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TRABAJO FIN DE GRADO

DESIGN AND MANUFACTURE OF A CARBON FIBRE MONOCOQUE CHASSIS FOR FORMULA STUDENT

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Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título

Design and Manufacture of a carbon fibre monocoque chassis for Formula Student

en la ETS de Ingeniería - ICAI de la Universidad Pontificia Comillas en el

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EL DIRECTOR DEL PROYECTO

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A mi familia por acompañarme y apoyarme en estos cuatro años de grado y a Ignacio Granell por haber tenido la posibilidad de hacer un TFG de un tema que me apasiona.

DISEÑO Y FABRICACION DE UN CHASIS MONOCASCO DE FIBRA DE CARBONO PARA FORMULA STUDENT

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RESUMEN DEL PROYECTO

El principal objetivo del proyecto es implementar el primer chasis monocasco en el ISC Formula Student Racing Team. El diseño final del chasis tiene una rigidez torsional de 3316 Nm/º (mayor que el anterior chasis) y un peso 49,5 kg. El proceso de fabricación que se ha llevado a cabo (cut and fold), garantiza la fabricación del monocasco con los medios actuales del equipo.

Palabras clave: Monocasco, chasis, rigidez, peso, ensayo, simulación, cut and fold.

1. Introducción

El principal objetivo de este documento es implementar el primer monocasco en el ISC Formula Student Racing Team. El chasis constituye la estructura principal del vehículo y en este caso estará constituido por materiales compuestos. Los materiales compuestos proporcionan una alta rigidez y en el caso de que el diseño sea optimo, una reducción de peso. En este caso, se empleará una estructura tipo sándwich. Los paneles de sándwich están compuestos por dos pieles, generalmente en forma de fibra y una matriz, que ne este caso, es honeycomb de aluminio. [1]

2. Metodología

El diseño está basado en la normativa de Formula Student, en el ensamblaje y en las limitaciones del proceso de fabricación. Una vez que el diseño final está terminado, para comprobar que el chasis cumple con los estándares de rigidez exigidos, un ensayo a flexión y otro a cortante se llevarán a cabo. Después, el ensayo a flexión se caracterizará en Ansys para demostrar que cada simulación que se haga en Ansys, concuerda con la realidad. A continuación, se llevarán a cabo varias iteraciones de diseño hasta conseguir un diseño optimo comparada con el chasis anterior. Por último, se explicará detalladamente el proceso de fabricación y el coste final del chasis.

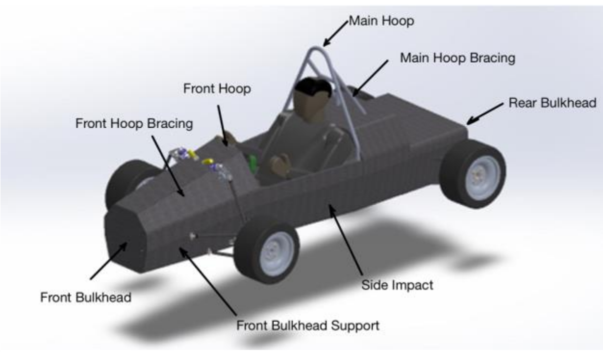

Ilustración 1: Diseño final del chasis

3. Resultados

Una vez que las planchas han sido laminadas con un proceso de laminado “wet lay-up”, con la siguiente configuración de capas, y se ha curado en bolsa de vacío, se procederá a ensayar el material.

Capa	Orientación	Fibra
1	± 45º	Biaxial
2	0º	UD
3	0º	UD
4	0º	UD
5	0º	UD
6	±45º	Biaxial

Tabla 1: Configuración de las capas

Para el ensayo a flexión por 3 puntos, se laminará un panel de 275x500 mm con la misma configuración de capas que en el chasis original. Dos soportes y un aplicador de fuerza de 50 mm de radio serán necesarios. La distancia entre los dos soportes fijos será de mínimo 400 mm. En el caso del ensayo a cortante, la muestra debe medir 100x100 mm. Ambos paneles deben representar las mismas propiedades mecánicas de tubos de acero (Ø25 x 2.5 mm). [2]

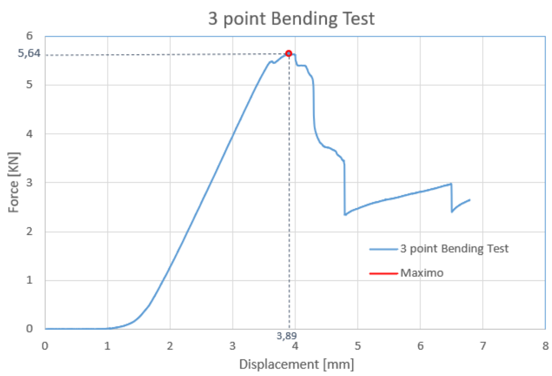

Ilustración 3: Ensayo a flexión

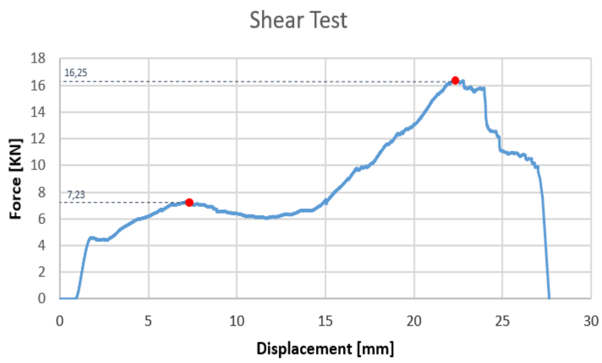

Ilustración 2: Ensayo a cortante

Con estos datos, se obtener de manera matemática las propiedades de la piel, con las siguientes formulas [3]:

$$\delta = \frac{k_b P l^3}{D} \qquad D = \frac{E_f t_f h^2 b}{2} \qquad \sigma_f = \frac{M}{h t_f b} \qquad M = \frac{PL}{4}$$

D= Rigidez a flexión	h = Distancia entre la mitad de las dos caras
E_f= Modulo de Young de la piel	b= Ancho
t_f= Espesor de la piel	σ_f= Tension de la piel
k_b = Coeficiente de deformación a flexión	δ = Deformacion
l= Longitud entre los dos paneles	M= Maximo momento flector
F= Maximum shear force	P= Applied load

Con los datos de la piel y los datos del honeycomb proporcionados por el fabricante, una similar simulación se ha obtenido en Ansys. Demostrando que las siguientes simulaciones concuerdan con la realidad.

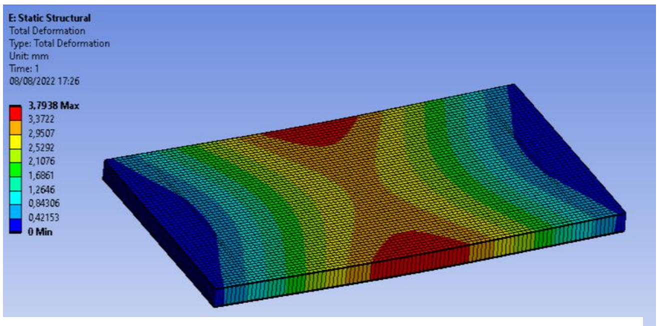

Ilustración 4: Deformación en ansys

El anterior chasis tiene una rigidez torsional de 3000 Nm/º. Diferentes iteraciones del diseño se llevarán a cabo hasta que un diseño con una mayor rigidez torsional y con el mejor coeficiente rigidez-peso sea seleccionado. En este caso, la segunda iteración es la elegida.

Iteración	Rigidez Torsional [Nm/º]	Peso total [kg]	Configuración de capas
Base	2264	46,1	[1x±45º/4x0º/1x±45º]
Primera	3533	52,9	[2x±45º/4x0º/2x±45º]
Segunda	3174	49,5	[2x±45º/3x0º/2x±45º]
Tercera	2846	52,9	[1x±45º/6x0º/1x±45º]
Cuarta	3326	52,9	[1x±45º/1x90º/4x0º/1x90º/1x±45º]
Quinta	2955	49,5	[1x±45º/1x90º/3x0º/1x90º/1x±45º]

Tabla 2: Iteraciones del diseño

4. Proceso de fabricación

La técnica cut and fold consiste en eliminar una tira de piel de una cara del sándwich, permitiendo que el panel se doble con el ángulo requerido consiguiendo la estructura deseada. Los siguientes pasos se deberán llevar a cabo:

1. Laminar la plancha “con las dimensiones antes del plegado de cada parte del chasis. Cada plancha estará sobredimensionada para proporcionar una fabricación más sencilla y un mejor acabado.
2. Corte. Una vez que el compuesto ha curado, el sándwich se cortara para conseguir las dimensiones finales antes de ser doblado. Para conseguir un corte preciso, se empleará corte por agua.
3. Eliminar la tira de piel para conseguir el ángulo de doblado deseado. La tira eliminada se calcula con la siguiente formula y esta será eliminada mediante una fresadora CNC para garantizar una mayor precisión.

$$x = \frac{2\pi * T * \theta^{º}}{360}$$

4. Doblado. Para doblar cada parte, todo hueco tiene que estar relleno de resina epoxy con glass microballons. Una vez que el adhesivo se ha colocado, se doblará el panel hasta la posición deseada. Se empleará una fibra de carbono para reforzar el área.[4]

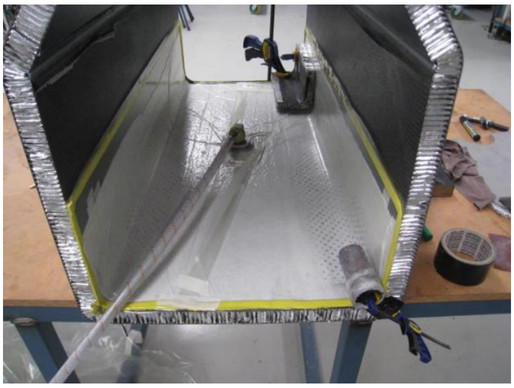

Ilustración 5: Paneles doblados

5. Presupuesto

	Cost [€]
Material para laminar	2474,39
Matriz	310,2
Proceso de fabricación	212,5
TOTAL	**2997,09**

6. Conclusiones

El diseño final presenta 10% de rigidez torsional, pero es un 5% mas pesado. Esto puede solucionarse mediante una optimización en el proceso de fabricación.

Además, se ha demostrado que cut and fold proporciona un bajo coste (2997,09 €), pudiendo conseguir un chasis monocasco de fibra de carbono con los actuales medios del equipo.

7. Bibliografia

[1] Hexcel Composites. (s.f.). *HONEYCOMB SANDWICH DESIGN TECHNOLOGY.*

[2] FSAE. (2022). *Formula Student Rules.*

[3] Hexcel Composites. (s.f.). *Sandwich Panel Fabrication Technology.*

[4] Tom James Ayres. *Design and Construction of Formula SAE Composite Chassis 2010.*

DESIGN AND MANUFACTURE OF A CARBON FIBRE MONOCOQUE CHASSIS FOR FORMULA STUDENT

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Supervisor: Granell Heredero, Ignacio
Collaborating Entity: ICAI - Universidad Pontificia Comillas

ABSTRACT

The main objective of this project is to implement the first monocoque chassis for ISC Formula Student Racing Team. The final chassis design has a torsional stiffness of 3316 Nm/º (higher than the previous chassis) and a weight of 49,5 kg. The manufacture process that has been followed (cut and fold), ensures that the team can fabricate a monocoque chassis with its current facilities.

Keywords: Monocoque, chassis, stiffness, weight, test, simulation, cut and fold.

1. Introduction

The main objective of the main document is to implement the first monocoque chassis for ISC Formula Student Racing Team. Chassis is the main support structure of the vehicle and in this case, it will be constituted of composite materials. Composites provides high stiffness structures and with the proper design optimization, it is also possible to reduce mass. In this case, a sandwich panel will be used. Sandwich panels are composed of two skins, generally in fibre form and a core which in this case an aluminium honeycomb has been chosen.[1]

The document encloses the design of the chassis, the test of the composite materials, structural analysis in Ansys, a design optimization, the manufacture process methodology and the final cost.

2. Methodology

The design is based on Formula Student Rules, package and the manufacture process limitation. Once the final design is done a 3-point bending test and a shear test will be carried out to check if the composite fulfils the stiffness requirements. Later, these tests will be characterized in Ansys to prove that every simulation concurs with reality. Afterwards, various design iteration will be considered in order to reach an optimal design compared to the previous chassis. Lastly, the manufacture process will be explained in detail and the final cost of the chassis will be shown.

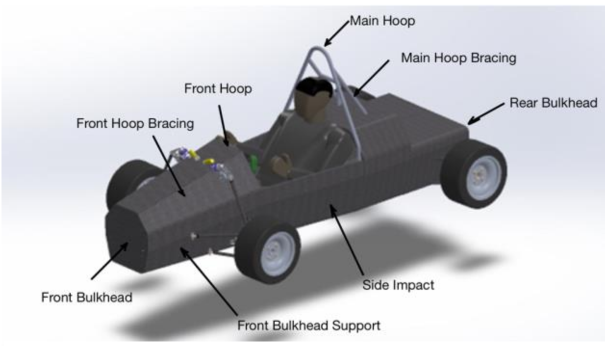

Figure 1: Final chassis design

3. Results

Once the plate for the bending test and the other plate has been laminated by wet lay-up with a vacuum bagging cured process with the following ply configuration, the bending test and shear test will be carried out.

