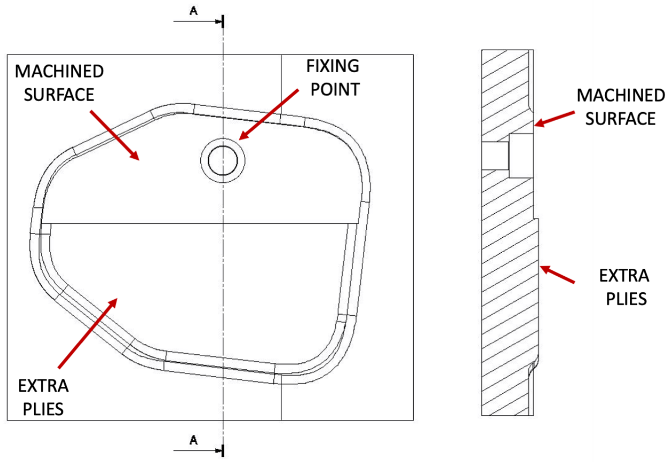

Figure 3.2: Machined planar surface

As possible to see, the monocoque designed for the 004C is only in the lower part of the survival cell. In order to maintain costs, the rollover protection has been made with a homologated roll-cage, fastened to the carbon fiber monocoque. The material used in this components is high strength steel that allow to respect safety requirements, but also to help the CFRP tub to reach the torsional stiffness target of the whole chassis. In fact, it is very important because create a "theoretical closed section" that performs in a better way if subjected to torsional moments. These aspects will be discussed in the next chapters.

3.2 Materials characterisation

The material choice follows a very complex path, in particular in structural component as monocoque. The most complicated thing is obviously deal with the carbon fiber material. As known, it has very noble properties that must be exploited in the best way. In fact it leaves the possibility to create an almost infinite combination of fiber types and resins, that combined with different cores can satisfy almost all the possible requirements. The driving principle behind the 004 carbon fiber monocoque was the ratio between cost and performance. In fact the small series production had implied the need to hold the costs and rely on a stable and repeatable process. These prerogatives have defined the exclusion of the unidirectional carbon fiber; Nonetheless this type of material gives a high increase in stiffness performances, but needs more time to be laminated. It can't be cut automatically by the plotter and due to the fact that is divided in small fiber and isn't a classic carbon fiber cloth is also very complicated to be handled. After this decision, the focus has been centered on two different types of twill carbon fibers: the T700 and the T800. The first one is more common and has a standard tensile modulus around 230 GPa and a strength of 4900 MPa. The other one is a more particular carbon fiber type with an high tensile modulus up to 294 GPa and a strength of 5490 Mpa. The T800 can give an increase in performance about 15 % respect to the standard modulus, allowing a possible reduction in weight maintaining the same behaviour. The drawback of this choice are principally two: the availability of the material, due to the singular high module fiber, and the cost. In fact the T800 has a price almost 3 times higher than the standard tensile modulus fiber. Having these considerations to be evaluated, the decision has been to use the T700 carbon in view of the production series. This choice will ensure no delay in the chassis furniture. Being also a road legal car, a good finishing surface was needed. To satisfy this requirement, a first twill ply of 200 gsm has been used. The main advantage related to its usage, has been the perfect adhesion of the ply to the mould and the ability of this type of ply to not leave the creation of resin deposits. Another step towards the target cost was the comparison between two different types of core material for the central tub: aluminum 3003 honeycomb and Airex ® C70. The first one is classical aluminum honeycomb with a density of 65 $\frac{kg}{m^3}$ that imply a two stage lamination process. Since it doesn't allow to fill perfectly all the angles of the monocoque, the first ply must be cured in the vacuum bag to well adhere to the mould and only successively the core and the second ply can be cured in a second vacuum bag. This processes brings an increase of production times and consequently in costs, but also guarantees a better performances in dynamic and safety conditions. Using the Airex ®, that is expanded foam with a density of 75 $\frac{kg}{m^3}$ reduction of performances but also of costs can be seen. In fact, this type of core can be CNC machined to copy well all the mould surface allowing a single cure vacuum bag. In term of performance losses, a reduction of 10 % in overall torsional stiffness and little reduction of MoS has been noticed. All these aspects can be recovered by add reinforcement plies in the more stressed monocoque areas. These evaluation can be seen in the following comparing graph.

3.3 Monocoque layup

The definition of the layup used in lamination process of the 004C monocoque passes through an iterative path of simulation. The aim of this design, as always, was to find the right compromise between weight, cost, safety and performance. In every simulation, the upgraded configuration has been always verified in all the safety requirements, being one of the more important constraint to be respected. As already said in the previous sections, the monocoque is an assembly of three different main parts, that glued together combine their singular characteristics to reach the target performances. These parts are: the central tub with a good finishing surface where the occupants and driver are carried, lateral door sill that composes the externally visible part of the monocoque and working as protection of the survival cell and the front bulkhead ensuring the connection between the two lateral door sill and working as barrier in front crash situation. The driving idea, that allows a combination of costs, aesthetic and stiffness aspects, has been the one to give to the doors sill more importance in the dynamic behaviour, increasing their stiffness and leaves the central tub cheaper and more aesthetic. The door sill has been made with a female mould, leaving to the external plies a better finishing surface. For this part a combination of aluminum honeycomb and carbon has been adopted, because they are substantially the more important glued parts from the

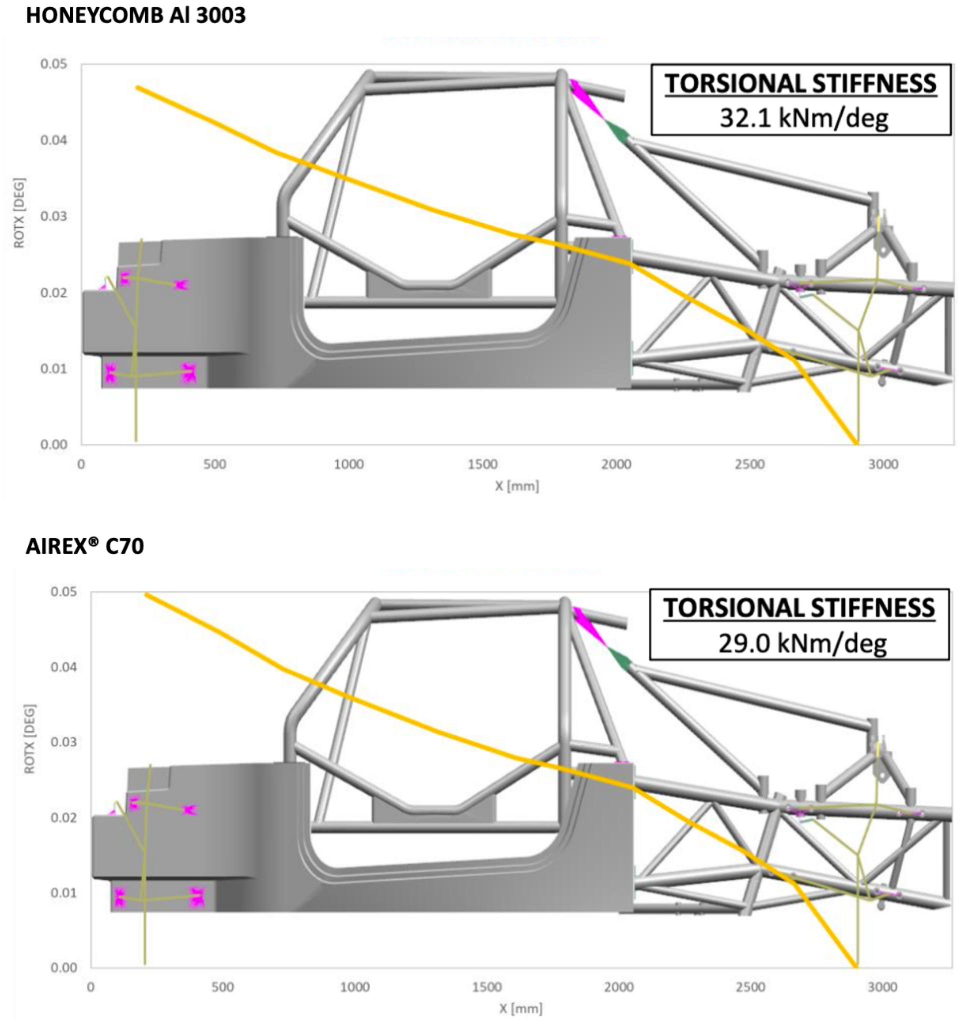

Figure 3.3: Honeycomb vs Airex ® torsional stiffness comparison

structural point of view, being responsible not only for the torsional stiffness, but above all for the lateral crash safety. Speaking about his layup, this has been made with an high level of optimizations, in order to find the right mechanical properties by limiting the weight. This have been obtained by an alternation of different ply orientations. This because the 45° plies increase the torsional stiffness, while the 0°-90° are responsible for the lateral and the longitudinal stiffness. The core selected has a thickness of 20 *mm* in order to give the desired displacement between the plies and give the correct moment of inertia to the panels. The overall thickness of the door sill can be seen in the following image, highlighting the different values by different colors.

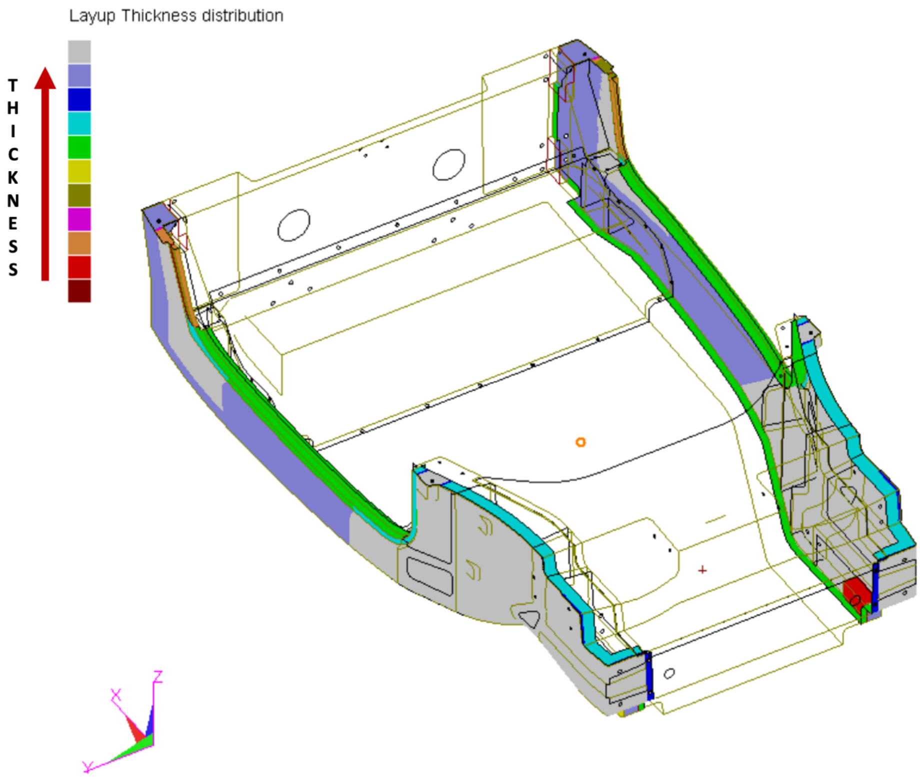

Figure 3.4: Door sill layup thickness

As shown, some parts have a very thick laminate, this is because they are used as gluing surface, creating the correct overlapping with the second the other components. In order to save weight by maintaining the same value of safety and torsional stiffness and to avoid increasing the number of plies without any real sense, an internal pre-cured carbon fiber ribs has been used in different part of the door sill. They are positioned in the lateral crash hitting zone and the front suspension zone, helping the lateral stiffness of the attachments and in the frontal crash situations. Their position is made during the gluing process of the door sill to the tub. To better understand this solution, the following image is proposed.