Ply	Orientation	Fabric
1	± 45º	Biaxial
2	0º	UD
3	0º	UD
4	0º	UD
5	0º	UD
6	±45º	Biaxial

Table 1: Ply Configuration

For the 3-point bending a panel of 275x500 mm with the same design of the original chassis must be built. Two test panel supports and a load applicator of 50 mm of radius, will be required. The distance between the two supports must be at least 400 mm.
For the shear test, the sample must measure 100x100 mm. It will be measured the force required to push a 25 mm diameter flat punch to the panel. Both panels must represent the same mechanical properties as two steel tubes (Ø25 x 2.5 mm). [2]

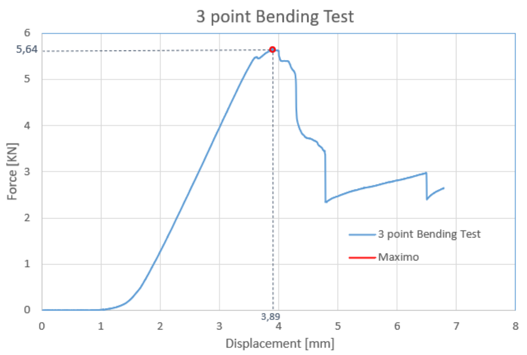

Figure 3: 3-point Bending Test

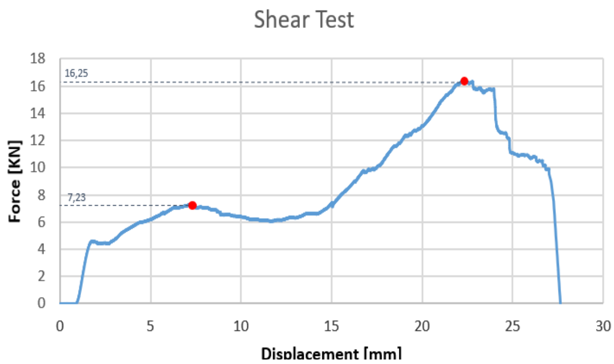

Figure 2: Shear Test

With this test data the characteristics of the sandwich skin can be mathematically obtained following the next equations [3]:

$$\delta = \frac{k_b P l^3}{D} \qquad D = \frac{E_f t_f h^2 b}{2} \qquad \sigma_f = \frac{M}{h t_f b} \qquad M = \frac{PL}{4}$$

D= Bending Stiffness	h = Distance between facing skin centres
E_f= Young modulus of the skin	b= Width
t_f= Thickness of facing skin	σ_f= Facing Stress
k_b = Bending deflection coefficient	δ = Calculated deflection
l= Length between the two support panels	M= Maximum bending moment
F= Maximum shear force	P= Applied load

With this skin data and the honeycomb properties that the supplier provides, a similar simulation is obtained in Ansys. Proving that the following simulations concurs with reality.

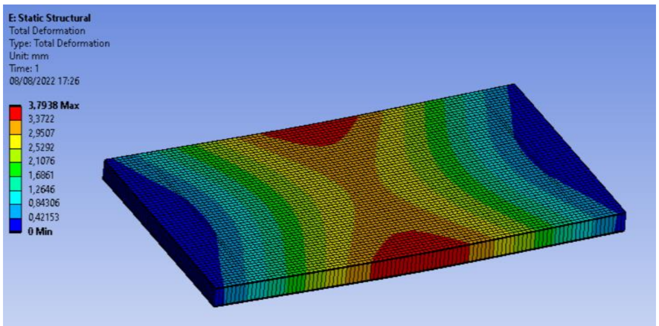

Figure 4: Deformation in Ansys

The previous chassis has a torsional stiffness of 3000 Nm/º. Different design iteration will be done until a design with higher torsional stiffness and the best stiffness-weight ratio will be selected. In this case the second iteration will be chosen.

Iteration	Torsional Stiffness [Nm/º]	Total weight [kg]	Ply configuration
Base	2264	46,1	[1x±45º/4x0º/1x±45º]
First	3533	52,9	[2x±45º/4x0º/2x±45º]
Second	3174	49,5	[2x±45º/3x0º/2x±45º]
Third	2846	52,9	[1x±45º/6x0º/1x±45º]
Fourth	3326	52,9	[1x±45º/1x90º/4x0º/1x90º/1x±45º]
Fifth	2955	49,5	[1x±45º/1x90º/3x0º/1x90º/1x±45º]

Table 2: Design ply iteration

4. Manufacture Process

Cut and fold technique consists of manipulating the panel by removing a strip of skin from one face of the sandwich composite, allowing the panel to be folded to create specific angles and a desired structure. The next steps should be followed:

1. Laminate the "unfolded" plate of each part of the chassis. Each plate will be oversized to make easier the manufacture process and provide a better finish.
2. Cut. Once the composite has cured, the sandwich will be cut to final dimensions before being folded. To achieve an accurate cut, waterjet cut will be used.
3. Remove the strip of skin required to the angle of bending. The strip removed is calculated with the following formula and it will be removed with a CNC milling machine to ensure a good precision and the folding process develops correctly.

$$x = \frac{2\pi * T * \theta^{º}}{360}$$

4. Fold. To fold each part, every cut groove must be filled with epoxy resin with glass microballons. Once the filler was set and the panel was placed into its proper position, a carbon fibre tape will be applied to reinforce the area. [4]

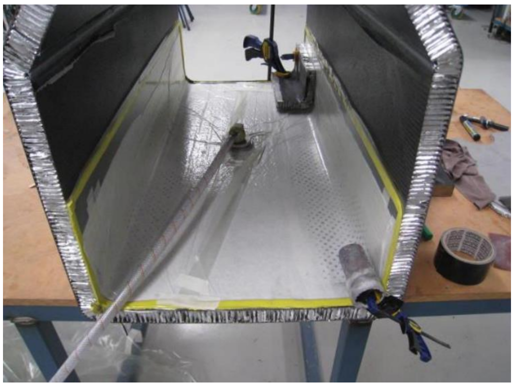

Figure 5: Folded Panels

5. Budget

	Cost [€]
Lay-up material	2474,39
Core	310,2
Manufacture process	212,5
TOTAL	**2997,09**

Table 3: Budget

6. Conclusions

The final design in terms of stiffness is optimal with a 10% rise on torsional stiffness, but in terms of weight, is 5% heavier. This can be solved by improving the manufacture process.

In addition, it has been demonstrated that cut and fold manufacture method offers a low cost (2997,09 €), providing the possibility to manufacture a carbon fibre monocoque chassis with the facilities that the team currently has.

7. Bibliography

[1] Hexcel Composites. (s.f.). *HONEYCOMB SANDWICH DESIGN TECHNOLOGY.*

[2] FSAE. (2022). *Formula Student Rules.*

[3] Hexcel Composites. (s.f.). *Sandwich Panel Fabrication Technology.*

[4] Tom James Ayres. *Design and Construction of Formula SAE Composite Chassis 2010.*

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Abreviations

FS	Formula Student
SES	Structural Equivalency Spreadsheet
PVC	Polyvinyl chloride
PS	Polystyrene
PU	Polyurethane
UD	Unidirectional
CNC	Computer Numerical Control
SI	Side Impact
MHBS	Main Hoop Bracing Support

1. INTRODUCTION

This project is developed in collaboration with ISC Formula Student Racing Team. The aim of this project is to develop the design and manufacture of the first carbon fibre monocoque chassis in the history of ISC Formula Student Racing Team, implementing the use of composites in structurally critical areas of the car. The chassis must meet the design requirements imposed by the competition (Formula Student) and the viability of the project will depend on different factors such as budget, facilities, sponsors or know-how.

1.1 FORMULA STUDENT

Formula Student is an international competition in which every team manufactures a Formula-style vehicle considering design criteria, business plan and participating in both dynamic and static events. The philosophy of the competition is to enable students to prove their creativity and engineering skills obtained during the degree, through the design, manufacture, and financing of a competition vehicle.

There are 3 modalities within this competition: combustion vehicle, autonomous vehicle and electric vehicle. All of them will participate in a series of tests, both static and dynamic.

Figure 6: Formula Student Netherlands

1.1.2 Static Tests

Static tests are composed of:

- Business Plan Presentation: Each team develops a business plan in which the judges should be treated as if they were potential investors or partners for the presented business model
- Cost and Manufacturing: The objective of the cost and manufacturing event is to evaluate the team´s understanding of the manufacturing process and costs associated with the construction of a prototype race car.
- Engineering Design: Evaluation of technical aspects of the design carried out by the students.[1]

To participate in the dynamic tests, a technical inspection must be passed first. This test must be carried out to prove the compliance of the vehicle with the technical regulations imposed by the organization. The technical inspection related to the electrical category consists of:

- Pre-inspection: for pre-inspection, all driver equipment and safety gears must be presented, two unused and in date fire extinguishers, one set of four tires on rims for wet conditions and one set of four tires rims for dry conditions.
- Accumulator inspection: accumulator documentation must be presented to prove the security of its use and manipulation. Also, the accumulator charger must be inspected.
- Mechanical Inspection: certain documentation will be shown to verify the mechanical security of the vehicle.
- Vehicle Weighing: all vehicles must be weighed in ready-to-race condition and all fluids of the car must be at their maximum fill level for weighing.
- Tilt Test: the vehicle must be placed upon the tilt table and to an angle of 60º. There must be no fluid leaks and all wheels must remain in contact with the tilt table surface.

- Rain Test: water will be sprayed at the vehicle from any possible direction. This test would be carried if the accumulator inspection has been passed previously.
- Brake Test: an acceleration and brake test is performed to check that the systems of the vehicle work properly. This test would be carried out if the previous tests have been passed previously. [1]

Figure 7: Tilt Test

These inspections follow a strict philosophy, and therefore, it is quite difficult to access to the dynamic tests. Almost half of the participants do not pass all the inspections mentioned before. Once all the technical inspections are passed, the dynamic events could be accomplished.

1.1.3 DYNAMIC TESTS

The dynamic tests are composed by:

1. Skidpad: The skidpad track consists of two pairs of concentric circles in a figure of eight pattern. It evaluates the performance of the car in terms of agility. The driver has two chances to reach the best run time without knocking down any cone.

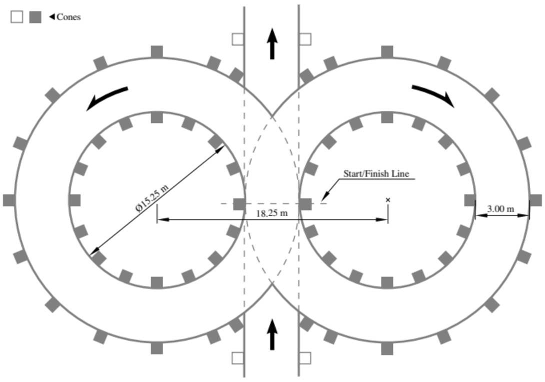

Figure 8: Skidpad

2. Acceleration: the acceleration track is a straight line with a length of 75 m from starting line to finish line. The fastest the team performs in the test the higher the score is.
3. Autocross: it evaluates the performance of the car in terms of acceleration, braking and corner speed. The autocross track has straights no longer than 80 m, constant turns, hairpin turns, slaloms and miscellaneous. The track length is less than 1.5 km. The lowest the lap time is, the higher the score is.

Figure 9: Autocross

4. Endurance and Efficiency: the aim of this test the autonomy of the car. The track is the same as the autocross, but the track length is approximately 22 km. [1]

After all tests have been completed the overall score of each team follow the next pattern:

	CV & EV	DC
Static Events:		
Business Plan Presentation	75 points	-
Cost and Manufacturing	100 points	-
Engineering Design	150 points	150 points
Dynamic Events:		
Skid Pad	50 points	-
DV Skid Pad	75 points	75 points
Acceleration	50 points	-
DV Acceleration	75 points	75 points
Autocross	100 points	-
DV Autocross	-	100 points
Endurance	250 points	-
Efficiency	75 points	-
Trackdrive	-	200 points
Overall	1000 points	600 points

Figure 10: Points distribution [1]

1.2 MOTIVATION

It is my third year in the chassis department of the ISC Formula Student Racing Team. Over the years, all our prototypes were composed by a tubular chassis made of steel. Currently we are finishing the design of the IFS-04 (the fourth prototype in the history of ISC), and a decision has been made to go the extra mile. My main motivation is to make this transition from a tubular chassis to a monocoque chassis become true, to improve the performance of our Formula-style vehicle in competition. The main reason why we develop a race vehicle is to improve its performance every year and to try to achieve the maximum number of points in Formula Student competition.

In addition, introducing the term of monocoque and implementing the use of structural composites in the vehicle will play a key role in the development of the ISC in the following years.

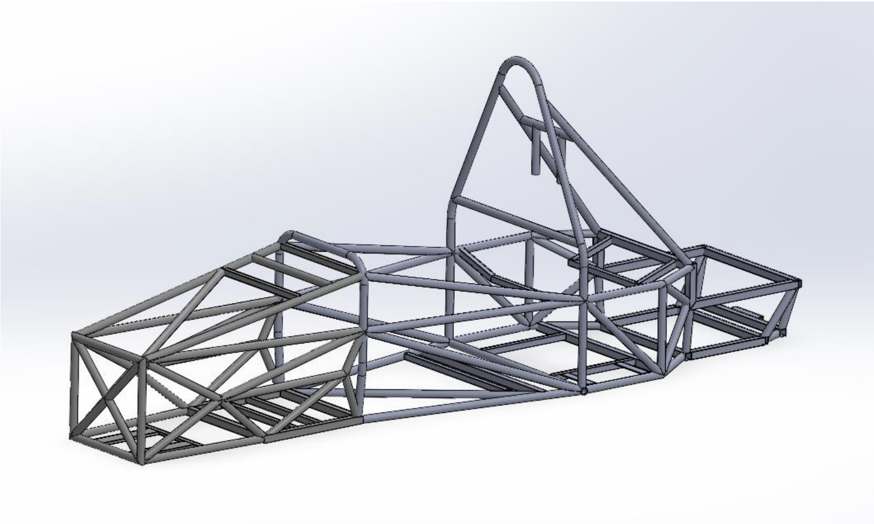

Figure 11: ISF-04 Space Frame

1.3 OBJECTIVES

As it has been stated, this document should provide a solid baseline for future generations of the ISC in terms of composite technology and improving the next possible monocoque. Objectives have been classified in two types: short-term objectives and long-term objectives. Firstly, short-term objectives:

1. Design a monocoque chassis considering the design restrictions imposed by the Formula student competition and the needs and design specs raised by the rest of the departments in the team (suspension, electronics…).
2. Implement a finite element analysis model, verifying that every part of the chassis fulfils the requirements imposed by the team and the competition rules
3. Test the honeycomb sandwich panel in the laboratory obtaining information about the material to prove its viability in terms of mechanical properties and its legality according to FS rules.

On the other hand, long-term objectives:

4. Manufacture the chassis and implementing it in the IFS-05 (prototype of next season)

1.4 RESOURCES TO USE

For the correct developing of this project, the following resources will be required:

1. CAD Programs: in this case, SolidWorks because is a sponsor of the team and a free licence is available.
2. CAE Programs: for the finite element analysis, Ansys is the program selected
3. Testing equipment (3-points bending machine…)
4. Materials (bought or obtained from sponsors)
5. Manufacturing requirements (jigs, tools…)
6. Facilities (space, machines, people…)
7. Budget

2. STATE OF ART

In this chapter, it will be shown the different type of chassis that are used in Formula Student. Depending on the objectives that the team establish a type of chassis should be chosen in order to fulfil the aims.

2.1 INTRODUCTION TO VEHICLE CHASSIS

Chassis is the main support structure of the vehicle, also known as 'Frame'. It bears all the stresses on the vehicle in both static and dynamic conditions [2]. This frame provides the security to the passengers in case of crash, so in terms of designing, the stiffness of the structure will be a key parameter. In addition, in motorsport, the weight also assumes an important role to have a good performance in competition.

Stiffness is characterised in two different kinds

- Torsional Stiffness: having a high torsional stiffness in the chassis is essential to obtain a good dynamic performance. Torsional stiffness is the ability of the chassis to withstand twisting loads in the form of the torque needed to twist the chassis 1 degree. It is important, in order to transfer the loads properly of the front and rear suspension. If the torsional stiffness is too small, the chassis will fail. If it is too large, it will be difficult to turn and tend to under-steer. [3]
- Bending Stiffness: is usually less important than torsional stiffness. A chassis with a good torsional stiffness usually has a good bending stiffness. It would be a design restriction, but it is a parameter that should be considered.

In the case of our chassis, is designed for Formula Student so the weight and the height of the centre of gravity should also be studied. In the terms of weight, in an electric vehicle, the most affected areas are: driver, chassis, batteries and motor.

Lastly, the height of the centre of gravity should be as low as possible, providing a good stability to the car and avoiding the overturn in extreme situations.

2.2 DEVELOPMENT OF CHASSIS IN COMPETITION

Most of the innovations and developments in current race and commercial cars have been developed in Formula 1 along the years. At the beginning of the Formula 1 championship (1950), every chassis of every team was space frame, with a fairing on.

Figure 12: Formula 1 in Monaco

It was not until 1962, when the monocoque was invented by the legendary designer and Lotus team boss Colin Chapman, who inserted a riveted lightweight metal (aluminium) case instead of the classic tubular spaceframe in his Lotus 25 in 1962 [4]. In this case, the aluminium plates were folded to adopt the pretended aerodynamic shape.

Figure 13: Lotus 25

In 1981, McLaren developed the first monocoque chassis manufactured from carbon fibre composite, the McLaren MP4/1. McLaren could reach the same stiffness of their competitors' vehicles with a weight reduction. Also, this type of chassis is safer than the aluminium one, incrementing the safety of the drivers.

Figure 14:McLaren MP4/1

2.3 TYPE OF CHASSIS

For this type of competition, teams usually adopt 3 different chassis styles depending on the restrictions that the vehicle has or needs, and the manufacturing resources available, which will depend mainly on the facilities available, which will depend mainly on the financing or sponsors available.

2.3.1 SPACE FRAME

Space frame chassis is the first structure that every Formula Student team starts with. It consists of a structure made of welded steel or aluminium tubes. It is not difficult to design and to fulfil the stiffness requirements imposed by the competition. Which makes it the most common configuration in first year teams. The welding technology that ISC uses is TIG, but other technologies can be use depending on the material, the cost, or the structural requirements. Bolted attachments could also be used.

Figure 15: ISF-03 Space Frame

2.3.2 MONOCOQUE

Monocoque chassis is a structure usually made of composite materials. The term monocoque means that the chassis is integrated with the complete body as one part. Monocoque construction is significant for reducing the vehicle’s overall mass by integrating the chassis and the body into a single unit. Other vehicle components such as powertrain, steering, suspension, and brakes are directly mounted to the vehicle’s body in this design, allowing more design freedom [5]. Although the monocoque can provide a higher stiffness and lower weigh than the tubular configuration, it presents some difficulties in terms of manufacturing. It is generally more expensive, but there are manufacturing methods that help reduce its cost.

Figure 16: Monocoque Chassis

2.3.3 HYBRID

Hybrid chassis is a combination of both mentioned before. The front is usually made of composites due to its stiffness and the possibility of developing more complex aerodynamic shapes, improving vehicle performance. The rear is composed of welded steel or aluminium tubes.

With this configuration we could reach a lower weight and more design freedom compared to the space frame, but the manufacture process is more complex. Compared to the monocoque, hybrid chassis is usually heavier, but the manufacture process is a little bit easier.

In terms of designing, the attachment between both parts, should be considered because it could be a critical point in terms of the stiffness of the structure.

Figure 17: Hybrid Chassis

3. CHASSIS DESIGN

The design of the chassis will be based on design requirements imposed by competition, Formula Student Germany, which is the most restrictive of all. Some chassis definitions should be mentioned to understand the following pages.

- Front bulkhead – A planar structure that defines the forward plane of the chassis and provides protection for the driver's feet.
- Front bulkhead support – A structure that defines the side of the chassis from the front bulkhead back to the top of the upper side impact structure and the bottom of the front hoop.
- Front hoop – A roll bar located above the driver's legs, in proximity to the steering Wheel
- Impact Attenuator (IA) – A deformable, energy absorbing device located forward of the front bulkhead.
- Main hoop – A roll bar located alongside or just behind the driver's torso.
- Roll hoops – Both the front hoop and the main hoop are classified as "roll hoops"
- Roll hoop bracing – The structure from a roll hoop to the roll hoop bracing support
- Side impact structure – The area of the side of the chassis between the front hoop and the main hoop and from the chassis floor to the height [1]

In the "FS Rules 2022 v1.0", the chassis design is focused on chapter T3 (General Design Requirements), T4 (Cockpit) and T5 (Driver Restrain System).

3.1 CHASSIS DESIGN BASIS

Since the idea of the monocoque is aimed for a Formula Student competition, the geometrical requirements will be all based on FS Rules. This is focused on safety aspects for the driver, as well as trying to define a standard structure, on which all teams will be based.

In this section, the most important requirements, will be taken into account mainly the ones that provide the cockpit pattern design, one of the most important parts of the car to ensure the physical integrity of the driver.

3.1.1 TEMPLATES

These templates are designed to ensure drivers' safety, there are two types of templates, the cockpit opening template (left) and the cockpit internal cross section template (right). The last one, must pass from the cockpit opening to a point 100 mm rearwards of the face of the rearmost pedal in an inoperative position. The template may be moved up and down. Adjustable pedals must be in their most forward position. Steering column may pass through the area indicated in the next figure. The cockpit opening template should pass 320 mm downwards the cockpit. The steering wheel could be removed in both inspections. [1]

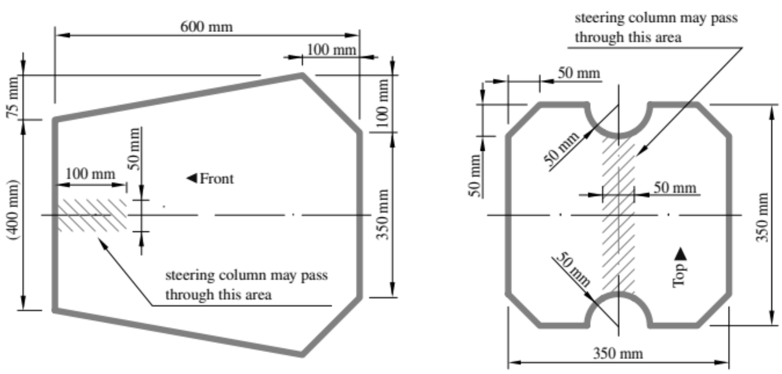

Figure 18. Templates [1]

3.1.2 PERCY 95

The aim of this rule is to define the driver position in the vehicle, restricting distance between neck and head restraint or the pedals with the seat bottom. The dimensions of this Percy 95, englobe the dimensions of the 95% of male population. The illustrative measurements of this Percy 95 are shown in the next figure. This would determinate the ergonomics and some dimensions of the chassis. [1]

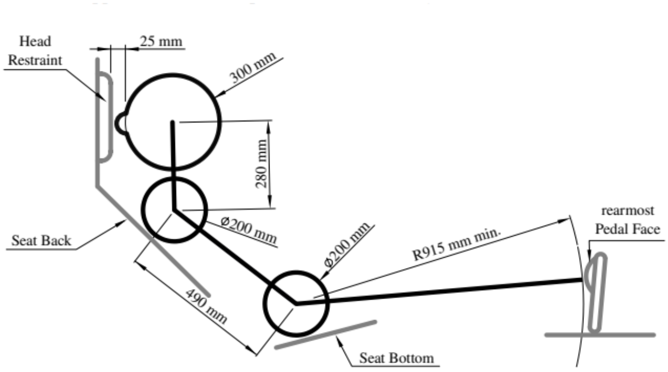

Figure 19: Percy 95 [1]

3.1.3 HELMET DISTANCE

When seated normally and restrained by the driver's restraint system, the helmet of a 95th percentile male and all the team's drivers must:

- Be a minimum of 50 mm away from the straight line drawn from the top of the main hoop to the top of the front hoop.
- Be a minimum of 50 mm away from the straight line drawn from the top of the main hoop to the lower end of the main hoop bracing if the bracing extends rearwards.
- Be no further rearwards than the rear surface of the main hoop if the main hoop bracing extends forwards [1]

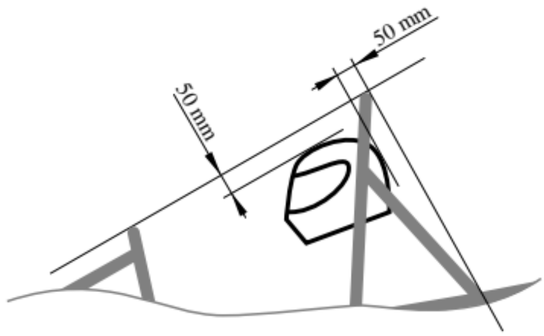

Figure 20: Helmet distance [1]

3.1.4 SIDE IMPACT

As the chassis is constituted of composite materials the rules change slightly. FS rules are based on a steel space frame. When dealing with composite materials, some equivalences must be met. In this case, the side impact must have an EI equal to 3 baseline tubes (steel Ø25.4x2 mm), the shear strength (7.5 KN) and absorbed energy. EI is defined as flexural rigidity, which provides the resistance of the material against a bending load. The shear strength is defined as the material property that describes material's resistance against a shear load before the component fails in shear, this shear action occurs parallel to the direction of the force acting on a plane [6]. The energy absorption is defined as the surface below the load-displacement curve [7]. For this kind of equivalences, the competition provides a SES, to verify that the materials that has been chosen, satisfy the requirements. In terms of dimensions, the region that is longitudinally forward from the main hoop and to the front hoop must be 320 mm height from the lowest point inside of the chassis.

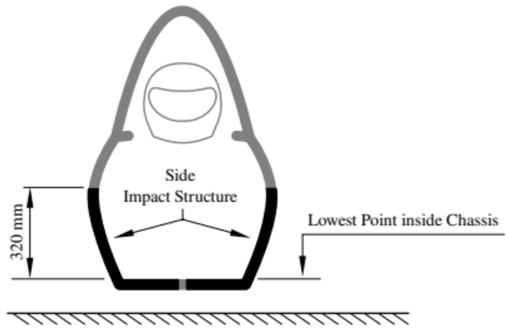

Figure 21:Monocoque Side Impact

3.1.5 Roll Hoops

The main hoop as well as the front hoop must fulfil:

- The minimum radius of any bend, measured at the tube centreline, must be at least three times the tube outside diameter. Bends must be smooth and continuous with no evidence of crimping or wall failure.
- The main hoop must be constructed of a single piece of uncut, continuous, closed section steel tubing.
- In side view the portion of the main hoop which is above its upper attachment point to the side impact structure must be inclined less than 10° from vertical.
- The front hoop must be constructed of a continuous and closed section.
- In side view, no part of the front hoop can be inclined more than 20° from vertical [1].

3.1.6 MAIN HOOP BRACING

The main hoop must be supported to the front or the rear by bracing tubes on each side of the main hoop. Main Hoop Bracing must fulfil the following requirements:

- The main hoop braces must be attached to the main hoop no lower than 160 mm below the top-most surface of the main hoop.
- The included angle formed by the main hoop and the main hoop braces must be at least 30°.
- The main hoop braces must be straight [1].

3.1.7 STRUCTURAL EQUIVALENCY SPREADSHEET (SES)

The SES is an Excel table to prove that the car is safe to compete. As it was mentioned before, the SES is used to verify that the materials that has been chosen, satisfy the requirements. For the chassis, the SES is divided in different pages depending on the part of the chassis (Front Hoop, Front Hoop Bracing, Main Hoop, Main Hoop Bracing, Side Impact, Front Bulkhead and Front Bulkhead Support). If the chassis is a steel space frame, the number and the dimensions (external diameter and thickness) of each tube should be fulfil in order prove the stiffness required for each part of the car. If the chassis is composed by composite materials, a 3-point bending test and a shear test must be done, to prove the structural equivalency compared to steel.