The central tub is the bigger carbon fiber part of the whole chassis and it is created all in one cure cycle. In fact thanks to the PVC foam used as core material,

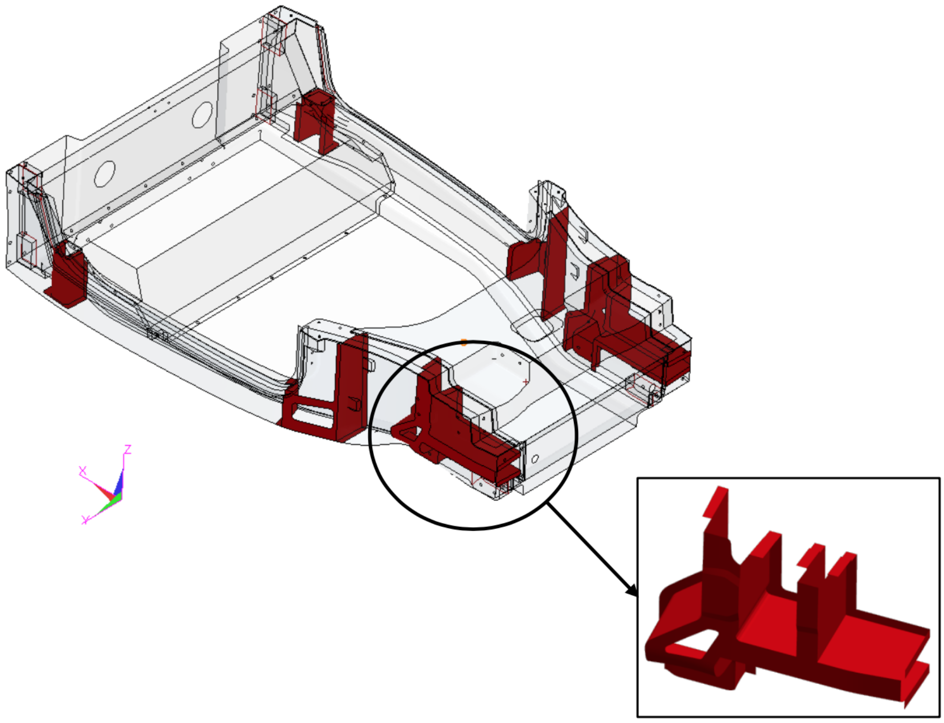

Figure 3.5: Ribs layup

a perfect machined structure can be made, ensuring the correct adhesion to the mould also with one overall vacuum bag. In this case the internal surface is obtained in contact with the mould, while the external one is characterized by the presence of the vacuum bag. This not represent a problem, because in the lower part in completely covered by the screwed under-tray and the rear face through the engine is covered by an insulating adhesive film, that reflect the heat. The surfaces used to fix the under-tray and the rear chassis are machined in order to have the right positions and planar surfaces. As possible to see in the picture, the dimensions of the panels are variable: in the bottom part of the monocoque the core used had a thickness of 20 mm, while in the vertical-lateral zones the value is reduced to 15 mm, in order to have the correct interface with the door sill. On the sides of the tub, two channels have been created by removing the core and make fully carbon fiber sections: externally an attachment was created for the cooling water pipes and HVAC pipes, together with the hard brake lines.

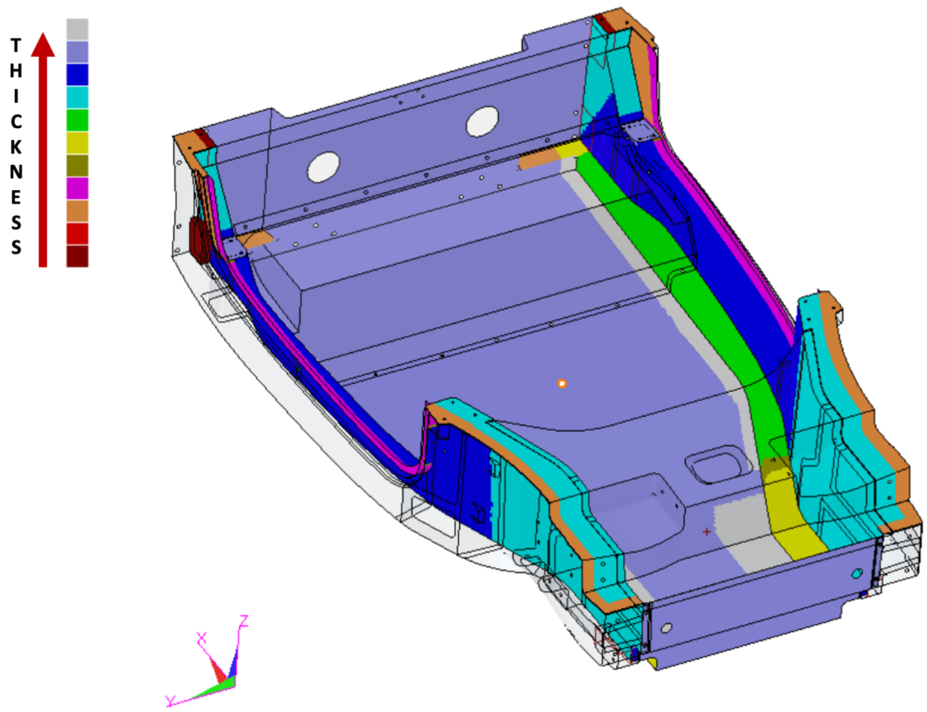

Figure 3.6: Tub layup

The last structural part needed to complete the monocoque is the front bulkhead. This component is not only important for the driver safety, being a primary structure in case of front crash, but also for the torsional stiffness on the entire monocoque. This is allowed because after being glued, it creates a continuous structure that allows the distribution of the forces. In fact, it can be sketched as a circular closed section, that is the best shape in these situations. As shown, an increasing number of plies reinforcements have been placed around the two suspension inserts, giving the desired support during the track loads. In this component, an aluminum honeycomb core with a thickness of 15 mm has been used. Also here, overlap laminates has been produced, allowing a correct gluing process.

After screwing the roll-cage in position on the monocoque, a final component is needed in order to create a closed driver cockpit: the main cabin. This element hasn't been designed to be structural, but has the only purpose to support the windscreen and the external bodywork. Due to this target, the layup of the cabin

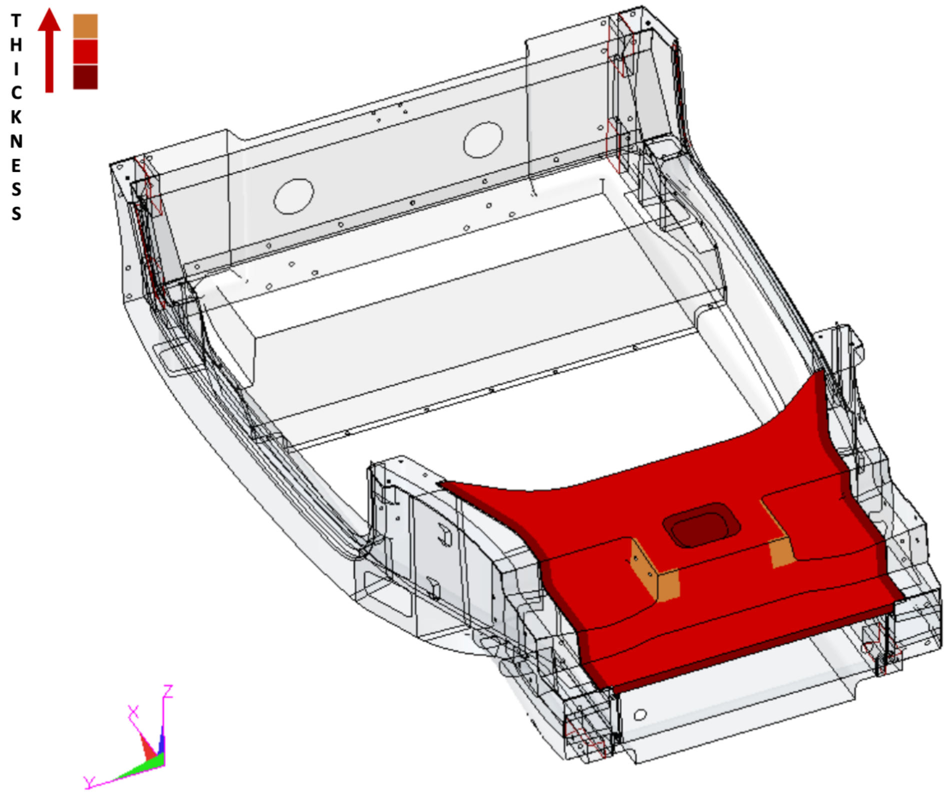

Figure 3.7: Front bulkhead layup

has been made very simple: only carbon fiber plies with a variable thickness, around the 3 mm. The stiffness of this components is ensured by the fixation to the monocoque and from the glued windscreen.

3.4 Attachment inserts

Around a monocoque can be found a very high number of attachments points, where every component that has to be supported is fixed. This includes the structural connection points of the rear frame, roll cage and suspension brackets, passing through the bodywork structure up to all the cockpit elements that must be placed. Substantially there are two types of attachments points: the structural and the non-structural ones. The difference between them is the presence or the absence of a laminated insert inside the composite structure. Speaking about the non-structural, they have been used inside the cockpit to fix ECUs and cockpit instruments. This type has been managed by using Deform-Nuts: a special rivet with the threaded internal part, that clamps the carbon fiber plies when the monocoque is already done. As a matter of fact, their positioning is decided after the monocoque has been fully laminated, through the holes created by the milling machine. Thanks to the absence of an insert, they are very easy to move in case of new required fixing point. More attention has been reserved to the structural attachments for what concerns the laminated metal inserts, the machining details and the threaded reported inserts. As is possible to see in the following image, they are positioned around all the vehicle and in order to keep them in position during the lamination process pins are used in the moulds.

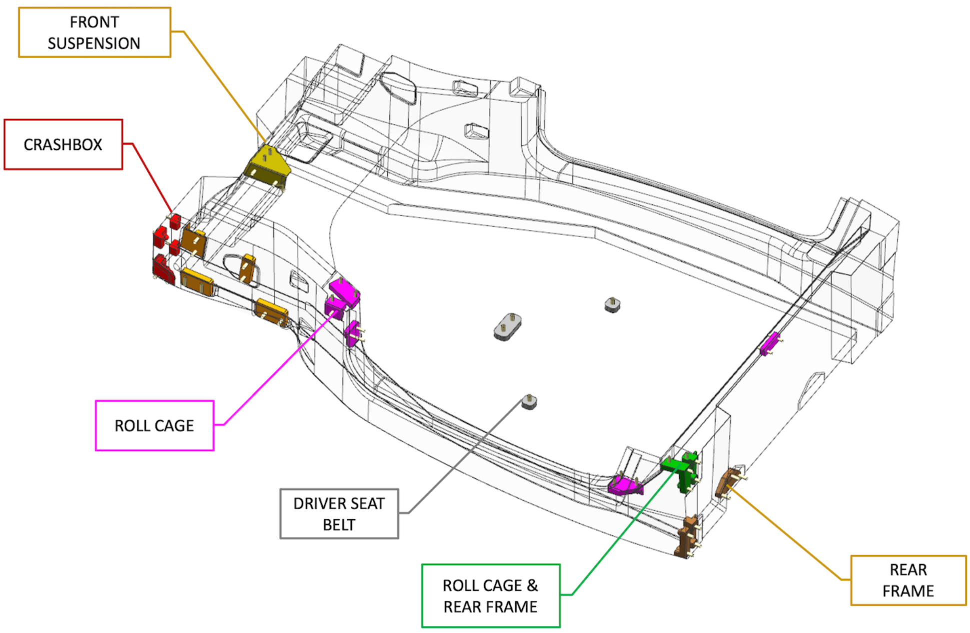

Figure 3.8: Insert positions in half car

Starting from the dimensions of the inserts, the worst load cases derived from the crash test and from the tracks simulations. To evaluate the pull-out strength of the inserts, the shear stresses on the CFRP plies must be evaluated. In fact the worst case of an attachment insert in a composite panel is the axial load on it. In this case only the perimeter combined with the thickness of the skin plays the crucial role. Basing on the following image that is an example of how the inserts are laminated inside a 004C composite panel, the next equations have been taken in account:

$$\tau = \frac{F}{P * t_k} \tag{3.1}$$

$$MoS = \left(\frac{ILSS}{\tau * SF}\right) - 1 \tag{3.2}$$

where:
τ: Pull-out shear stress *[MPa]*
MoS: Margin of Safety
F= Pull-out force *[N]*
P: Insert Perimeter *[mm]*
t_k: Layup thickness *[mm]*
$ILSS$: Inter-laminar shear strength, taken as 50 MPa
SF: Safety Factor, taken as 1.5

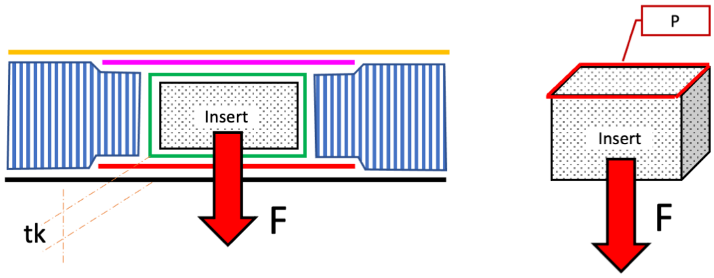

Figure 3.9: Pull-out shear evaluation

This simulation process results in an optimization regarding the ply number for each attachment based on the load case on each of them. Reinforcement plies are used in different positions and orientations, with the correct amount of overlap, to ensure the desired strength. Regarding the front suspension inserts, two different configurations are used, as shown in the following image. Each one of the five inserts is stressed by different loads, that causes axial force broken down respecting the suspension geometry.

In all the inserts, the MoS factor is always over 0, making them acceptable.