Powertrain Type: **Electric Vehicle**
Is proof of equivalency for your design required for any of the rules?
Yes. Chassis deviates from baseline requirements

Baseline Material Used	Alternative Material Used	Rule No.	Rule Description	Design Description and/or Material Name	Tube and Laminate Equivalency: EI / Safety Factor	Area	Yield	UTS	Yield as Welded	UTS as Welded	Max Bending Load at UTS	Max deflection at max baseline load	Energy absorbed during bending
YES	NO	T3.8	Main Roll Hoop Tubing		NA	NA	NA	NA	NA	NA	NA	NA	NA
YES	NO	T3.9	Front Roll Hoop Tubing		NA	NA	NA	NA	NA	NA	NA	NA	NA
NO	YES	T3.10	Main Roll Hoop Bracing Tubing		113	##	##	##	##	##	##	88	##
NO	YES	T3.10.5	Main Hoop Bracing Support - Tube Frames		115	##	##	##	##	##	##	87	##
YES	NO	T3.11	Front Hoop Bracing - Tube Frames		NA	NA	NA	NA	NA	NA	NA	NA	NA
YES	NO	T3.13	Front Bulkhead - Tube Frames		NA	NA	NA	NA	NA	NA	NA	NA	NA
NO	YES	T3.14	Front Bulkhead Support - Tube Frames		153	##	##	##	##	##	##	65	##
YES	NO	T3.15	Side Impact Structure - Tube Frames		NA	NA	NA	NA	NA	NA	NA	NA	NA
YES	NO	T4.5	Shoulder Harness Bar		NA	NA	NA	NA	NA	NA	NA	NA	NA
NO	YES	T3.17.3	Impact Attenuator Anti-Intrusion Plate		CH								
N/A	N/A	T3.11/T3.5	Front Hoop Bracing - Monocoques		NA	NA	NA	NA	NA	NA	NA	NA	NA
N/A	N/A	T3.13 /T3.5	Front Bulkhead - Monocoques		NA	NA	NA	NA	NA	NA	NA	NA	NA
N/A	N/A	T3.14 /T3.5	Front Bulkhead Support - Monocoques		NA	NA	NA	NA	NA	NA	NA	NA	NA
N/A	N/A	T3.15 / T3.5	Side Impact Structure - Monocoques, Side		NA	NA	NA	NA	NA	NA	NA	NA	NA
N/A	N/A	T3.15 / T3.5	Side Impact Structure - Monocoques, Floor										
N/A	N/A	T3.10.5/T3.5	Main Hoop Bracing Support - Monocoques		NA	NA	NA	NA	NA	NA	NA	NA	NA
N/A	N/A	T3.16	Main Hoop Attachment - Monocoques		NA								
N/A	N/A	T3.16	Front Hoop Attachment - Monocoques		NA								
N/A	N/A	T3.16	Hoop Bracing Attach. - Monocoques		NA								
N/A	N/A	T1.2.1 / T4.8	Firewall		PA								
N/A	N/A	T3.17.5	Impact Attenuator Attachment - Monocoques		NA								
N/A	N/A	T4.5	Safety Harness Attachment - Monocoques		NA								
N/A	N/A	EV5	Accumulator Container										

Rule No.	Tube 1: Tube Material	Tube type	Outside Dimension	Wall thickness	Tube 2: Tube Material	Tube type	Outside Dimension	Wall thickness	Tube 3: Tube Material	Tube type	Outside Dimension	Wall thickness	Comp: Material	Panel Thickness	Inner Skin Thickness
T3.8	Steel	Round	25,0	2,50											
T3.9	Steel	Round	25,0	2,50											
T3.10	Steel	Round	25,0	2,00											
T3.10.5	Steel	Round	25,0	1,50											
T3.11	Steel	Round	25,4	1,60											
T3.13	Steel	Round	25,0	2,00											
T3.14	Steel	Round	25,0	1,50											
T3.15	Steel	Round	25,0	2,50											
T4.5	Steel	Round	25,0	2,50											
T3.17.3															
T3.11/T3.5															
T3.13 /T3.5															
T3.14 /T3.5															
T3.15 / T3.5															
T3.15 / T3.5															
T3.10.5/T3.5															
T3.16															
T3.16															
T3.16															
T1.2.1 / T4.8															
T3.17.5															
T4.5															
EV5															

Figure 22: Structural Equivalency Spreadsheet (SES)

3.2 DESIGN JUSTIFICATION

For the design justification the following points have been considered:

- FS Rules
- Package

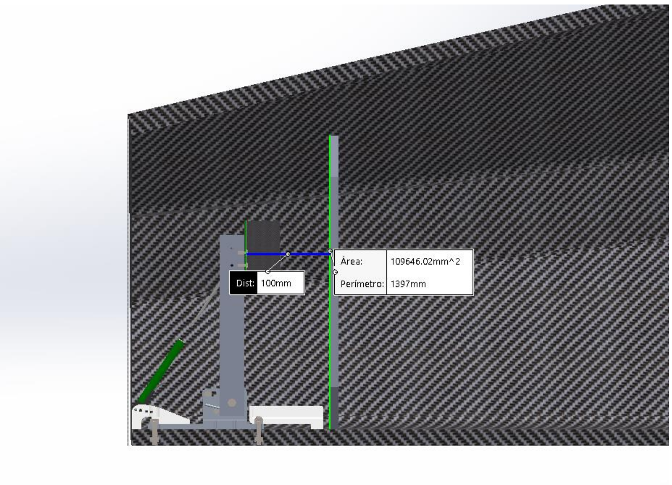

Figure 23: Design based on the cockpit internal cross section template

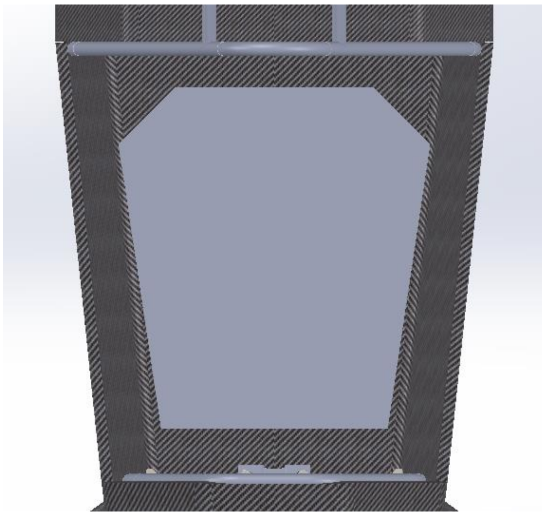

Figure 24: Design based on the cockpit opening template

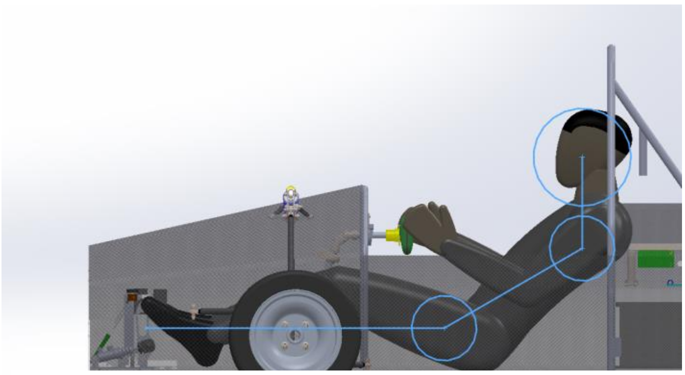

Figure 25: Side view of the ergonomics design

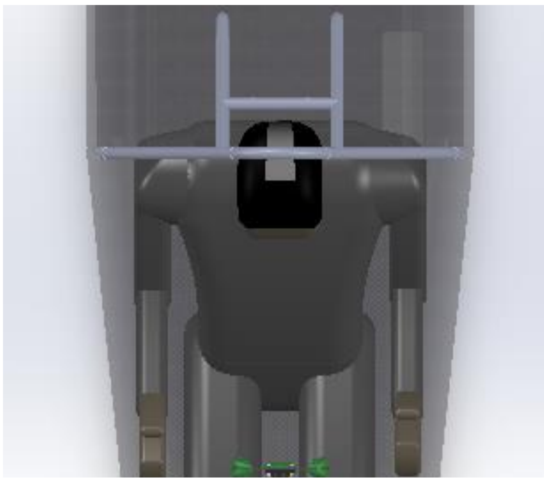

Figure 26: Top view of the ergonomics design

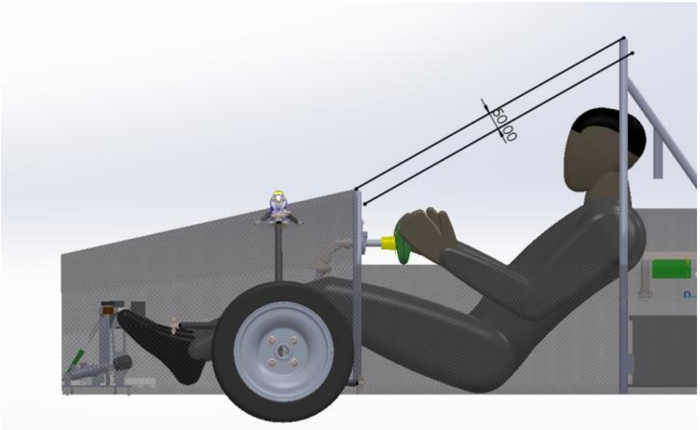

Figure 27: Helmet distance

Figure 28: Front Hoop

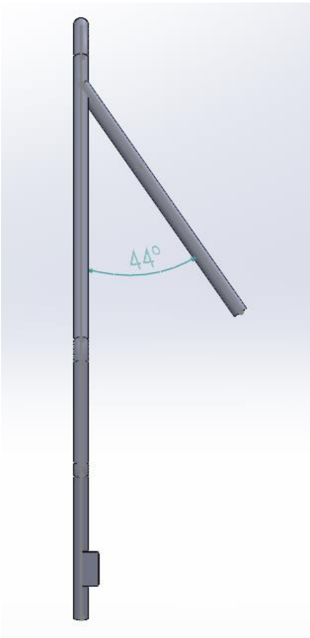

Figure 29: Main Hoop Bracing

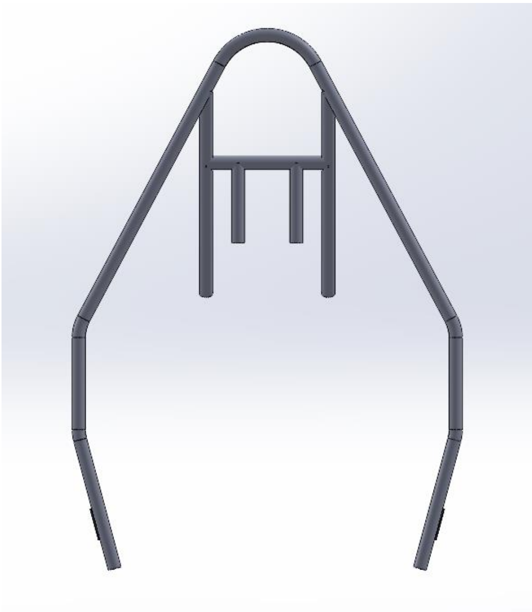

Figure 30: Main Hoop

For the package, all the following components must fit on rear part of the chassis:

- Battery accumulator
- Low voltaje battery
- Electronics box
- Powertrain
- Inverter

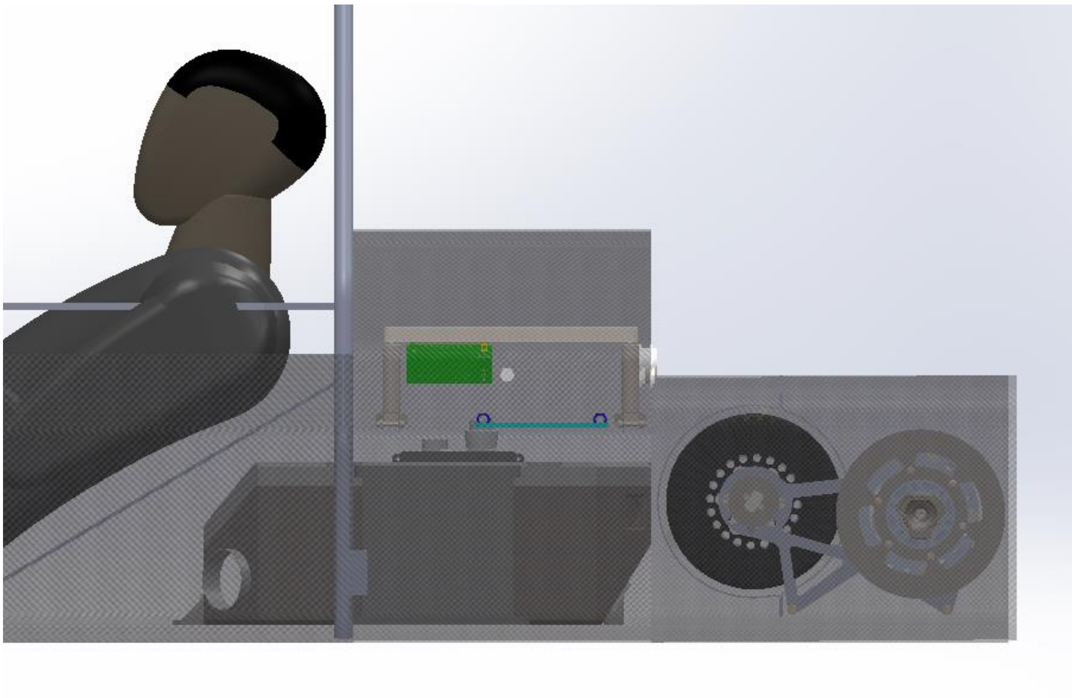

Figure 31: Package

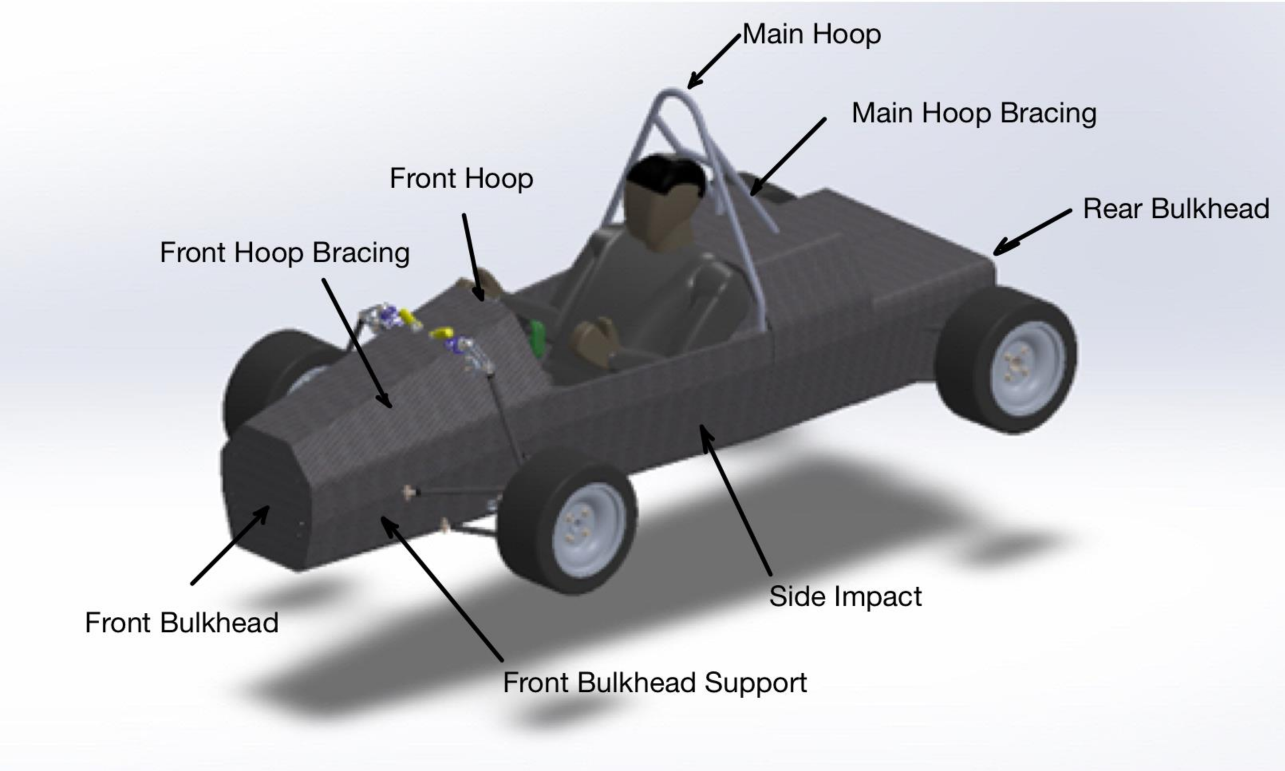

Figure 32: Final Design

Before selecting the materials for the monocoque chassis, a definition of how composite materials works will be useful to understand the design justification.

3.3 COMPOSITES MATERIALS

Composite materials are the ones which are composed of at least two elements. These components usually can be combined at different proportions for different final properties of the composite. The combination of these elements can have better properties than other elements acting alone. These composite structures are usually composed by a matrix and reinforcements. The reinforcements are usually in fibre form. [8]

Composites enable us to create structures with better stiffness and with the proper design optimization is also possible to reduce mass. Compared to metal structures, with composites we can reach lighter structures with the same or better mechanical properties. Composites provide freedom in terms of designing, offering the possibility of getting complex shapes and reaching an optimal design via sandwich structures. [9]

As we can appreciate in the table, what makes composites different from metals is that they possess much lower densities, providing a higher specific modulus (E/ρ) that enable the production of lower weight components and structures.

Material	Density (gcm^{-3})	Tensile strength, σ (MPa)	Tensile modulus, E (GPa)	Specific strength (σ/ρ)	Specific Modulus (E/ρ)
Steel	7.8	1300	200	167	26
Aluminium	2.81	350	73	124	26
Titanium	4.42	900	108	204	25
Magnesium	1.8	270	45	150	25
Al 62%Be	2.1	386	186	193	93
E glass	2.10	1100	75	524	21.5
Aramid	1.32	1400	45	1060	57
IM Carbon	1.51	2500	151	1656	100
HM Carbon	1.54	1550	212	1006	138

Table 4: Mechanical properties comparison [9]

Most of metals and plastics are isotropic, which means that the mechanical properties are independent of the direction of the stress, instead, composites are anisotropic, mechanical properties depend on direction of the stress or the fibre orientation, this is a fact that must be considered in terms of designing. [9]

To optimize the design, we will establish a honeycomb sandwich structure. Reaching the stiffness required with the lowest possible weight is the main objective when designing a chassis for FS. Honeycomb sandwich structure provides a higher stiffness with a low weight rise, the thicker the core is, the higher the stiffness of the component for minimal weight gain [10]. This is the reason why this composite structure will be implemented on the monocoque. But firstly, the different types of reinforcements and core would be shown.

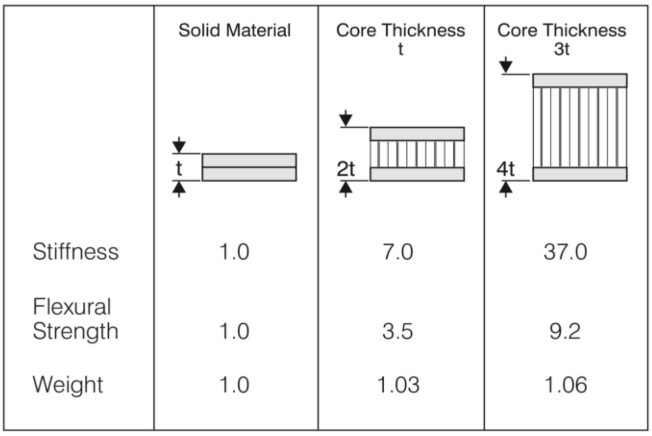

Figure 33: Effect of core thickness [10]

3.3.1 REINFORCEMENTS

Carbon fibre is the reinforcement that will be used because is the strongest one. There are two types of carbon fibre: Dry Fibre Impregnation and Prepeg.

Prepeg is preimpregnated with the ideal amount of epoxy resin reaching an ideal balance between resin and fibre. While Dry Fibre Impregnation must be mixed with epoxy resin to conform the skin of the sandwich structure during lamination. On next table are shown some of the main characteristics of both. [9]

Dry Fibre Impregnation	Prepreg
✓ Low cost plant and materials	✓ Stability of mechanical properties
✓ Oven/vacuum cure	✓ High quality reproducible intermediate product
✓ No major storage issues	✓ Best consolidation and defect reduction
× Poor quality and reproducibility	× Expensive
× Large and unpredictable defect quantity	× Generally, requires autoclave
	× Limited materials out-life requiring refrigerated storage

Table 5: Comparison of Dry Fibre Impregnation and Prepeg [9]

The mechanical properties of the composite depend on:

- The properties of the carbon fibre
- The properties of the resin (epoxy)
- The Fibre Volume Fraction and the Resin Volume fraction
- The carbon fibre orientation [11]

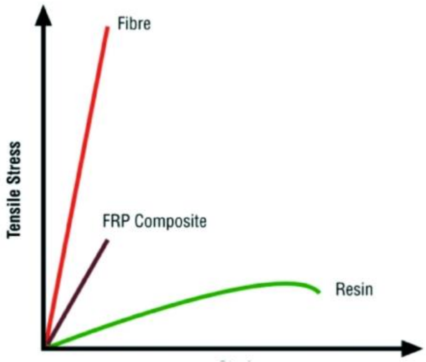

Figure 34: Tensile Properties of Fibre, Resin and Composite [11]

The properties of the composite depends on the tensile stress of the fibre and the resin and the strain of the fibre. The mechanical properties of the fibre are higher than the resin ones, so the higher the fibre volume fraction the higher would be the stiffness of the composite. The fibre volume fraction and the resin volume fraction depend on the manufacturing process. In the prepreg configuration the minimum needed resin volume fraction is reached, this is one of the reasons its mechanical properties are better than dry fibre impregnation with manual resin injection. The fibre orientation is also important in terms of stiffness, but it will be discussed later.

$$E_c = v_m E_m + v_f E_f$$

Equation 1: Rule of mixtures

E_c= composite Young Modulus

E_m= matrix Young Modulus

E_f= reinforcement Young Modulus

v_m = matrix volume resin

v_f = reinforcement volume fraction

3.3.1.1 Fabric types

Fabric types are classified by the orientation of the fibres used, and by the different construction methods used to hold the fibres together [11].

The three main fibre orientation categories are: Unidirectional, Bidirectional (woven) and Multiaxial.

- Unidirectional Fabrics (UD)

  The unidirectional (UD) fabric is the one in which most fibres are oriented in one direction only (more than the 90%). This type of fibre presents a very high stiffness only in the direction that the fibre runs.[11]

- Bidirectional or Woven

  Bidirectional fabrics are produced by interlacing 0º fibres and 90º fibres. They are used when more than one orientation of the fibres is required. This type of fibre presents high stiffness but lower than UD in two directions and can be heavier than UD. Depending on the way the fibres are interlaced the characteristics of the composite could be different. The most frequent one is the "Twill".

- Multiaxial

  The manufacture process of Multiaxial fabrics is similar to the bidirectional, but it can be interlaced fibres in other directions like 45/-45.

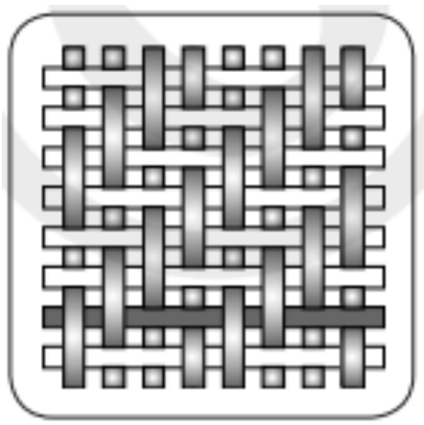

Figure 35: Twill Fabric

3.2.2 CORE MATERIALS FOR SANDWICH CONSTRUCTION

In terms of designing a sandwich structure, is important to choose a core that suits the design requirements. There are three types of core material: foam cores, thermoplastic cores and honeycomb cores.

- Foam cores
  Foam cores can be manufactured from a variety of synthetic polymers such as polyvinyl chloride (PVC), polystyrene (PS) or polyurethane (PU). Their main characteristic is their low density. In the case of PVC, it has good properties in a large temperature range (-240ºC to 80ºC) or PU presents good acoustic isolation. [11]
- Thermoplastic cores
  Thermoplastic cores are very cheap, but it can be difficult to bond the core to the skin.
- Honeycombs cores
  Honeycomb cores can be found in different materials for sandwich construction. The two main honeycomb cores are made from Aluminium and Nomex (aramid). Honeycomb stiffness and strength (shear and compression) is proportional to density. Also, the shape of cells and the cells size have an important role in terms of core behaviour. [10]

  There are two types of cell shape, hexagonal cells and rectangular cells. Hexagonal cells are the most common ones, providing a low density. The cell size also affects to the final properties of the honeycomb. The standards cell size are 1/8",1/4",1/2" and 3/4". The bigger the cell size is the lighter and cheaper is the core but may result in a dimpled outer surface of the sandwich structure if the faces are thin. Finally, the effect of the core thickness in the sandwich structure plays a key role in the matter of stiffness and flexural strength. Honeycomb panels can range from 3 to 50 mm of thickness [11]. When choosing between aluminium or Nomex (made of aramid) honeycomb core, some points should be considered. Aluminium honeycomb has one of the highest strength/weight ratios and lower density, main reason to select, although Nomex honeycomb also has high strength and a very good fire resistance but is the most expensive core [11]. The aluminium honeycomb will be selected due to its price and high stiffness.

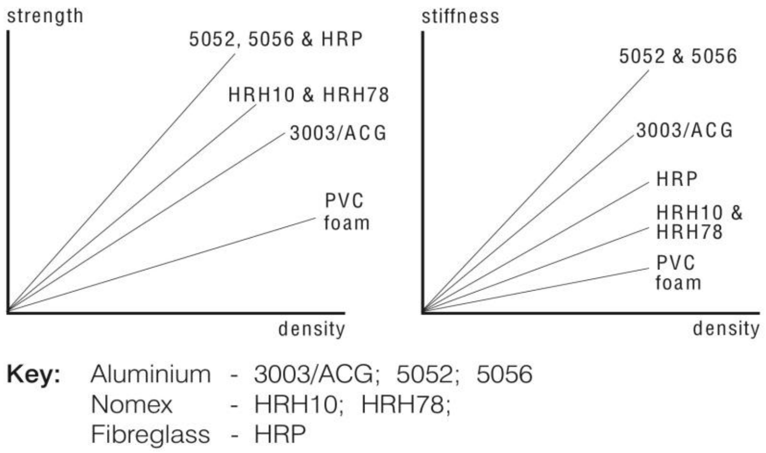

Figure 36: Strength and Stiffness of different honeycombs [10]

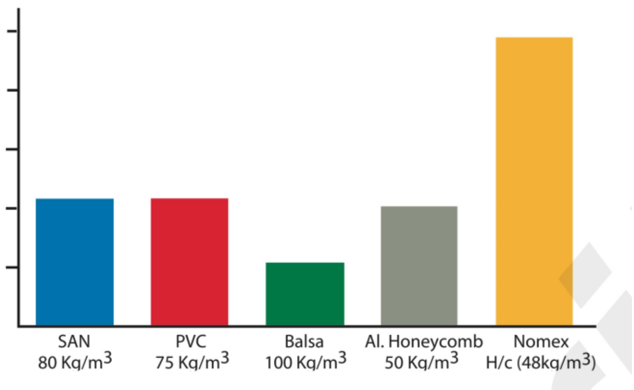

Figure 37: Comparative core costs [11]

3.2.3 DESIGN WITH COMPOSITES

Before considering which type of core, adhesive and face skin that will be used, the kind of behaviours that the core and skin has according to the different type of stress should be considered.