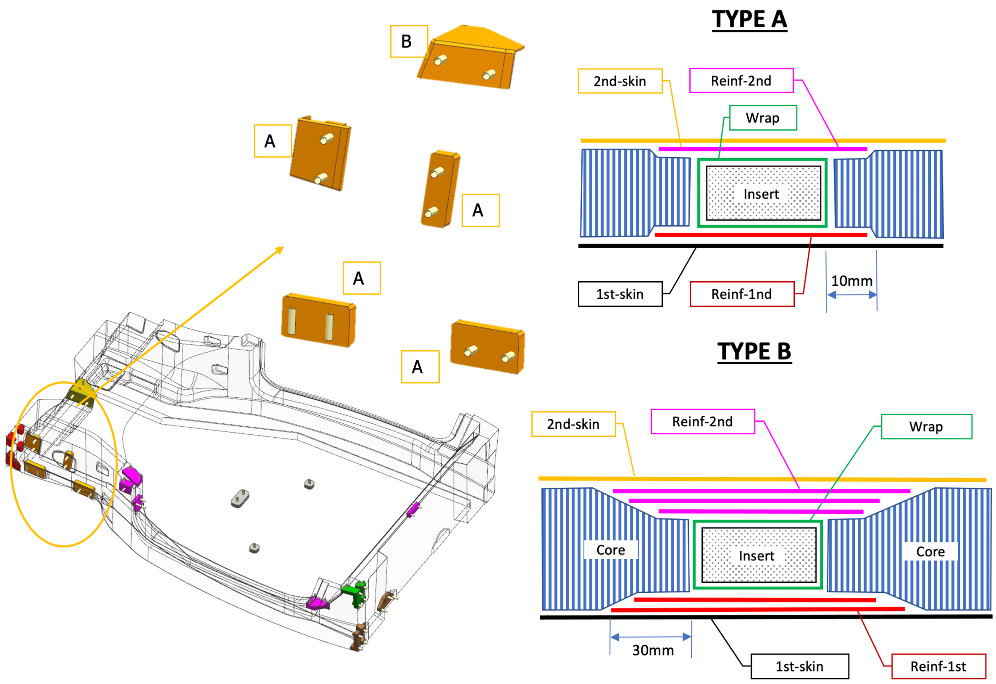

Figure 3.10: Front suspension insert lamination scheme

Only the most critical is below 0, the B type, that in the condition of braking while hitting a kerb is stressed by 28700 N. In this case more plies of reinforcement are needed to obtain a good result, but that does not ensure a positive safety factor. Moreover, to avoid that the weight increases too much, a more deep analysis has been done. This insert has been designed to have also a complete face in contact with a carbon ply surface (parallel to the force direction) that allows to have a large margin on the stresses. As a matter of fact, the FEA analysis gave a reserve factor value bigger than 3, reported to the minimum value that is 0, as can be seen on the image below.

Moving on the front crash structure attachments, the worst load case is represented by the frontal crash that arrives up to 25g with an axial force of 84000 N. In this case, due to the manufacturing technique, the two internal inserts are laminated on the tub and the two external are on the door sill allowing to use also the lateral surface to carry loads. Despite the manual stress calculation give a MoS factor slightly lower than one, the FEA verification leave a reserve factor on the carbon plies bigger than 3. The gluing of the tub with the door sill and the steel

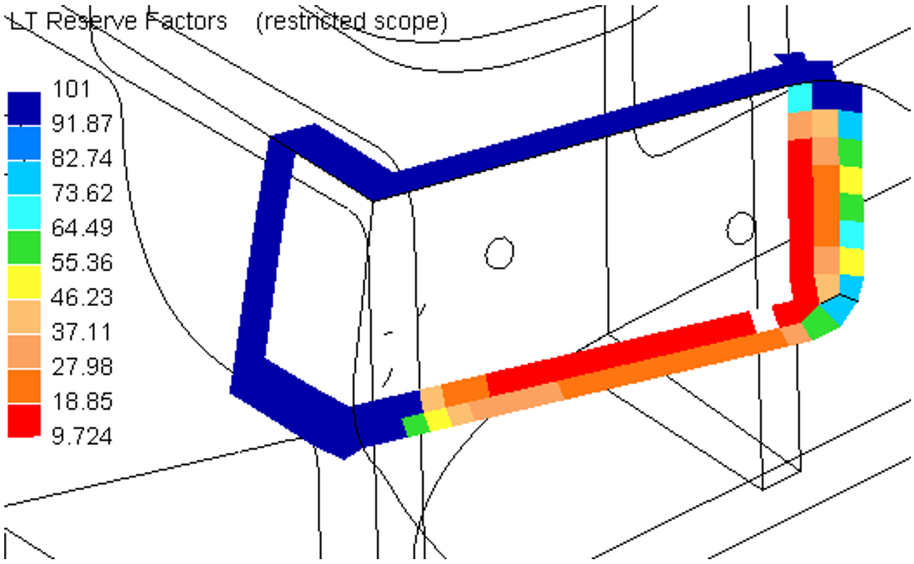

Figure 3.11: Miniature on suspension insert

plate screwed to them, makes the two inserts working as one. Due to the fact that these four inserts work mainly in compression, as possible to see from the image below, there is a high number of reinforcement plies in the internal face respect the external one.

Speaking about the roll-cage and the rear chassis attachments it is possible to see that they are very similar. In fact the worst cases for these two types of fixing points, are the front crash impact and the brake during hit a kerb, due to the fact that both are stresses in the dynamic circumstances. The roll-cage inserts help the monocoque to maintain intact the survival cell during the crash, while the rear-frame fixing points are stressed by the deceleration given to the power-train compartment. They are also important from the point of view of the dynamic behaviour due to the fact that they are stressed by the torsional moments. Also in this case, two different types of reinforcements have been used, arriving up to three extra plies in the more stressed ones.

For the seats inserts and seats belts a dedicated lamination has been studied. In fact, they must sustain high loads only in front crash case, keeping in safe position the driver. They are stressed only in one pull-out direction. As shown in the

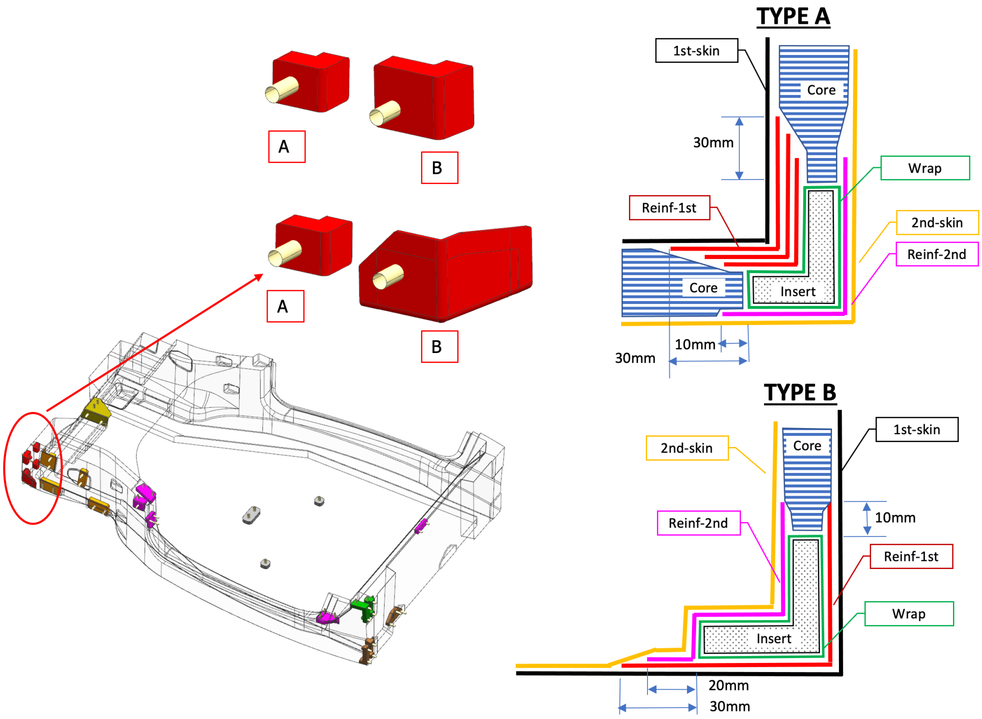

Figure 3.12: Front crash structure lamination scheme

following image, the reinforcement plies are asymmetric with an "omega" on the side where is more loaded.

Moving on the verification of the threaded insert, the choice was between three different commercial components: Time-sert ®, Keensert ® and Helicoil ®. They are a particular type of threaded commercial inserts, made by high strength steel, that have various dimensions, with a bigger male eternal thread and smaller internal one. The there different type of inserts are shown in the following image.

The metallic inserts that have been laminated in the monocoque are made by AL7075. This allows to maintain controlled the weight increase, ensuring good mechanical properties. Besides these two pros, the components can't be screwed directly to them, but a steel interface is needed. In fact, the process of tightening and loosing the fasteners can cause damage to the aluminum. On the other hand, the dimension of the external thread of the commercial components are bigger than the original one, ensuring an higher strength. To evaluate the more indicated one, pull-out tests on sample panel have been performed. The obtained results have

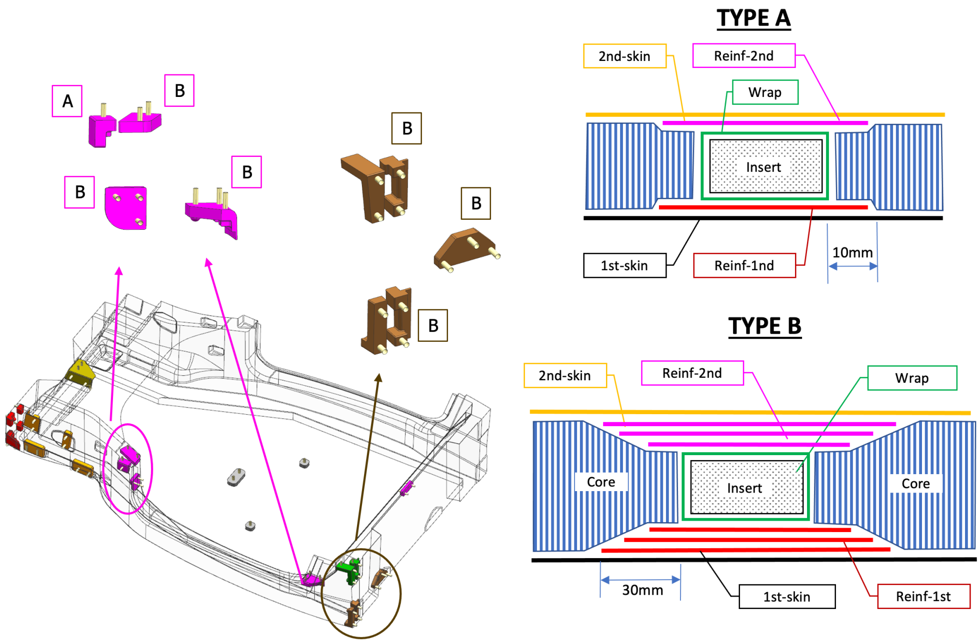

Figure 3.13: Front crash structure lamination scheme

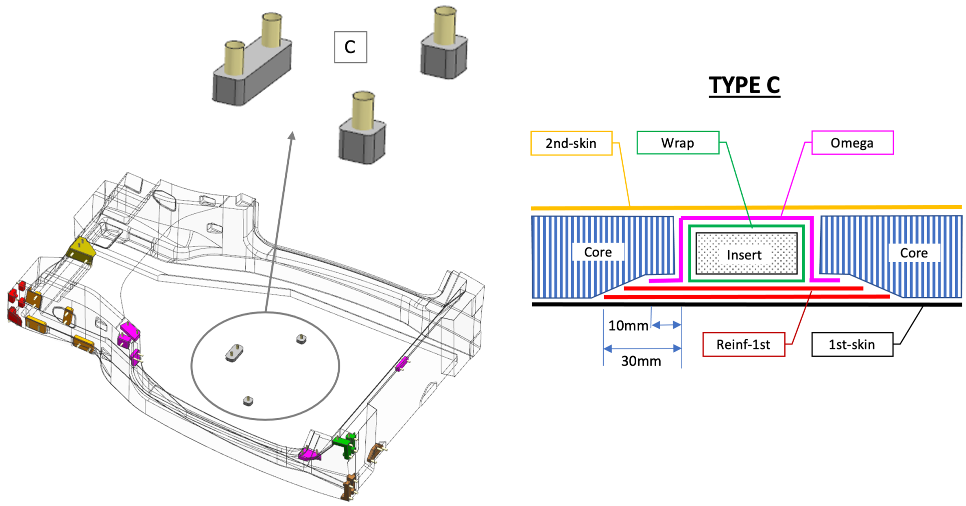

Figure 3.14: Front crash structure lamination scheme

allowed a particular evaluation. Excluding the Time-sert ® that didn't reach the requirement target, the other two have passed the test becoming both usable. The Keensert ®, due to his bigger external diameter, reached the strength of a 12.9

Figure 3.15: Threaded inserts: Time-sert ®, Helicoil ® and Keensert ®

screw, causing its rupture. The Helicoil ® didn't reach the previous value, but they have been chosen since the load is higher than the requested one and because of their lower cost and dimensions. Furthermore their lower eternal dimension allows a possible substitution in case of damage. The graph reporting the forces is shown in the following images.