- Tension: skin dominant property. Dependant on the tensile stiffness and strength of the fibre, which are much higher than the mechanical properties of the epoxy resin [9].

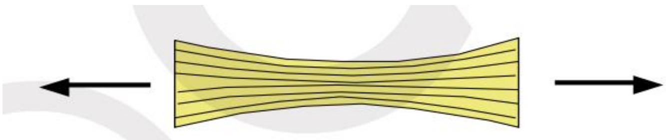

Figure 38: Tension stress

- Compression: matrix dominant property. Dependant on the stiffness and adhesion qualities of the resin being able to maintain the fibres as straight columns and not buckle.[9]

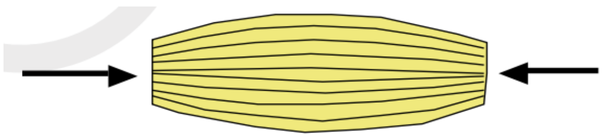

Figure 39: Compression stress

- Shear: matrix dominant property, transferring stresses across the composite.

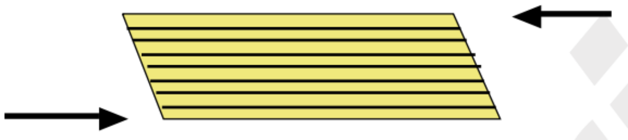

Figure 40. Shear stress

- Flexure: combination of above three: upper=compression: lower=tension; middle=shear

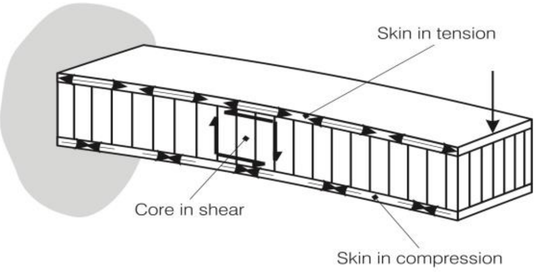

Figure 41: Bending stress

3.2.4 FAILURE MODES

When testing the material, all potential failure modes should be known. A summary of the key failure modes is shown below:

1. Strength
   The skin and core materials should be able to resist the tensile, compressive and shear stresses caused by the applied load. The skin to core adhesive must be capable of transferring the shear stresses between skin and core. [10]

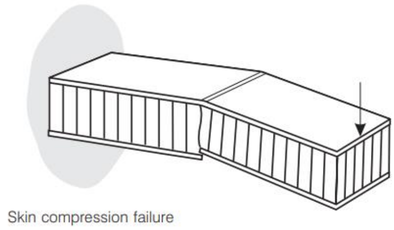

Figure 42: Skin compression failure

2. Stiffness
   To prevent excessive deflection, the sandwich should have enough bending and shear stiffness. [10]

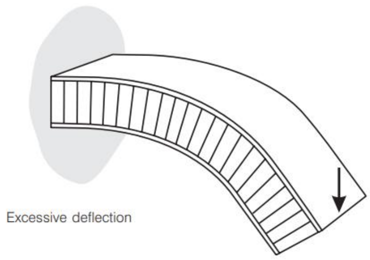

Figure 43: Excessive deflection

3. Panel buckling

   The core thickness and shear modulus must be adequate to prevent the panel from buckling [10].

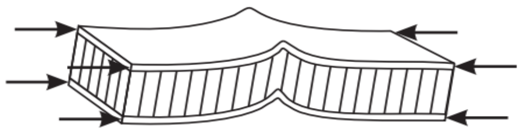

Figure 44: Panel buckling

4. Shear crimping

   The core thickness and shear modulus must be adequate to prevent the core from prematurely failing in shear under end compression loads [10].

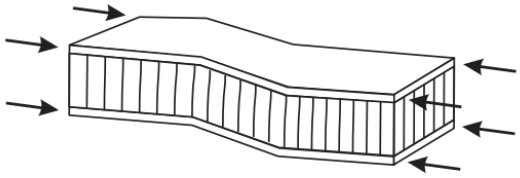

Figure 45: Shear crimping

5. Skin wrinkling

   The compressive modulus of the facing skin and the core compression strength must both be high enough to prevent a skin wrinkling failure [10].

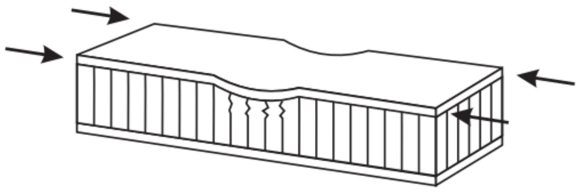

Figure 46: Skin wrinkling

6. Intra cell buckling

   The core cell size must be small enough to prevent intra cell buckling. [10]

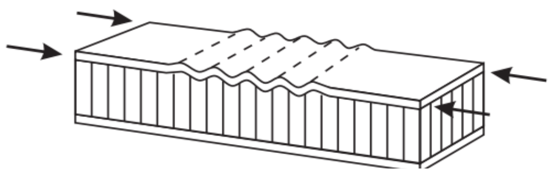

Figure 47: Intracell buckling

7. Local compression

   The core compressive strength must be adequate to resist local loads on the panel surface. [10]

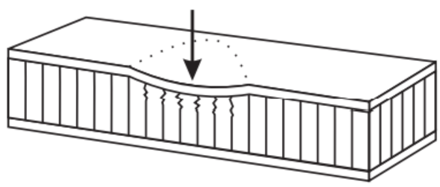

Figure 48: Local compression

3.2.5 FAILURE CRITERIA

For the monocoque results, it is necessary to define the material failure criteria to be considered during the tests for CFRP and honeycomb. The failure criteria are:

- Rankine criteria: the material will withstand until the maximum normal stress does not exceed the admissible stress, in this case, the yield strength.

$$\sigma_{adm} = \max\left(|\sigma_1|, |\sigma_2|, |\sigma_3|\right)$$

Equation 2: Rankine criteria

To be checked: $\sigma_{adm} < \sigma_y$

- Von-Mises criteria: the Von Mises criteria is a formula for combining the three principal stresses into an equivalent stress, and the equivalent stress is then compared to the yield stress of the material to judge the failure condition of the material.[12]

$$\sigma_{adm} = \sqrt{\frac{1}{2}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2\right]}$$

Equation 3: Von-Mises criteria [12]

- Tsai-Wu criteria: is failure criteria for anisotropic composite materials and it is based on Von Mises criteria for isotropic materials. This criteria predicts the rupture of the layer as a function of the maximum stresses in the longitudinal, transverse and shear directions between the layers.

4. MATERIAL TESTING

To justify the following simulations with Ansys and to prove that the material used in each section of the chassis satisfy the design requirements to race a material testing will be carried out. The section of the chassis that will be tested is the side impact structure, the most restrictive one.

4.1 MANUFACTURE TECHNIQUES

The manufacture process plays a key role to define the final mechanical properties of the composite. This is the reason why the different manufacture techniques should be taken into account in order to know the influence of each process on material selection.

4.1.1 SPRAY LAY-UP

The spray lay-up process is a method that uses a handgun to spray resin and chopped fibre. A low-cost mould is used, and it is usually used for manufacturing big parts. [13]

Advantages	Disadvantages
Low-cost tooling	Only glass roving fibre could be used
Quickly way to deposit fibre and resin	The resin must be low viscosity to be sprayable. This affects to the mechanical/thermal properties of the composite.[11]
	Laminates tend to have a high resin ratio and heavy.[11]

Table 6: Advantages and disadvantages of Spray lay-up [11]

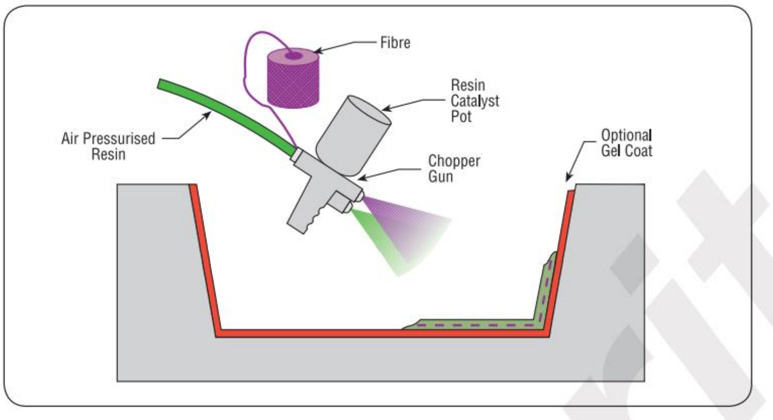

Figure 49: Spray Lay-up [11]

4.1.2 HAND LAY-UP

Hand lay-up is the easiest method a in which resins are impregnated by hand into fibres (dry fibres). This is fulfilled by rollers or brushers. Laminates are left to cure under standard atmospheric conditions.

Advantages	Disadvantages
Most of resins and fibres can be used	Laminate resin content would depend on the skills of the laminator
Low-cost tooling	The resin must be low viscosity to be workable by hand. This compromises their mechanical/thermal properties. [11]
Complex shapes could be reached with a decent precision	

Table 7: Advantages and disadvantages of Hand lay-up [11]

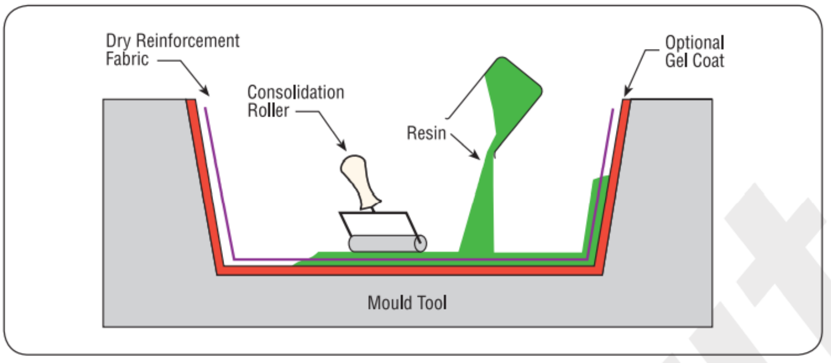

Figure 50: Hand Lay-up

4.1.3 VACUUM BAGGING (WET LAY UP)

This process is an extension of the previous one. Instead of the laminate being cured under atmospheric conditions, once the laminate is laid-up, pressure is applied to improve its consolidation. A vacuum bagging film is sealed on the wet laid-up laminate and a vacuum pump extract the air underneath. [11]

Advantages	Disadvantages
Most of resins can be used	This process is more expensive because of bagging materials
Better fibre wet-out	A higher level of skills is required by the laminator

Table 8: Advantages and disadvantages of Vacuum bagging

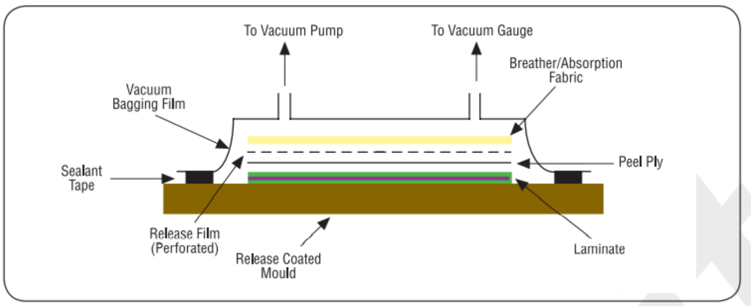

Figure 51: Vacuum Bagging [11]

4.1.4 PREPREG LAY-UP

It is a manufacturing process for prepreg fabrics. The prepregs are laid up onto a mould surface. For the cure process, to obtain the optimal mechanical properties, temperatures between 80 and 120 ºC must be reached. For this purpose, there are two options:

- Oven
- Autoclave

For a better consolidation of the material an autoclave is recommended. On the next table are shown some of the advantages and disadvantages of autoclave.

Advantages	Disadvantages
The volume of resin is accurately set by the manufacturer. The properties of the fibre would be maximized.	Expensive
Great control of curing	Difficult to operate
Pressure control	

Table 9: Advantages of disadvantages of Autoclave [14]

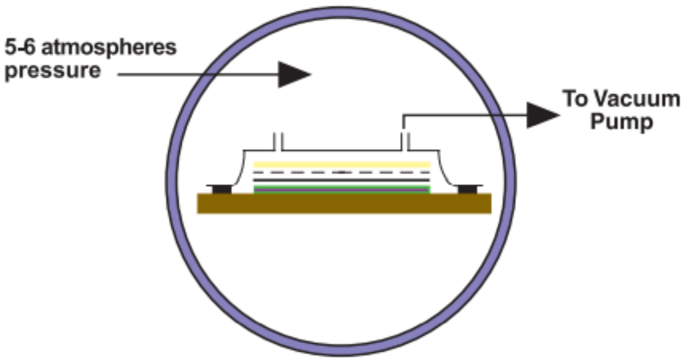

Figure 52: Autoclave [11]

Once the different techniques have been mentioned, the Vacuum Bagging (wet lay-up) process would be the optimal one. It is the method that we are more involved with, so the laminator skills will not be a huge problem.

4.2 LAMINATING PROCESS

The skin of the sandwich panel for the side impact follows the following configuration. This configuration has been chosen due to literature.