Another important part of the attachment points creation is the machining details. In fact, the insert are only placed in the right position inside the tub and only after the curing process, holes and machining operations have been made. As it has been discussed in the previous page, around the aluminum inserts there is an high number of carbon fiber plies, in some case up to 10 mm. To ensure the desired strength of the threaded inserts, they must be positioned on the metallic part for their entire external thread. In order to leave space for the installation tools and to avoid possible pull-out force due to the pre-load of the fasteners, counter-bore have become necessary. This machining detail has been made 3 mm down in the aluminum, making also the role of locating device. They will be successively filled by a custom steel bush or by the stud collars, to recover the gap between the external surface planes and the start of the threaded inserts. An explanation technical drawing is shown:

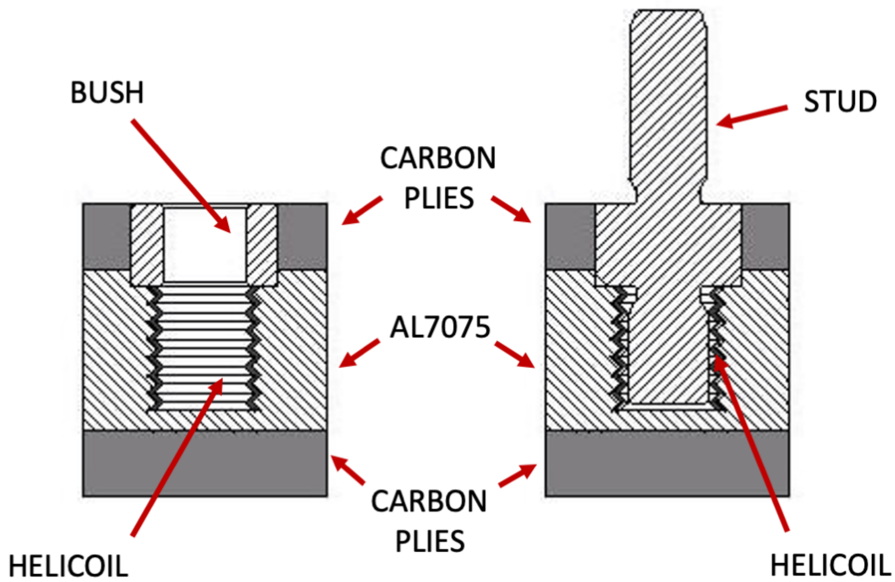

Figure 3.16: Inserts machining details

Chapter 4

FEM analysis

4.1 Front impact

As discussed in chapter two, one of the three safety verification that the vehicle must respect is the front crash impact. During the designing phase of the component that must fulfil the requirements, two considerations have to be made: the deceleration must be maintained under the rule limits and the monocoque must exit from the crash possibly without damages. In fact, the front impact structure is usually built separately from the chassis, allowing a rapid replacement in case of necessity. In the 004C this safety component has been made by welded aluminum struts, assembled with steel rivets and screwed to the front of the monocoque with machined CNC plates, as it can be possible to see in the following image.

A first simplified evaluation has been made on the crash structure itself, comparing two different thickness of the struts, 3 mm and 3,5 mm. The material used in these components is Al6060 T6, that combine good mechanical characteristics, allowing the welding process of the parts. The material properties used can be found in the following table:

As completeness, a small recap of the requirements for this crash are collected:

- The average deceleration of the trolley must not exceed 25 g .It is calculated from the unfiltered deceleration data, from the instant of impact T_0, defined by electronic contact, to the first instant the trolley speed is less than $\frac{0m}{s,soV_0.}$
- The deceleration in the chest of the dummy must not exceed 60 g for a

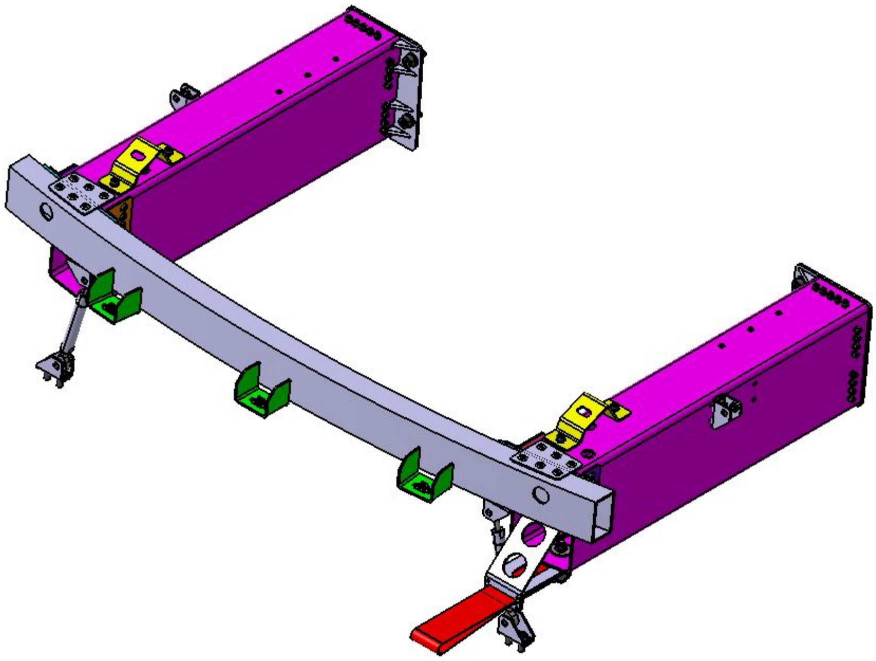

Figure 4.1: 3D model of the front crash structure

Symbol	Description	Value
$\rho[\frac{kg}{m^3}]$	Density	2700
$E[GPa]$	Elastic modulus	70
$\nu[-]$	Poisson's ratio	0.33
$S_y[MPa]$	Elastic limit stress	210
$S_u[MPa]$	Ultimate stress	275
$epsilon[\%]$	Ultimate elongation	12

Table 4.1: Material properties Al6060 T6

cumulative time of more than $3ms$. The deceleration in the chest of the dummy (the resultant measured along the three axes) must be measured with channel frequency class CFC 180.

- The final deformation must be contained within the zone situated more than

100mm ahead of the driver's feet. There must be no damage to the survival cell or to the mountings of the safety belts or fire extinguishers or battery.

Basing on these assumption, the preliminary FEA model of the only crash structure has been created, as shown in the image below.

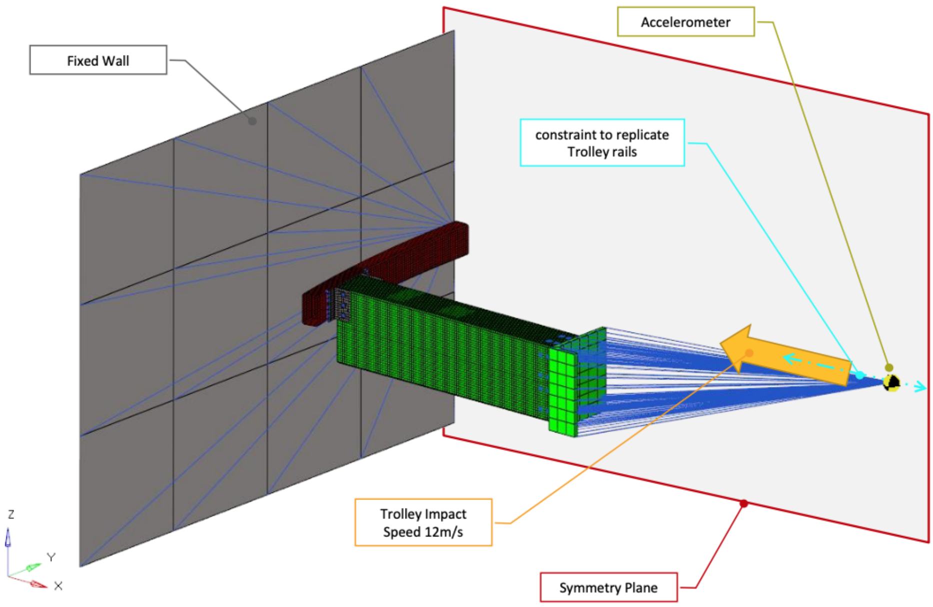

Figure 4.2: Front crash structure FEA model

The results obtained gave a positive result in both cases, making them compliant with the DMSB rules. The differences between the two configurations can be seen in the following values. The 3mm struts gave a lower deceleration peak, exit more damaged. On the other hand, the 3.5mm struts allowed an increased residual length, costing an increase in the interface force. The chosen solution has been the one with the contained deceleration. The crashed model and the graph with the deceleration value can be found here.

After these evaluations, to be considered valid for the homologation, the front crash event is evaluated with the entire chassis. The position of the two steel plates on one hand aim to help maintaining connected the glued tub and door sill, while on the other hand allow the distribution of the forces on the stiffer door sill. Nonetheless, the simulation takes into account all the glued surface in the monocoque, ensuring the right mechanical characteristic of tub. Together with

Result type	$3mm$ **struts**	$3.5mm$ **struts**
Maximum Trolley Deceleration $[g]$	18.3	22.2
Average Trolley Deceleration $[g]$	13.5	17.7
Maximum Force @ Interface $[kN]$	146	175
Residual Length $[mm]$	163	254

Table 4.2: Front crash test results: only crash structure

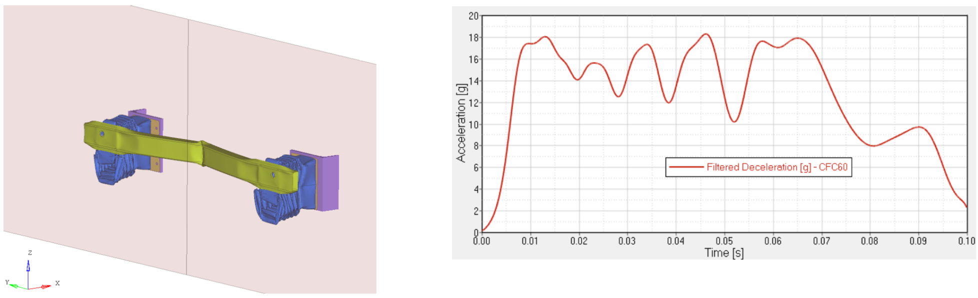

Figure 4.3: Crashed $3mm$ components at the end and deceleration vs time graph

them, also the roll-cage is subject to stresses, being important from the point of view of survival cell shape. The virtual test setup has been created by adding the rear powertrain mass positioned in his center of gravity connected rigidly to the monocoque and roll-cage as the realty. Also the trolley rails and retaining system have been modelled and the section were the interface forces are measured, have been placed in the last section of the front struts.

The resultant values can be found in the following table. These supported the preliminary studies made on the crash structure alone, both in terms of average accelerations, residual length and interface forces. This confirms that the absorbing structure coupled with the chassis model can work together without any problems.

As already said, the stresses have been evaluated for the monocoque in general, that fulfil easily all the requirements, conforming that the loads used for the quasi-static dimensioning are larger than the transient one experienced here; also the adhesive joint stresses didn't highlight any problematic behaviour, as for the roll-cage, that always stayed in the elastic field, never exceeding the allowable yield stress. Contours images confirming these considerations can be found here.

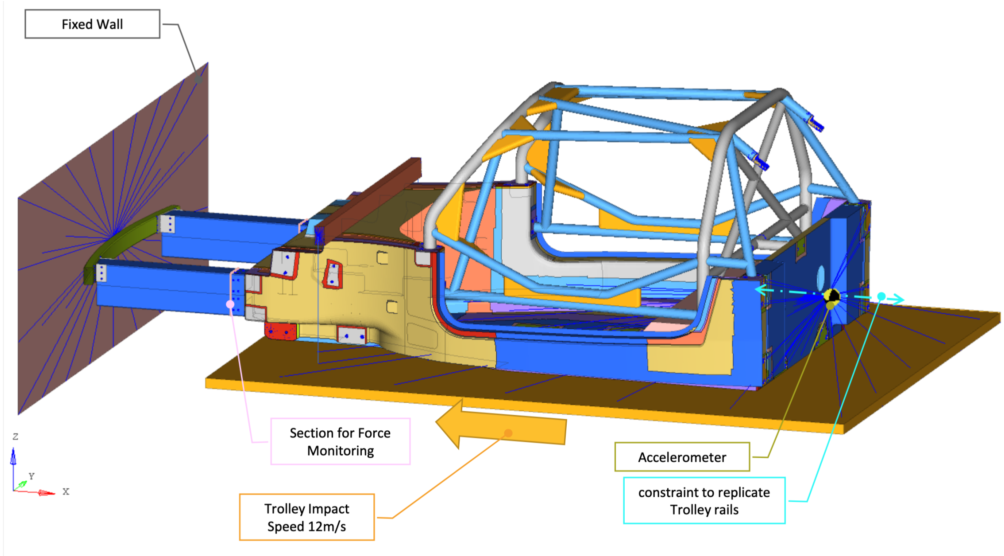

Figure 4.4: Chassis FEA model for front crash

Result type	Full model test
Maximum Trolley Deceleration $[g]$	20.1
Average Trolley Deceleration $[g]$	14.9
Maximum Force @ Interface $[kN]$	314
Residual Length $[mm]$	177

Table 4.3: Front crash test results: full chassis model

4.2 Safety cage verification

The other safety component that needs to respect requirements to be homologated is the roll-cage. This complex safety cage, made by high strength steel 25CrMo4, respect all the basic design standards and is created in co-design with OMP for the SCG 004C. The material characteristics can be found in the following table.