Ply	Orientation	Fabric
1	± 45º	Biaxial
2	0º	UD
3	0º	UD
4	0º	UD
5	0º	UD
6	±45º	Biaxial

Table 10: Side Impact ply configuration

The core of the sandwich panel is an aluminium honeycomb 20 mm thick with 1/4" cell size. The rest of sandwich panel configuration will be mentioned on the next chapter.

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Figure 55: Epoxy resin

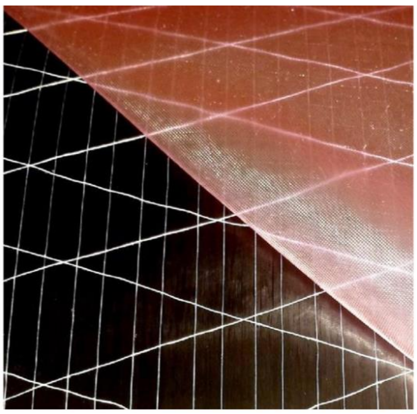

Figure 54: ±45 Biaxial Fabric

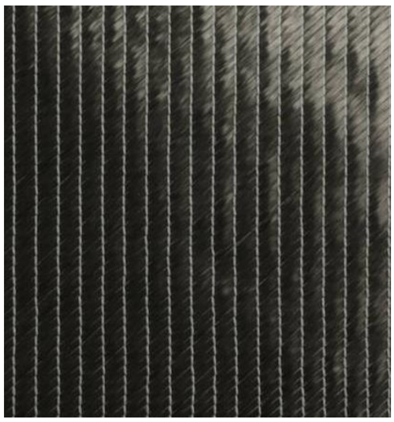

Figure 53: UD Fabric

To manufacture the sandwich panel the next steps have been followed:

1. First, carbon fibre must be cut. It is necessary to build two sample, one of 275x500 mm and another one of 100x100 mm. Following FS Rules, the sample of 275x500 mm will be used for the bending test and the sample of 100x100 will be used for the shear test. To optimize the laminate process, it was decided to laminate a bigger sample (550x430 mm), which would be cut afterwards with a special saw to obtain the sample required. Due to this, the dimensions of each layer of carbon fibre are 550x430 mm. Also, the honeycomb must be cut. In this case, the honeycomb was already expanded, so it just has to be cut with a cutter.

2. Afterwards, the mould should be prepared. In this case the sample is flat, so the mould used is a PVC plate. It must be ensured that the plate is clean. The area of laminating should be delimited with masking tape, to have a clean surface where the vacuum bag could be sealed. Afterwards, mould release should be applied on the surface.

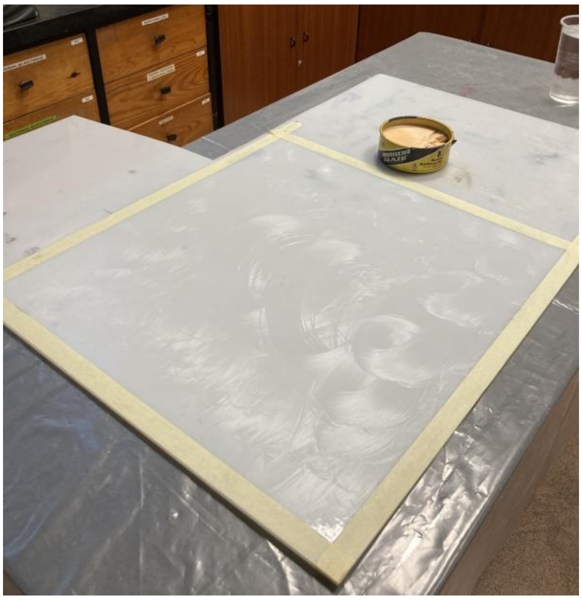

Figure 56: Mould preparation

3. Once the surface is prepared, carbon fibre should be weighted to define the amount of epoxy resin that is going to be used. The total weight of the fibre was almost 500g. The manufacturer provides the next mix ratio by weight: 100 g resin /30 g hardener. A correct overall ratio of resin and hardener should be maintained to ensure a proper cure. In this case, 500 g of resin and 150 g of hardener to be used.

4. The first step in a wet lay-up process is to apply a coat of resin on the surface of the mould. Afterwards, we place the fabric on the mould and apply another coat of resin. This process is repeated until we laminate the first six layers of fabric.

5. Once the first six layers of fabric are laminated, we placed the honeycomb. It is important that the surface underneath has a thick coat of resin to ensure the union of the core and the skin. The same as the surface on top of the core. For the top skin, the same process has been carried out.

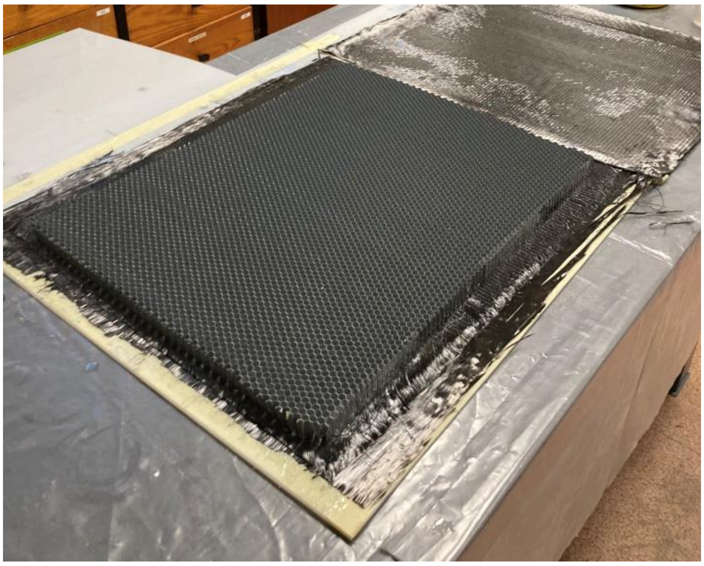

Figure 57: Placing the Honeycomb

Figure 58: Hand lay-up process completed

6. To vacuum bag the part, peel ply, breather and a vacuum bag is required. Firstly, we place the peel ply on the skin surface. The next layer is the breather and lastly, it is placed into the vacuum bag which now can be sealed. Once is correctly sealed, we can turn on the vacuum pump to apply pressure, improving the consolidation of the sandwich.

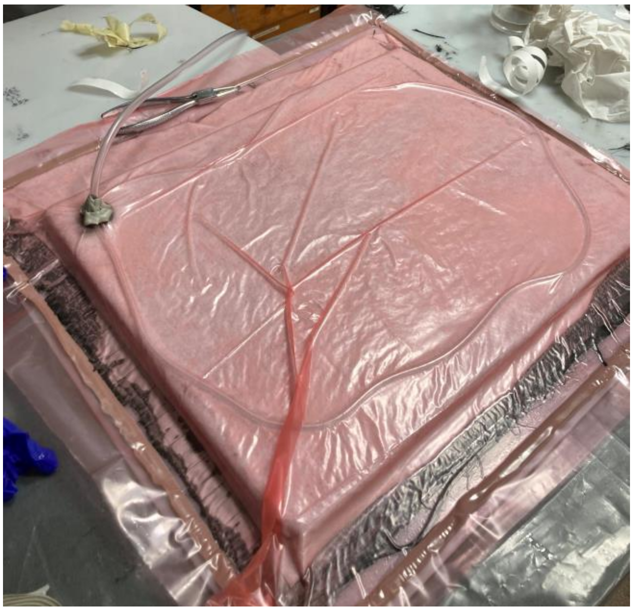

Figure 59: Vacuum bag on the sandwich

7. 48 hours later the vacuum bag and the peel ply were removed, obtaining the sandwich structure. Afterwards, it was cut in two different parts, for the bending test (500x275 mm) and the shear test (100x100 mm). This was made with a vertical band saw. This saw has a tungsten carbon band to cut composite materials. Once all this has been done, the test should be developed.

4.3 TESTING CHARACTERISTICS

According to the FS Rules, we should perform a 3-point bending test and a shear test.

4.3.1 THREE-POINT BENDING TEST

A test panel must be built which measure 275x500 mm that has the same design, laminate and fabrication method as the one used for the respective part of the original chassis. In this case, as the panel represents the side impact, the panel must represent, at least the same properties as two steel tubes (Ø 25x 2.5 mm) for yield strength, buckling modulus and absorbed energy. The distance between the two test panel support must be at least 400 mm and the load applicator must be metallic and have a radius of 50mm. All the measures obtained in the test must be included on the SES to verify that the panel fulfil the corresponding equivalence. [1]

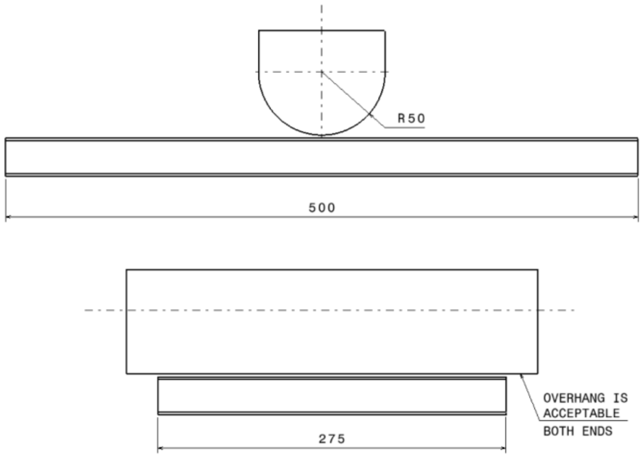

Figure 60: 3-Point Bending Test

The results of the bending test will be used to determine the fracture toughness and to measure stiffness parameters of the panel and parameters such as the elastic modulus of the skin Ef

4.3.1.1 Testing Results

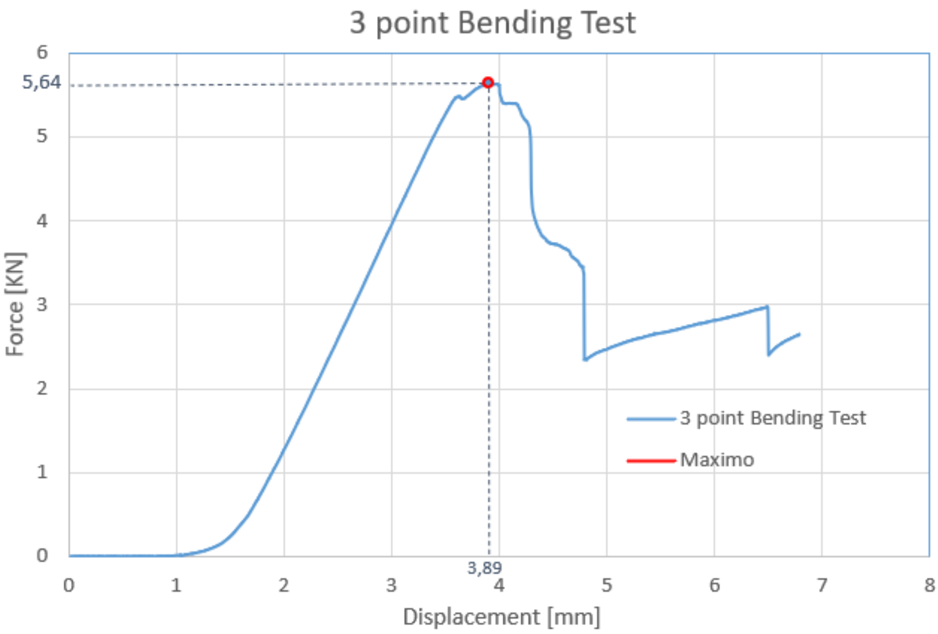

Figure 61: 3 Point Bending test results

As it can be appreciated the maximum force is 5,64 KN with a displacement of 3,89 mm. With the SES it would be verified if the Side Impact structure passes the stiffness requirements. In the image below, it can be shown that this sandwich structure passes them successfully.

Figure 2: Load Deflection Curve for vertical Side impact structure

Enter values for minimum and maximum load/deflection in linear-elastic region.
Gradient must be >= that of two baseline steel tubes

x_1 (mm)	0	y_1 (N)	0	Gradient (N/mm)	1671
x_2 (mm)	3,89	y_2 (N)	6500		

##

Enter value for force at panel failure (max 12.7 mm deflection) or maximum tested force.
y_{max} (N) 5640 (>= bending strength of two baseline side impact tubes)

Enter value of absorbed energy, must be >= that of two baseline tubes
Energy (J) 40,626

Enter details of test setup, panel core and skin thicknesses below

l (mm)	400	Panel Support Span
h (mm)	275	Panel Height (should be 275mm)
b (mm)	20	Core Thickness
t_1 (mm)	1,8	Inner Skin Thickness
t_2 (mm)	1,8	Outer Skin Thickness
I (mm^4)	117889	Second moment of area
E (GPa)	18,9	Skin modulus of elasticity
σ_{UTS}(MPa)	56	UTS of skins

Figure 62: Side Impact SES from bending test

To prove that all the simulations that will be done with Ansys make sense and can concur with reality, the same test will be simulate in Ansys.

To personalize the material properties in Ansys in accordance with the "real" test some calculation should be done.