It is composed by a main hoop, behind the driver seat and by a front hoop, positioned in front of the car, just behind the windscreen. The two structures are connected by complex scheme of tubes and gussets, allowing the right stiffness and strength to sustain heavy vertical and lateral load. In fact the protection of the cockpit area from rollover situation is needed. During his design, ergonomic issues have to be faced. In fact also with the roll-cage assembled, exiting and entering in

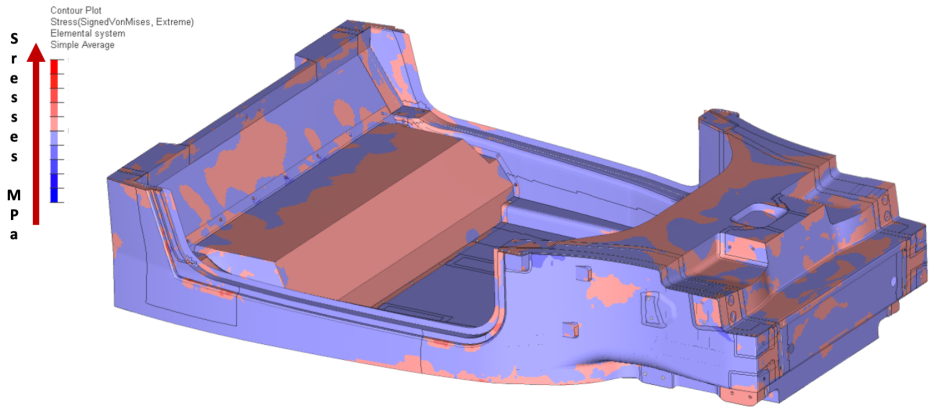

Figure 4.5: Front crash impact: monocoque stresses

Symbol	**Description**	**Value**
$\rho[\frac{kg}{m^3}]$	Density	7850
$E[GPa]$	Elastic modulus	200
$\nu[-]$	Poisson's ratio	0.3
$S_y[MPa]$	Yield Strength	450
$S_u[MPa]$	Ultimate strength	850

Table 4.4: Material properties 25CrMo4

the car must be easy and need to be done quickly, for the driver change or crash situations. On the upper part, just over the driver head, a sufficient space must be left, in order to allow the extraction on the driver directly with the immobilising stretcher, avoiding physical damage to the body. Being directly screwed to the monocoque all the loads are transmitted to it. For this reason for all the load cases, their behaviour must also be tested and verified for the carbon fiber part. A small

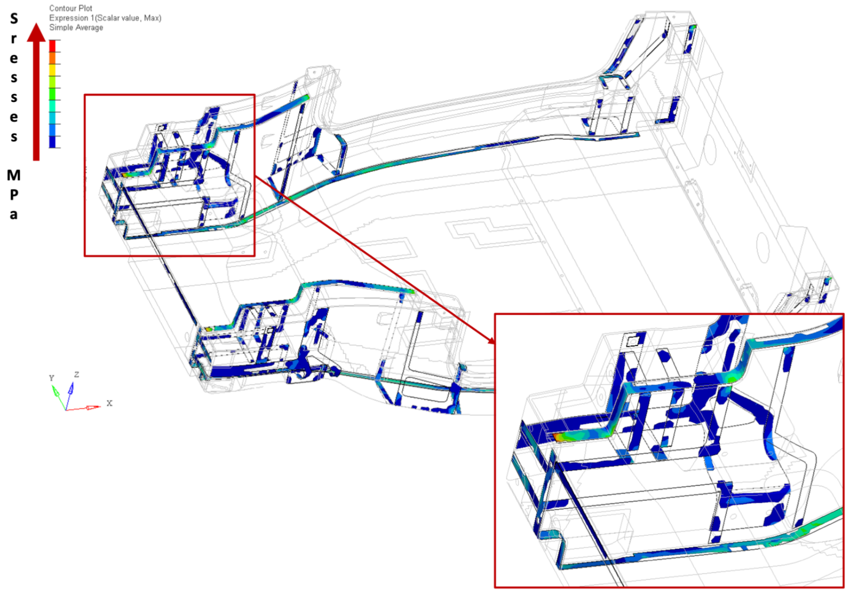

Figure 4.6: Front crash impact: glued surfaces stresses

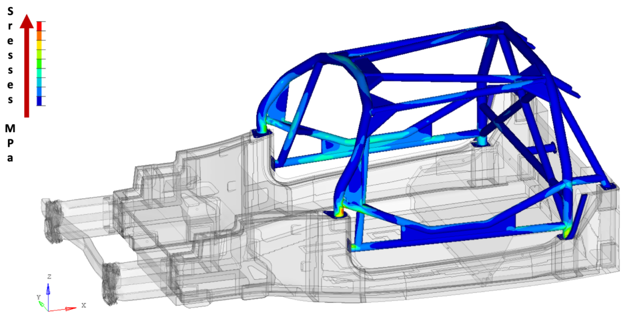

Figure 4.7: Front crash impact: roll-cage stresses

recap with the tests done is reported here:

- Vertical load of $130kN$ on the main hoop, with a maximum deflection of $50mm$
- Lateral combined load of $60kN$ on the front hoop, with a maximum deflection of $100mm$

The two tests have different procedures and different test structure. A description of the two types will be performed. Starting from the main hoop, the load is applied by a square pad placed in the middle plane. The test rig is a simple structure that allows to push downward on a desired area. The two elements can be seen in the next image.

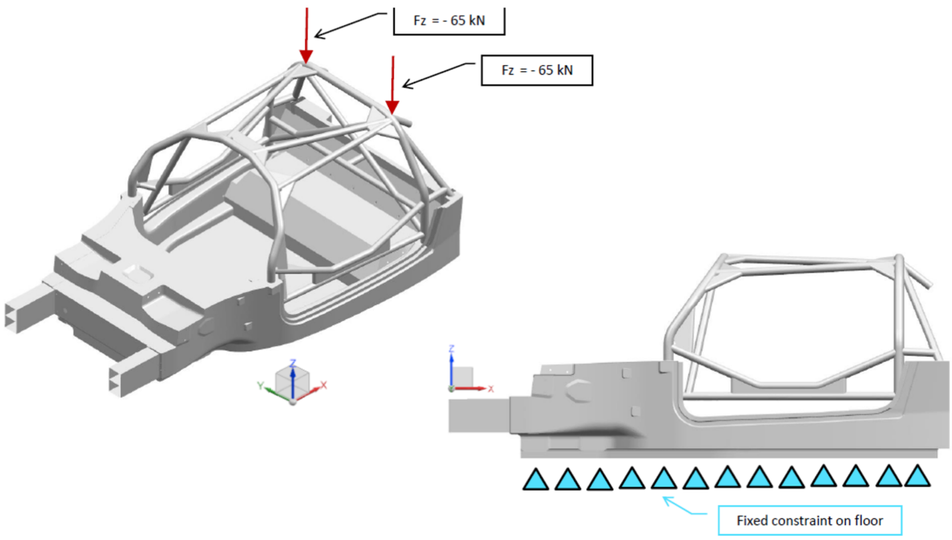

Figure 4.8: Main hoop test

The front hoop is tested in a different way. The pad has a different shape respect to the previous one and the direction of the force has a particular direction: it is inclined by 25° on the plane YZ and by 5° on the plane XZ as it is possible to see.

In these load cases, different stresses in the roll-cage and consequently in the monocoque could be experienced. The results of the tests can be found in the following table. Two considerations have to be done: in the main hoop test the material stayed in the elastic field, while in the front hoop test a plastic strain of 3.8 % has been seen.

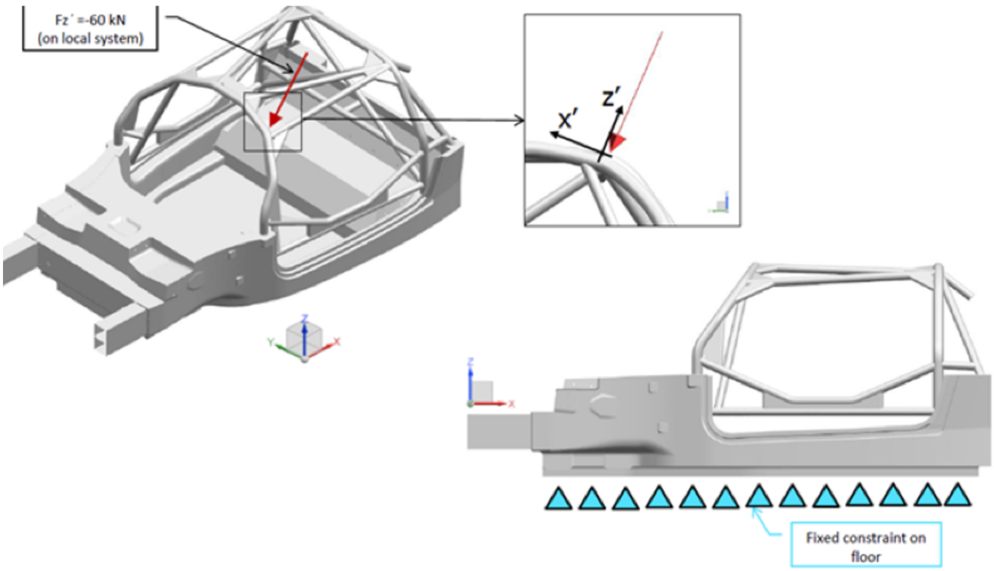

Figure 4.9: Front hoop test

Load case	**Test deform.** $[mm]$	**Target deform.** $[mm]$
Main Roll-bar test	2.2	< 50
Front Roll-bar test	22.6	< 100

Table 4.5: Front hoop test results

Due to diagonal reinforcements and to the bracing connect to the rear chassis, the rear main hoop can withstand to the load without any plastic deformations and the stresses have been kept under the limit value for the material. Also the displacements are under the limit value, with a good margin. As shown in the following image, there are some areas, the red ones, where the stresses are quite high, but lower than the yield strength. Another consideration can be made: they are only concentrated locally, in the conjunction with two tubes, where the weld bead is present.

Moving on the front hoop, the situation is more critical. In fact, after the test, the structure has been resulted plastic deformed, but in the limits imposed by the rules. This is caused by the front hoop that can't be centrally supported, because of visibility. In fact, it cannot interfere with the windscreen and must leave the correct field of view for the driver. Despite everything, the stresses are under the

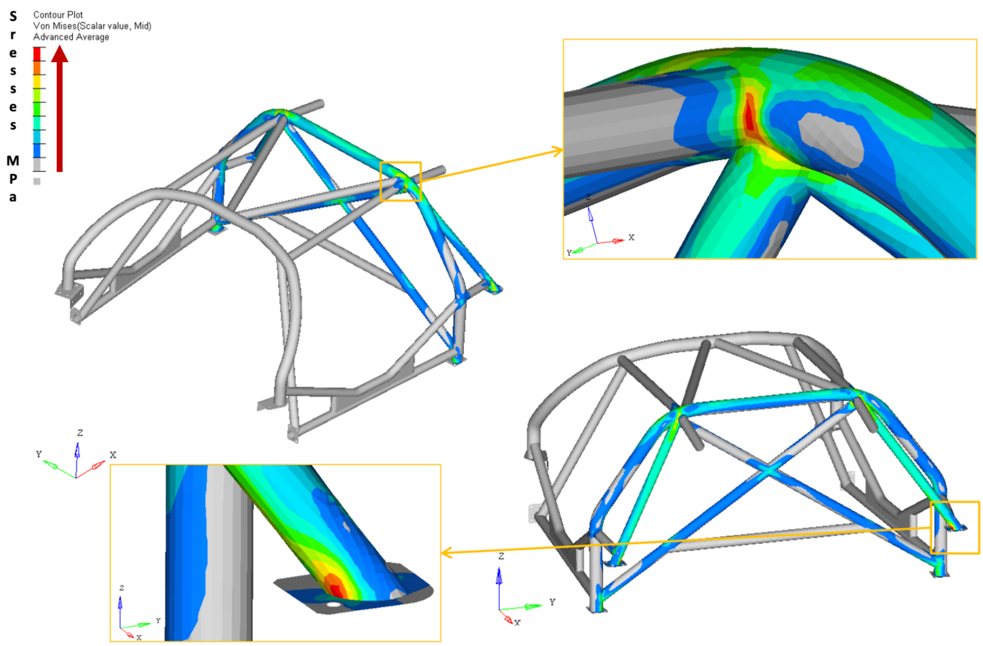

Figure 4.10: Main hoop test stresses

ultimate strength. As explained before, also in this test there are some peak values in the stresses because of the welding beads. However the maximum displacement, also in the plastic field, is under the limit value imposed by the rules.

Being the situation of the front hoop a little bit above the expected results, has been decided to upgrade the configuration, helping the structure to sustain the load, with the addition of local gussets as can be seen the in following image. The change had the desired impact, reducing the plastic strain around the 10 %, limiting the deformation at 16.2 mm. A comparing graph reporting the force vs displacement is here reported.

Moving the attention to the carbon fiber monocoque, these evaluations on the steel roll-cage can be considered valid in the case that the monocoque didn't get damaged. The simulations have been performed with real monocoque lamination layup. The result gave a high level of confidence, highlighting that in all the situations the MoS of the composite always had a positive value. In the following image it is possible to see the deformations in the two load cases.

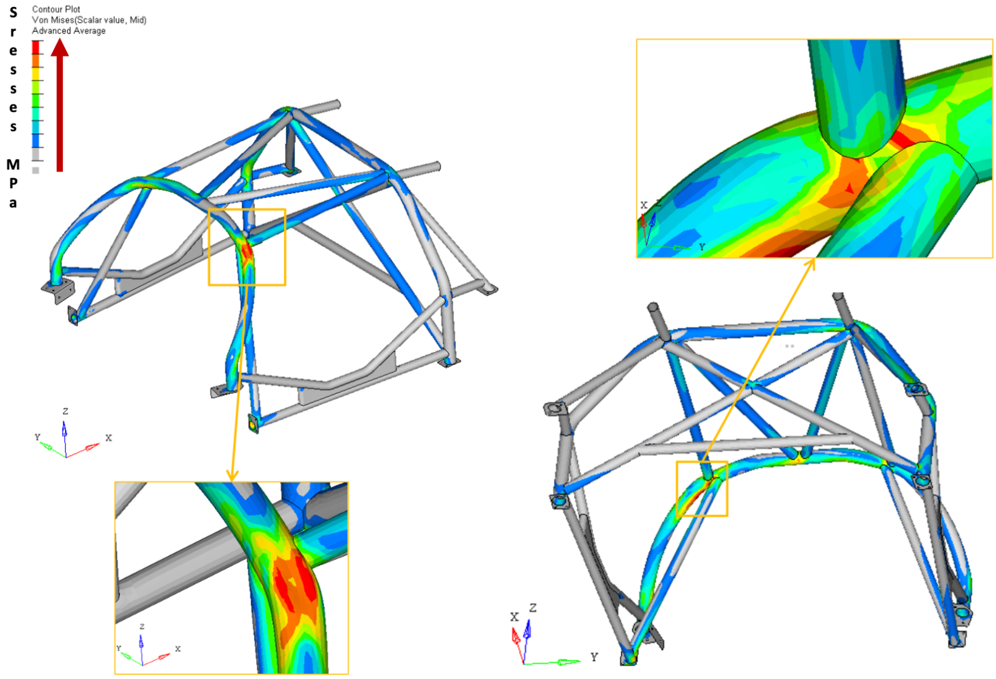

Figure 4.11: Front hoop test stresses

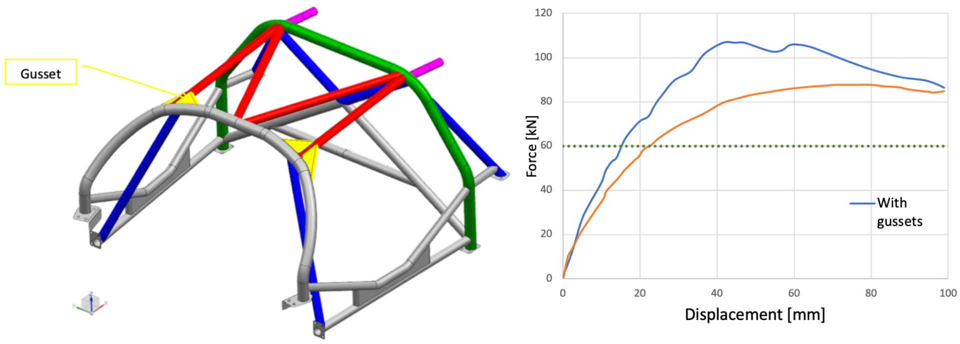

Figure 4.12: Front hoop behaviour with gussets and no gussets

4.3 Lateral impact

The lateral impact crash test is a characteristic requested by the US Code of Federal Regulations. In fact, the road car, for now, could only be sold in the United States of America, due to its homologations. This is allowed because the race version of the 004, shares the same monocoque tub of the road legal car. As already explained

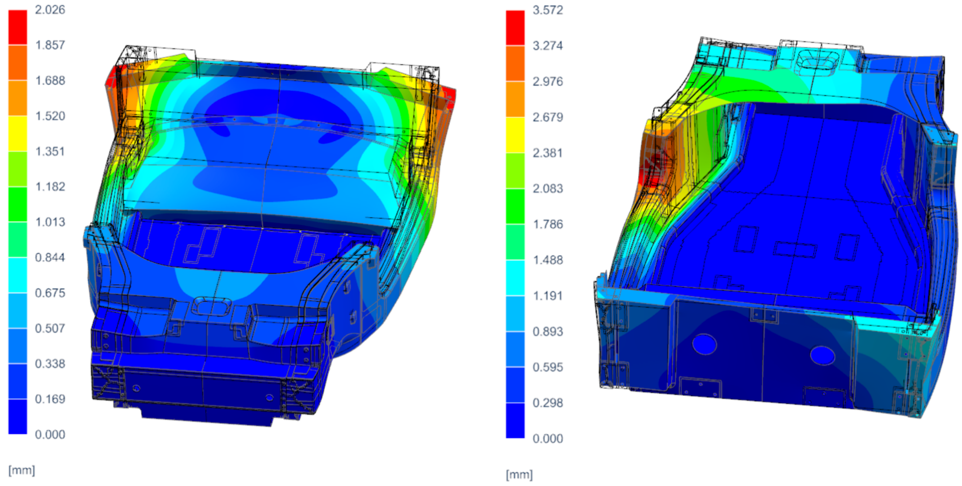

Figure 4.13: Monocoque deformations: main hoop and front hoop test

in chapter 2, the test involves the verification of the acceleration to which the occupants are subjected and of the deformation of the survival cell. Their values have to be evaluated with the HIC coefficient that must be lower than 100. Starting from the movable barrier, it has been modelled as the requested one, with the front deformable barrier and the height from the ground of 100 mm. The compliance of this testing tools has been assessed against a rigid wall in order to have a precise evaluation of its behaviour. This values and the model can be seen in the following image.

The simulation has been performed with the complete vehicle model of the road car, created with all the specifications developed up to here. The only difference between the two car models is the roll-cage dimensions, that in the case of the race version is more stiff, being FIA homologated. The test has been carried out considering only the survival cell, because the H point of the occupants stay under the line defined by the door sill. This allows to not include the doors, because it is the previous element that is responsible for the lateral anti-intrusion purpose. Being the disposal of the three occupants very unique, the two lateral passengers are very close to the external surface of the monocoque. Due to this fact, during the design, it must be sure to dimension correctly the door sill, in order to avoid possible permanent deformation and so intrusion inside the cockpit. This is also very important for the fuel tank integrity. The regulation establishes also that

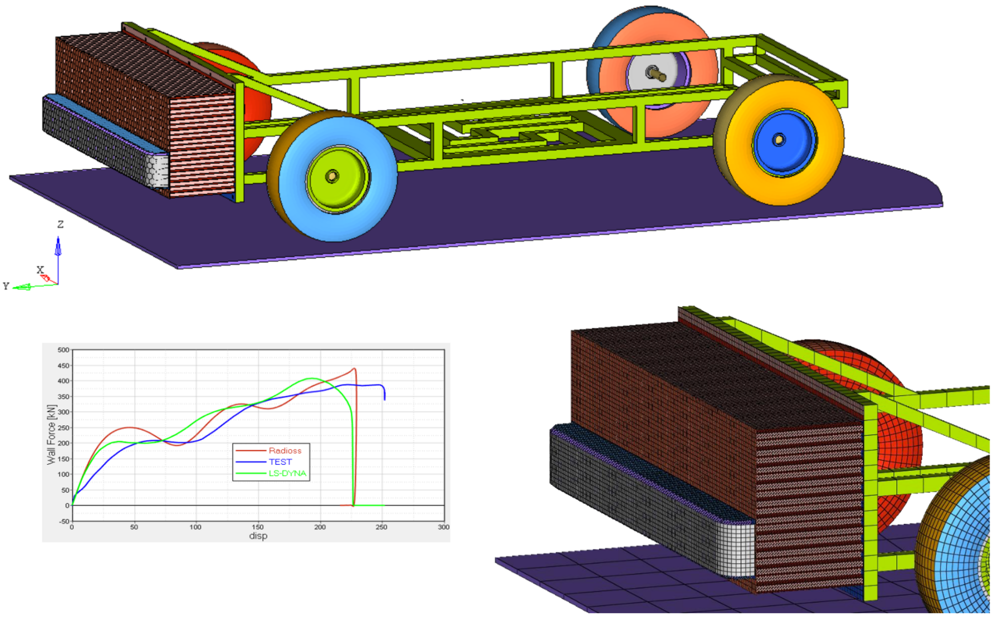

Figure 4.14: Movable test barrier

the fuel tank must not have damage that creates fuel spilling. Based on these considerations, the test setup had followed the guidelines of the real one, described on the FMVSS 301. The impact speed has been settled at 53 $\frac{km}{h}$ (14.7 $\frac{m}{s}$) with a mass of 950 kg and the direction of the movable barrier has been settled at 27° respect to the car,as shown in the following image.

The value obtained regarding the lateral acceleration measured in the driver seat gave a good response. As a matter of fact, the maximum acceleration of 12.7 g is on the left passenger, the one closer to the impact point. As it is possible to see from the following graph, the acceleration peak is situated at 46 ms, after the impact started. Introducing these numbers in the HIC formula the value of 264,4 can be obtained, that is lower than the established limit.

Moving onto the evaluation of the damage to the monocoque helps to understand how the fuel tank compartment has reacted. As revealed in the following images, after the crash, some areas of the monocoque have been damaged, due to a failure in the glued surfaces between carbon fiber parts and to roll-cage attachments. However, after having experienced a deformation of the external plies of 8 mm, the fuel tank can be deformed without fuel leakages. From this results, because

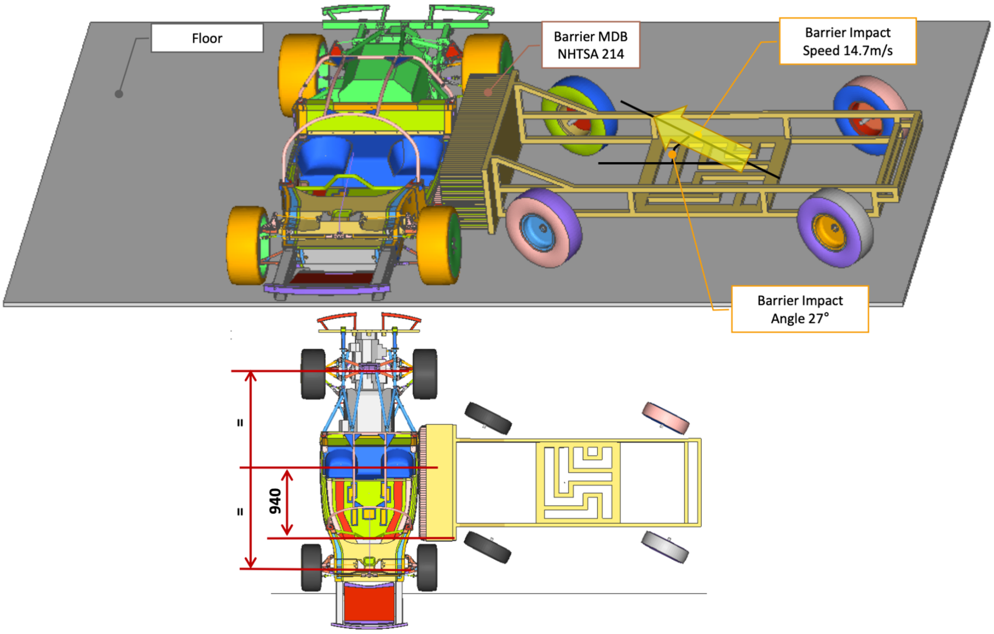

Figure 4.15: Side crash test setup

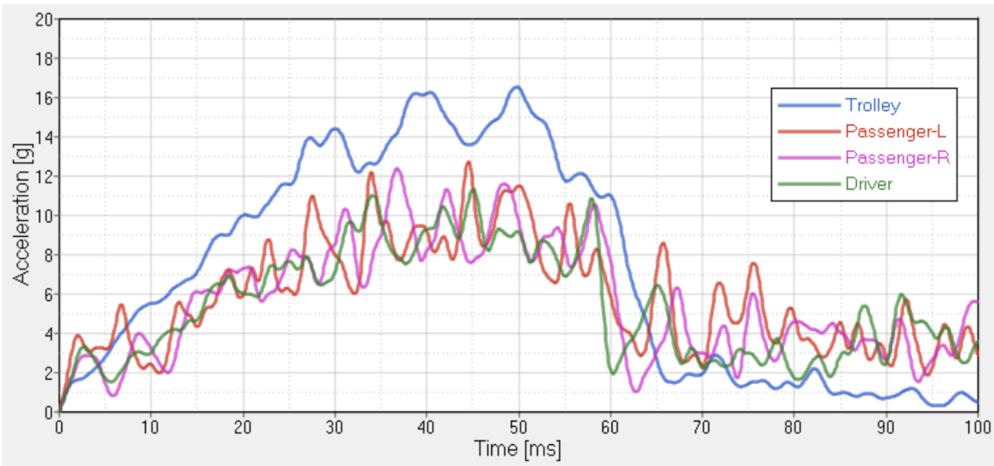

Figure 4.16: Side impact test: accelerations

of the hitting position of the movable barrier against the side of the chassis, the introducing of the glued pre-cured ribs between the door sill and the central tub have been introduced. Thanks to this improvement the previous achievements could be reached.

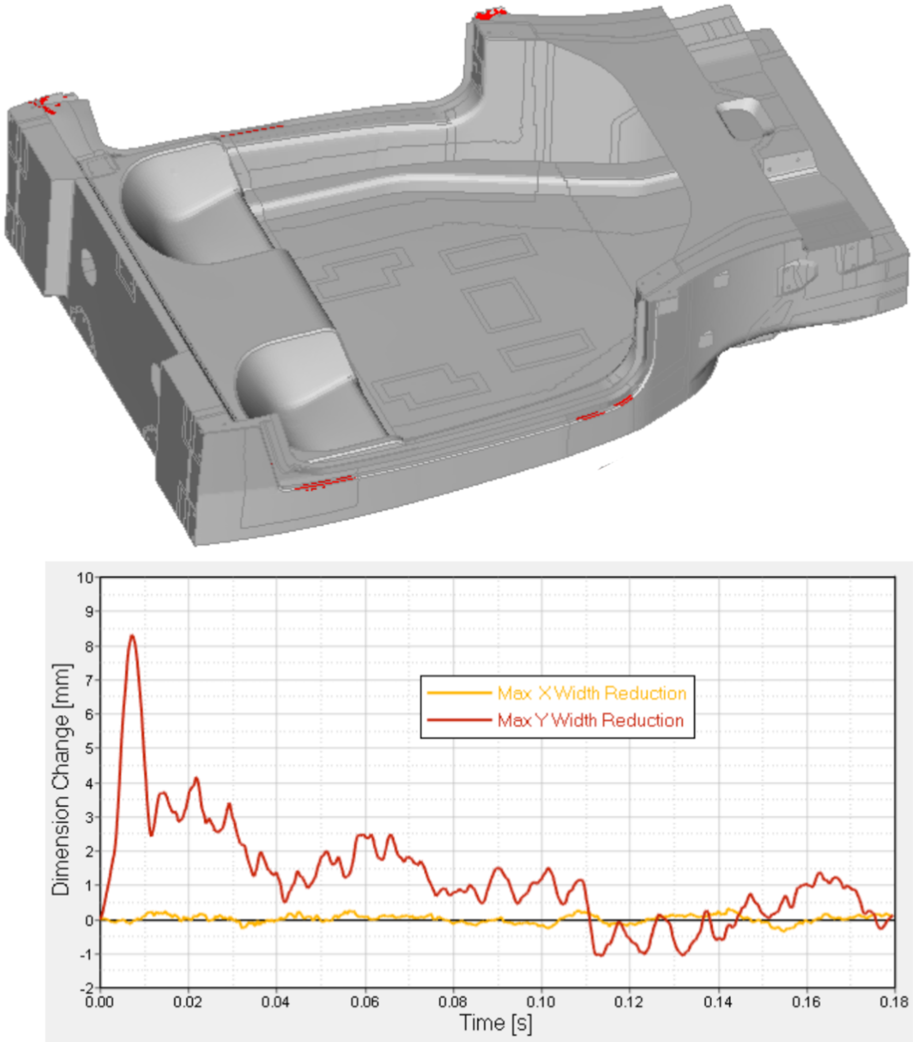

Figure 4.17: Side crash: damage results

4.4 Torsional stiffness

The last evaluation made during the chassis design is strictly related to the dynamic behaviour and competitiveness of the car. The torsional stiffness of the chassis, as described in the second chapter, plays a fundamental role to reach the best performance of the car. In fact, during race events the skeleton of the car is subjected to a large number of load cases and, if from one side the reliability must be ensured, on the other side, desired stiffness and low weight must be reached. The torsional behaviour has been subjected to a precise series of FEA analysis, in order to find the right mix between the combination of the very stiff carbon fiber monocoque and the less stiff rear steel frame. In fact, just to give some dimensional orders, the monocoque on its own can reach easily the torsional stiffness of 60-70 $\frac{kN*m}{deg}$, while the rear steel chassis can reach only 40-50 $\frac{kN*m}{deg}$. Since the two chassis components work in series for the evaluation of the torsional stiffness, the final value is less consistent than the single one. Starting from the model creation, the entire chassis has been constrained as in the image below, ensuring to not create a over constrained model. The suspension damper has been replaced by a rigid structure: this allows to measure only the stiffness of the chassis, removing any compliance of the suspensions. All the A-arms have been modeled as rods, making them working in a proper way.

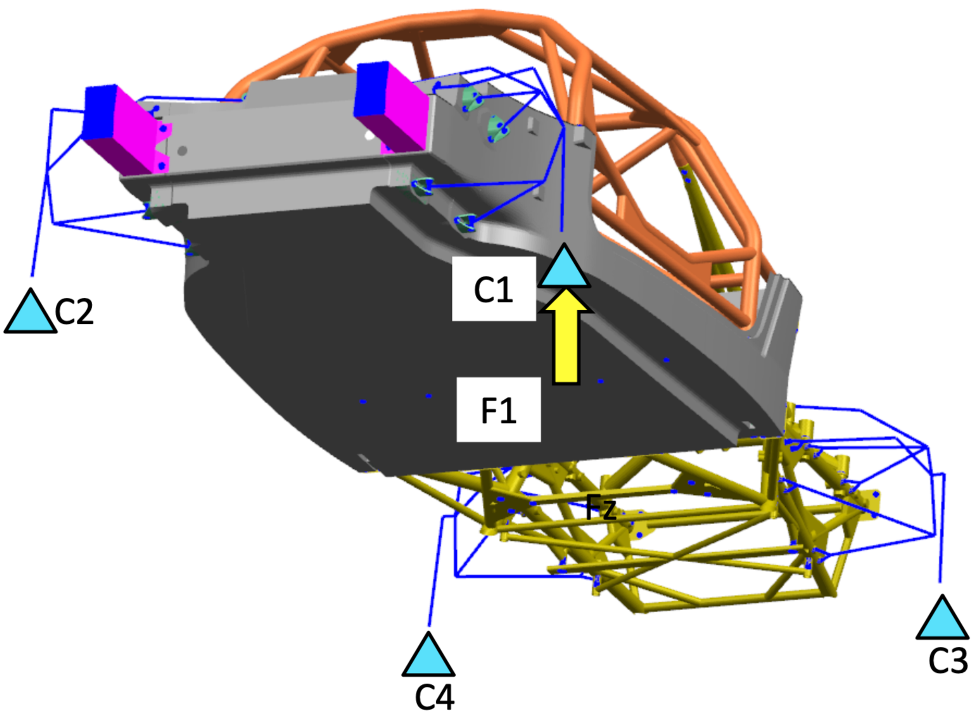

Figure 4.18: Torsional stiffness test setup

The applied load in vertical direction $F_z = 1kN$ is placed on the front wheel, while the other three are constrained as the following table. Then the vertical displacement has been recorded and the torsional stiffness, expressed in $\frac{kN*m}{deg}$, has been found through this expression:

$$K_\theta = \frac{F_z * \frac{t}{2}}{\arctan\left(\frac{dz}{\frac{t}{2}}\right)} \tag{4.1}$$

where F_z is the vertical applied force, dz in the vertical displacement on the wheel hub and t in the track of the car.

Point	**Constraints**
C1	-
C2	TY , TZ
C3	TX, TZ, RX, RZ
C4	TX, TY, TZ, RX, RZ

Table 4.6: Torsional stiffness test constraint

The design process has passed in different shape update, guided also by the definition of the surrounding parts, as suspensions geometry and components, wheels and cockpit structure, together with the aerodynamic integration. Starting from the first analysis, the shape was not very clear with a lot of preliminary surfaces and together with not-well defined laminates, gives a results of over 90 kg, when the target was 85 kg and a torsional stiffness of 31.1 $\frac{kN*m}{deg}$. The over weight has to be reduced, combining laminate optimizations and shapes improvements. The second FEM analysis take in account all these aspects. The bottom floor shape has been updated to leave space for the pipes, the edges have been defined, inserts and all the surfaces become more clear around the other components. The ribs glued between the tub and the door sills have been introduced, together with an updated roll-cage and rear chassis. These changes have allowed to reduce the weight at 86.2 kg, but with a small lowering in the overall torsional stiffness that reach the value of 30.8 $\frac{kN*m}{deg}$.

The last optimization keeps improvement in the rear chassis upper cross beam, making it more solid and stiff ensuring a continuity in the stresses also on the rear chassis. In the monocoque a more stiff door sills and the introduction on the fuel

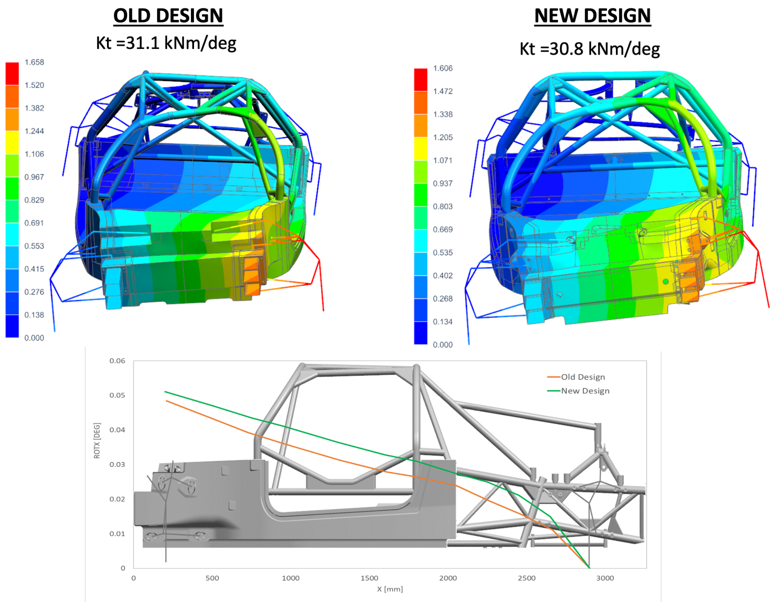

Figure 4.19: Torsional stiffness: 1^st and 2^nd run

tank structural cover, allow to increase the overall torsional stiffness up to 32.3 $\frac{kN*m}{deg}$, almost keeping unchanged the weight of the only monocoque. The final result can be seen in the following image:

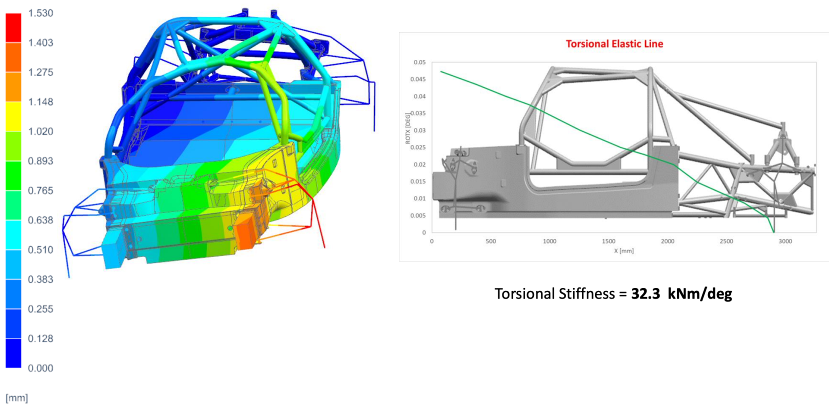

Figure 4.20: Torsional stiffness: final value

Chapter 5

Manufacturing

5.1 Monocoque production

The production and assembly phase are two of the most important periods during the creation of a complete project. In fact, often these phases are not considered at the same level of the design period, but they could decide the fate of a new vehicle. Above all in a new and young project as the SCG 004, where all the parts have been designed from a sketch, not always is easy to combine them also in reality. As already said the procedure to create the 004 monocoque passes through: the lamination process of the different parts, the gluing phase to reach the final monocoque and then the holes and machining moment. The safety cage welding and the lamination of the main-cabin are made in parallel, that together with the monocoque create the cockpit survival cell. Going more in details, two different lamination techniques have been used in the production:

- Curing process with one vacuum bag
- Curing process with two vacuum bag

The first one has been chosen for the central tub, allowing to reduce cost and manufacturing times. This process consists to place the first plies, than positioning the machined foam core material, the inserts and the second ply, all in one shot. The vacuum bag is created and cured all together, without increasing too much the autoclave pressure, that could damage the components, deforming the core.

Despite these positive aspects, this technique in very complicated, causing possible problems in the aesthetic aspect of the plies on the mould. This is due to the fact that is difficult to be sure that the pressure of the vacuum bag on the core material is sufficient also for the first plies. The second method is longer in time and higher in cost, but is more controllable. In fact, the first skin is placed and cured lonely with the vacuum bag and with an high value of autoclave pressure. Then the core is put in position with the inserts and the second skin is placed. At this point a second vacuum bag is made and the cure process restarted. Regarding the lamination sequence, a detailed ply-book has been created from the FEM analysis results. As the name explains, this documents contains all the indications for a correct posing sequence of the different plies, regarding the type of carbon, the resin and their orientations. This defines also the type of core with all the characteristic and highlight the presence of all carbon fiber reinforcements. It is in every sense a real book, that when used in the proper way during the lamination process, could speed up the production phase. Related to this, the program Laminate Tools, gives also the 2D file useful for the plotter cutting of the carbon fiber plies.

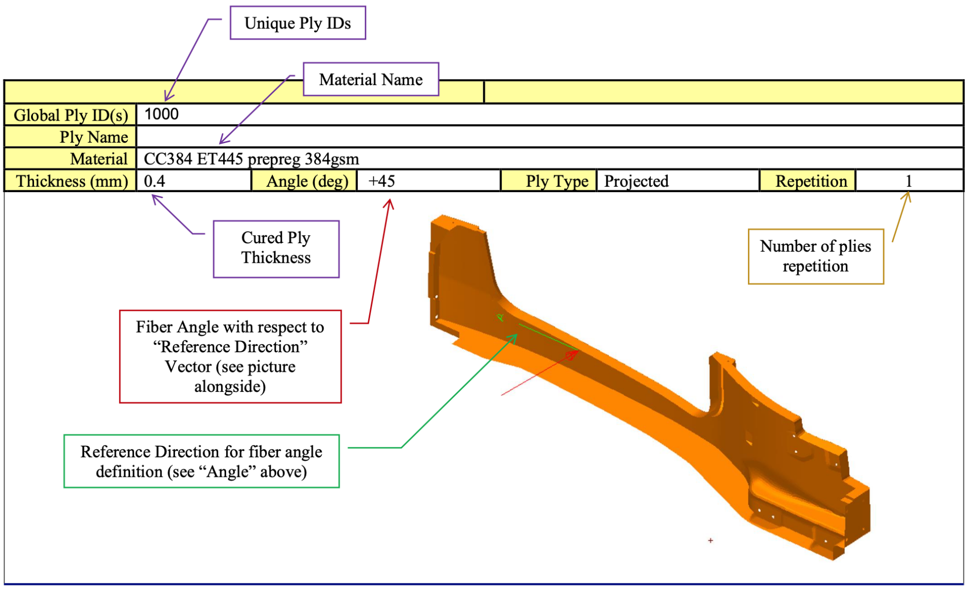

Figure 5.1: Ply-book example

The aluminum and steel inserts used in the the processes above need to be machined before the starting of the lamination. In fact usually, because the high level of optimization, they have strange shapes and dimensions, each different from the others. In the case of the foam core, the machining phase is expected also for it, because a perfect adhesion with the first skin on the mould is needed. The moulds are very complex elements that needs to be studied in order to avoid problems during parts' removal. For the tub a male mould has been created, in order to have a good surface finishing inside the cockpit and to make simple as possible the moulds combinations, avoiding the assembly of different moulds. For the door sill and front bulkhead a female mould has been designed, to guarantee a good external surface. In the case of the 004 monocoque, that is composed by different parts that need to be glued together, bonding jig has been made in order to ensure the correct positioning and the correct spaces for the glue. During the lamination phase of the the tub, the four inserts in the red circles, placed with locating pins, will be used for starting the machining phase. This begin with the plane creation on these 4 point, that will be the starting points for next machining procedures.

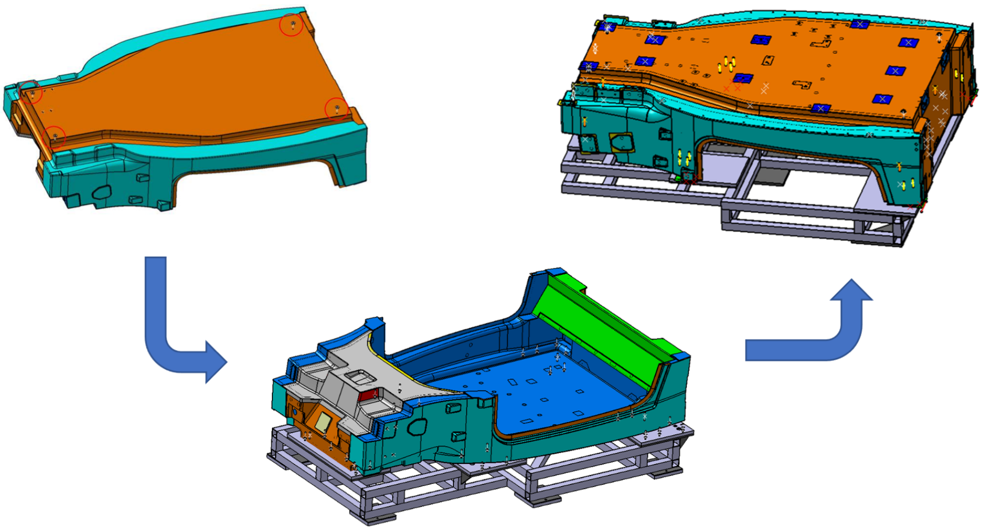

Figure 5.2: Monocoque machining phases

Then the monocoque is turned upwards and fixed on a jig, allowing the correct positioning on the CNC machine. All the features on the attachments points are done, from the stud holes, up to the surface machining and deform-nut holes. Using the previous made attachments, the monocoque is turned again in order to finish all the features on the bottom of the monocoque. After these processes, the threaded inserts are positioned and locked. As already explained, this method allow to reduce the possible errors due to thermal dilatation, to gluing variability and to the manual lamination process. Having extra sacrificial plies on all the attachment points allows to center the machining procedures and create always a monocoque that follows the tolerances. All these features needs to be collected in a file, where the positions of the holes, the types and their characteristics together with the location of the machining surface have to be specified in order to create the correct CNC program.

Figure 5.3: Monocoque machining details

5.2 Components verification

Before starting with the vehicle assembly procedures, the monocoque needs to pass a quality check, in order to verify all the possible wrong details. Nonetheless being the result of a very complicated and manual process, have a difference between the designed monocoque and the real one is not so impossible. A wrong fixing point holes or a not planar surface at the wrong quote can cause difficulties during the assembly and above all problems during the car usage. This process has been developed in parallel with the monocoque manufacturing, after the evaluations made on some test chassis, where the higher number of problems has been found. In order to ensure these quality, a report of the manufactured monocoque is requested to the supplier. This document consists of a real control procedure, that includes lot of checks, which purposes are to detect any dimensional or aesthetic discrepancies of the carbon fiber tub. All the procedure has been made and agreed with the supplier and it can be summarized in 5 different steps. The first is not a real step of the process, but it is very important since it concerns the definition of the reference documents that will be used to manufacture the monocoque and so that will be fundamental during its verification. Reference 3D models, technical drawings for dimensional tolerances, ply-book and other operating instructions regarding finishing and bonding specifications are stated at this stage. As an example, below it is reported one of the indications given regarding the interface and fixing surfaces of the front suspension attachments to the monocoque. These tight tolerances are due to the fact that machined components have to be fitted on them, as the suspensions brackets or rear chassis attachments.

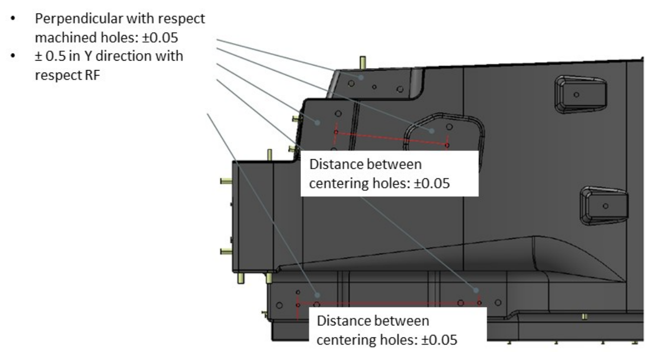

Figure 5.4: Accepted tolerances on monocoque machining

Other interesting reference documents are those related to the manufacturer quality know-how , acquired over years of experience in manufacturing CFRP high performance monocoques. Company standards regarding both quality acceptability requirements and technical verification guidelines are followed during the check of the tub. Particular attention is reserved to check the bonding and lamination of the various parts. A sophisticated and economical non destructing test is performed to find delamination of plies, simply by tapping on the surface of the component with an appropriate hammer. Based on the different acoustic resonance during the operation compared to the nominal value of a sample, it is possible to detect any damage on the panels. However, the method is difficult to apply on thick laminates where it is more difficult to recognize the location and depth of the damage.

The second phase of the process is the actual monocoque measurement phase. It consists in the 3D scan of the monocoque: as output, all the values of deviation related to specific surfaces and machined holes found with respect the values of the 3D CAD model are highlighted. As example, it is reported in the next figure one slide of the report, referred to the position and planarity of all the front right interface surfaces of the monocoque.

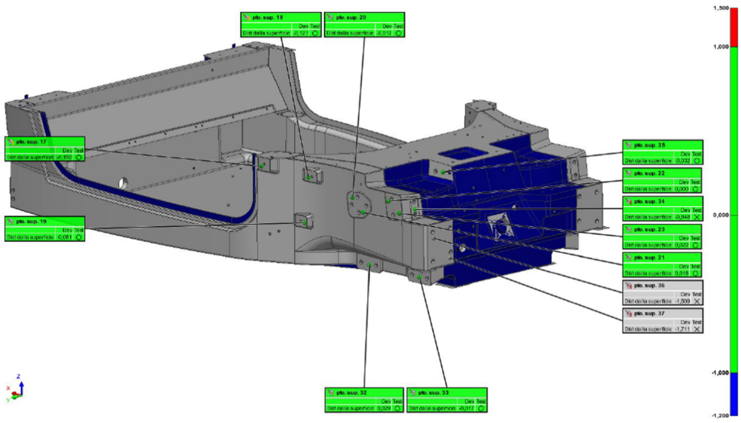

Figure 5.5: Planarity surface measurments

As previously mentioned, after the production of the first monocoque it was possible to improve the manufacturing process thanks to having found some large deviations during the measuring process. In particular, on the second monocoque produced, by comparing the results between left and right side of the monocoque, a strong asymmetry was found: this was related to a wrong and not precise positioning of the monocoque during the milling phase, that was improved going to use a positioning jig during the machining phase, as already explained. Same comparison is made for all the fixing holes, in order to check their positioning and the concentricity between them and their counter-bore.

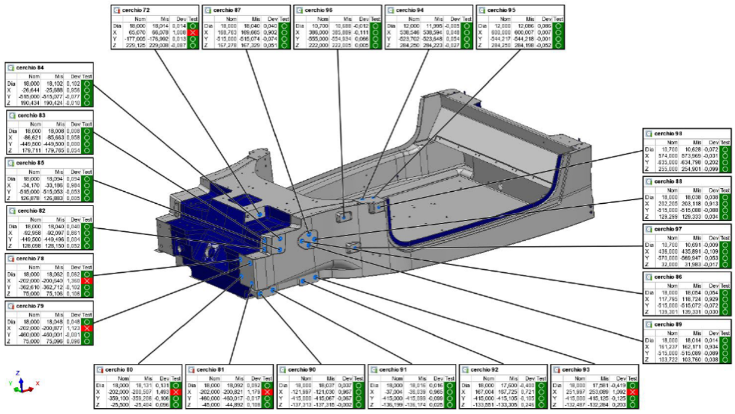

Figure 5.6: Hole positions surface

After the dimensional check, the third step is the installation and verification of all the inserts requested by Bill Of Material as Helicoil® and Deform-nut®. All the threads are then checked with the specified screws and custom studs.

The last check performed on the monocoque is the aesthetic one, whose requirements are different between the monococque of the race car, that mainly requires only to have a clean upper surface on the cockpit, without visible residual resin, and the one of the road legal vehicle, that has only two very small carbon look visible surfaces inside the cockpit of the vehicle.

5.3 Assembly procedures

The last part of the final chassis creation is the assembly of all the different parts together. Indeed as can be understood from the previous pages, all the components are created separately and from different suppliers. The first operation to be done is screwing the safety cage to the monocoque tub. This is done through M8 x 35 thick pitch hexagonal socket head screws, with strength class 12.9, as specified in the rules book. Making this step the safety cell has been created.

Before the definitive installation of the main cabin on the monocoque, all the cockpit components can be installed being the car more accessible. Starting from the screwing of the cockpit dashboard structure that will be the fixation of the

Figure 5.7: Survival cell assembled

steering column going to the installation of the fire extinguisher system that has all the pipes and nozzle fixed on the roll-cage. The next assembled part are the battery system together with all the electric loom and electronic devices, followed by the pedal-box. One of the more critic components that needs to be installed is the fuel tank, that fits very tight in the cockpit compartment, trying to contain the maximum possible quantity of fuel. Due to the fact that the fuel tank must be securely divided by the driver compartment, avoiding any passage of fluids, a carbon fiber structural cover has been designed ad installed on it, as can be possible to see in the next image.

The last operation to do in order to complete the cockpit compartment is the definitive bonding of the main cabin on the monocoque. The respectively positioning of the two parts is granted by specific insert on the gluing surface, that also keep the right space between the two parts. In fact, a structural bi-component adhesive is used to make a solid conjunction. The gap between the two surface that must maintained is of 0,5 *mm* as specified on the glue data-sheet to reach the maximum bonding strength. After the placement in position of the main cabin and fixed with the needed screws, the glue has to be left for 24 hours to complete the curing process.

At this point, the front crash structure can be assembled on the car. This

Figure 5.8: Fuel cell assembled inside the cockpit

structure is a unique replacement together with the front radiator and his ducts. This solution can be the game changer during a crash, in fact un-tightening 8 screw the complete front structure can be substituted. Also the rear frame chassis has a very easy assembly procedure. It is screwed to the rear bulkhead of the monocoque and reinforced with a upper and a lower cross beam, sustained by two bracing directly connected to the roll-cage. This very complex structure of tubes allow to reach the desired torsional stiffness, combined with monocoque one.

Figure 5.9: The finished cockpit structure

Chapter 6

Conclusions

Starting from a blank sheet as the 004C project has not been easy. Facing both the design phase along with its problems and the manufacture phase too, with the right supplier choices, have been a very complex business for a small and young company as Podium Engineering. This document can be seen as summary of the knowledge developed by the company on the monocoque design and production. The management of all these activity gave its results, in fact the project 004 is going on for the Scuderia Cameron Glickhenhaus. The 004S is on the road testing phase and it is in the prototypes car finalization just before the start of production. While the 004C has completed successfully her first season on the Nürburgring, finishing the 6 hours qualify race after a fire problem and just 3 weeks later also the most important race: the 24 hours on the Nordschleife. The vehicle has performed a very consistent race, finishing the first ever endurance race in 14^th position overall, without any reliability issue. Speaking about the chassis, no problems has been faced, neither on the monocoque nor on the rear chassis, also from the structural point of view. The performance of the car was very sensible to the set-up changes, being a proof of the good stiffness on the chassis, that must be higher than the roll-rate as already explained, becoming negligible. In next months, the road legal vehicle will be tested in the reality to validate the here discussed simulations. The car will face all the crashes in order to get the homologation for the USA commercialization. The 004C program is now on the development phase for the new season 2021, where the vehicle will compete again in the NLS series and then in the 24 hours on the 4-5 of June. Being part of the development team to improve an already good vehicle is a very complex job, but at the same time a very rewarding one.

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