The equations will follow the next nomenclature:

D= Bending Stiffness	h = Distance between facing skin centres
E_f= Young modulus of the skin	b= Width
t_f= Thickness of facing skin	G_c = Core shear modulus
k_b = Bending deflection coefficient	k_s = Shear deflection coefficient
S= Panel shear deflection	δ = Calculated deflection
l= Length between the two support panels	M= Maximum bending moment
F= Maximum shear force	P= Applied load

The coefficients k_b and k_s depends on the load application and the type of support. In this case, is a simple support with a centre load application, so the value of k_b is 1/48 and k_s is 1/4.

$$D = \frac{E_f t_f h^2 b}{2}$$

Equation 4: Bending Stiffness [10]

$$h = t_f + t_c$$

$$S = b\ h\ G_c$$

Equation 5: Shear Stiffness

The total deflection of the panel is the sum of bending deflection and shear deflection:

$$\delta = \frac{k_b P l^3}{D} + \frac{k_s P l^3}{S}$$

Equation 6: Total deflection

Bending deflection will only be considered, as preliminary calculations has been done.

$$\delta = \frac{k_b P l^3}{D}$$

Equation 7: Bending deflection

P=5640 N	b=275 mm	l=400 mm	h=21.48 mm
δ = 3.89 mm	D=2013.58 Pa	E_f=20.27 GPa	

Facing Stress:

$$\sigma_f = \frac{M}{h t_f b}$$

Equation 8: Facing Stress

σ_f= 64.43 MPa

Once the characteristics of the sandwich skin have been mathematically obtained, we proceed to customize the carbon fibre in Ansys.

Ansys has a section in which you can customize the characteristics of a material, this section is called "Engineering Data". In this case, we will insert this theoretical data and iterate until we get a test data similar to the real one.

After several iterations, a result has been reached. The final deformation in Ansys is 3.79 mm. It should be noted that for each result analysed in Ansys there will be an error of 4%. This final iteration of material configuration will be used for the following simulations, in order to prove that all simulations concur with reality.

$$\text{Error} = 1\text{-}\ \frac{Ansys\ Measure}{Real\ Measure} = 0.04 = 4\%$$

Equation 9: Error

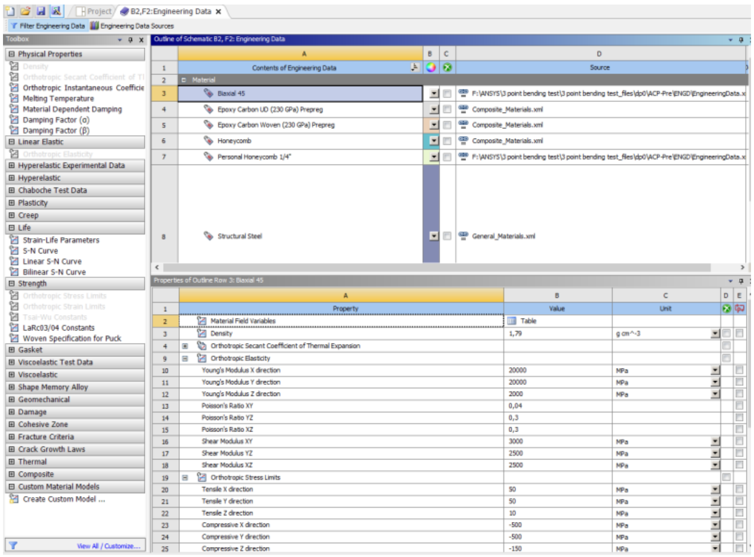

Figure 63: Engineering data on Ansys

The final properties of the material of the simulation will be given on the next table. The X axis is oriented in the longitudinal axis and is where unidirectional fibres are set.

Property	UD	Biaxial
ρ	1770 Kg/m^3	1790 Kg/m^3
σ_x	81 MPa	50 MPa
σ_y	10 MPa	50 MPa
E_x	27 GPa	20 GPa
E_y	2 GPa	20 GPa
G_{yz}	3.1 GPa	3 GPa
G_{xy}	4.5 GPa	2.5 GPa

Table 11: Final skin properties

The final properties of the skin depending on the orientation are as follows. Remembering that the skin is composed of 4 lays of UD and 2 of Biaxial.

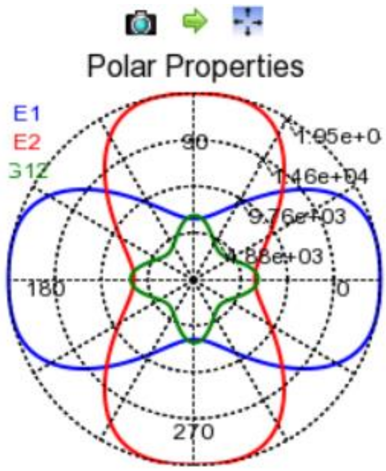

Figure 64: Side Impact polar properties

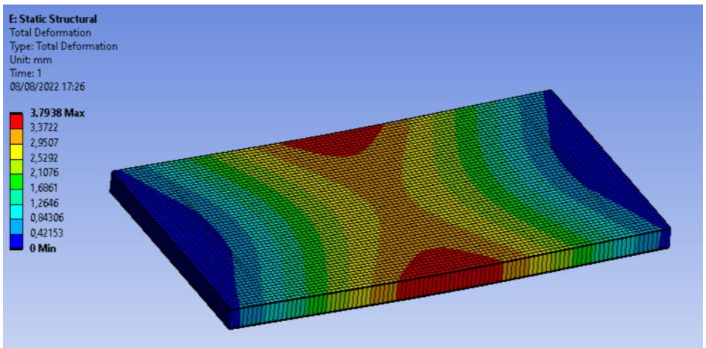

Figure 65: Deflection in Ansys

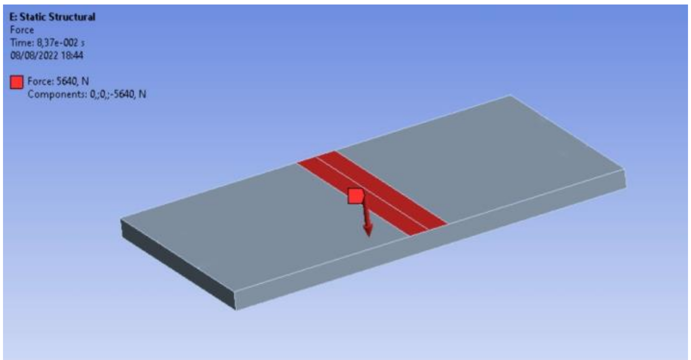

Figure 66: Force applied in Ansys

4.3.2 SHEAR TEST

In the shear test, the sample must measure at least 100x100 mm. It will be measured the force required to push a 25 mm diameter flat punch to the panel. As well as the 3-point bending test, the sample must have the same design and manufacture process as the side impact structure of the chassis. [1]

In this case, there will be 2 peaks in the displacement force graph. The first peak will be due to the fracture of the upper skin and the second peak will be due to the fracture of the second skin.

Figure 67: Shear Test

4.3.2.1 Test Results

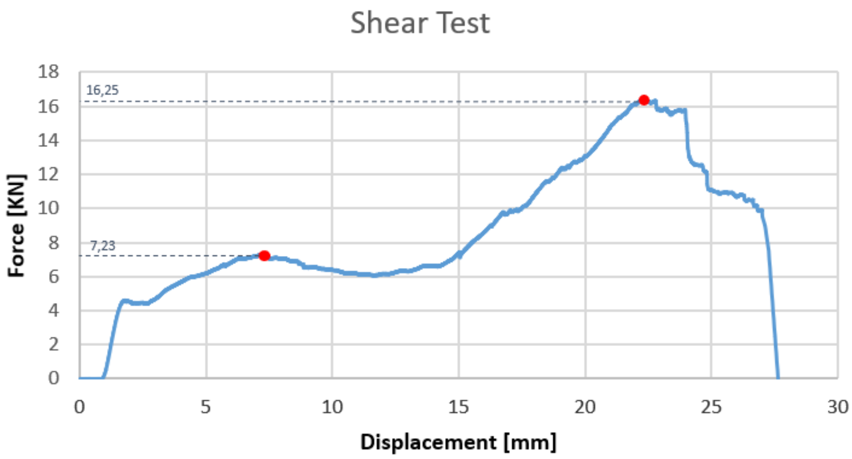

Figure 68: Shear Test result

As we can appreciate on the graph there are two peaks. First peak value is 7.23 KN and second peak value is 16.25 KN. Once the values of these test have been entered in the SES, it can be seen that it fulfils the requirements.

Figure 2: Load Deflection Curve Side Impact Structure

Enter values for force at lower and higher peak (see guidance notes)

Lower Peak	7230	(Determines Shear Strength for T3.15.2)
Higher Peak	16250	PASS

Enter details of skin thickness

t (mm)	1,48

σ_{shear} (Mpa)	62,2	Shear strength of skin, used for attachment calcs where appropriate

Figure 69: Side Impact SES from shear test

Defining the final properties of the honeycomb, some points have been considered.

$E_x \approx E_y \approx 0$

$G_{xz} \approx 0$

$\mu_{xy} \approx \mu_{yz} \approx \mu_{xz} \approx 0$ [10]

Property	Aluminium Honeycomb
ρ	56 Kg/m^3
σ_z	3,5 MPa
E_z	255 MPa
G_{xz}	327 MPa
G_{yz}	172 MPa

Table 12: Final core properties

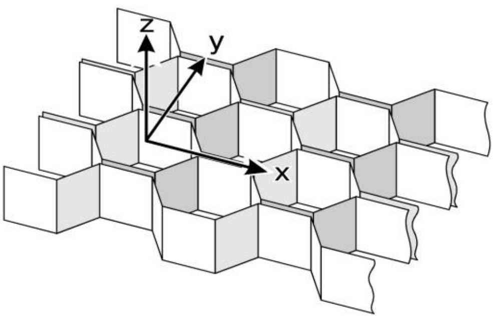

Figure 70: Honeycomb axis [10]

4.3.2.2 Test Conclusions

The manufacture process could be optimized to achieve better material properties. After the shear test, it could be seen that the adhesion between the core and the top skin (the one that was laminated on the honeycomb) was not adequate. This adhesive performance did not really affect to the shear test performance because it doubles the shear requirements (7,5 KN in the second peak) but this could affect the results of bending test.

The adhesive must rigidity attach the facings to the core material in order for loads to be transmitted from one facing to the other [10]. With this manufacture process, the adhesive performance is poor, affecting the loads transmission between the top and bottom skin.

To improve this adhesive performance, another manufacture process has been proposed. In this case, the composite will be cured twice.

On the one hand, bottom skin will be laminated with the honeycomb on, following the same process as before. On the other hand, the top skin will be laminated separately. Once the two parts are cured, a coat of resin will be applied on the top skin and the honeycomb with the bottom skin will be placed on. This will prevent the epoxy resin (in this case, the adhesive), from falling through the core due to gravity, ensuring proper adhesion.

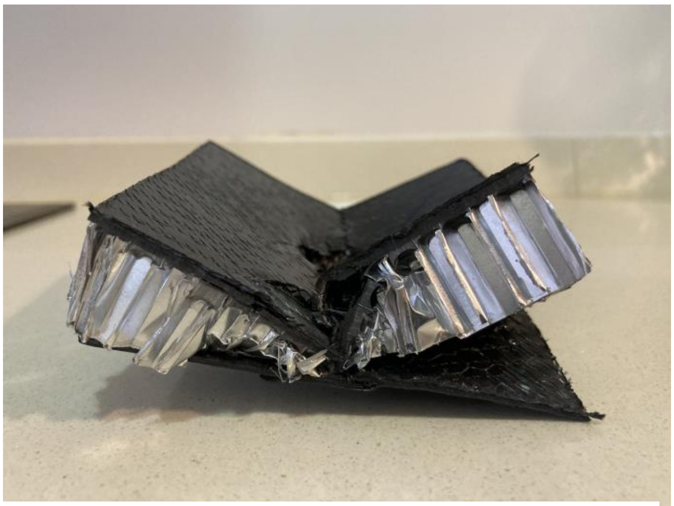

Figure 71: Sandwich after shear test

5. STRUCTURAL ANALYSIS

The structural analysis section in Ansys has three objectives:

- Explain the process that has been carried out to perform the different tests in Ansys.
- To propose different sandwich plies configurations to reach the best stiffness/weight ratio. Prove that the optimal configuration passes the required standards.
- Previous chassis comparison in terms of stiffness and weight

5.1 SIMULATION PROCESS

5.1.2 GEOMETRY

After having entered the data of the materials to be used, it is necessary to enter the geometry of the monocoque and make some preparations in order to perform the study correctly. First, the parts must be entered, the monocoque and the front and rear suspension. Then, the internal surface of the monocoque part will be kept as it is necessary for the use of the ACP (Ansys Composite PrePost) module. Some repairs on the geometry would be required. This would be solved by some Repair Tools that Ansys provides. Finally, the intersection of the suspension geometry with the monocoque will be used to see the points through which the forces will be transmitted. In addition, 4 origins were created located on each hub carrier, where the forces will be located on the static structural test. To avoid misunderstanding, a coordinate axis will be established. As it can be appreciated on the following picture, the Z axis will be the axis along the length of the car, X axis will be the lateral one and Y the vertical one.

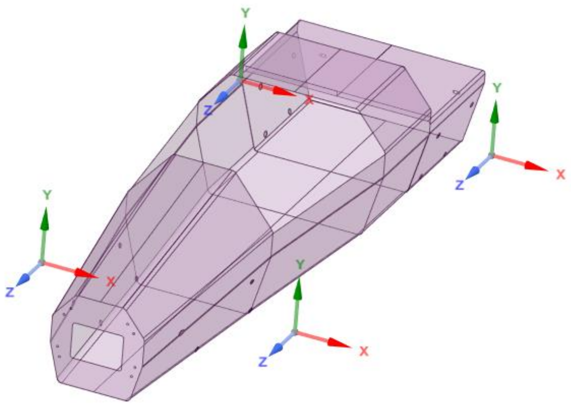

Figure 72: Surface geometry of the monocoque

5.2 *MESH AND NAMED SELECTIONS*

After preparing the geometry, it is time to mesh the part to perform the finite element simulation correctly. Good meshing is important to obtain accurate results with the shortest simulation time. In order to find the best relation between simulation time and accurate results, some simulations with different elements size has been carried out. The following graph shows the maximum deformation of the chassis depending on the elements size (30,20,15,10,7,5 and 3 mm). It can be seen that the deformation is higher when the element size is bigger, meaning that Ansys establish a security coefficient for bigger elements size.

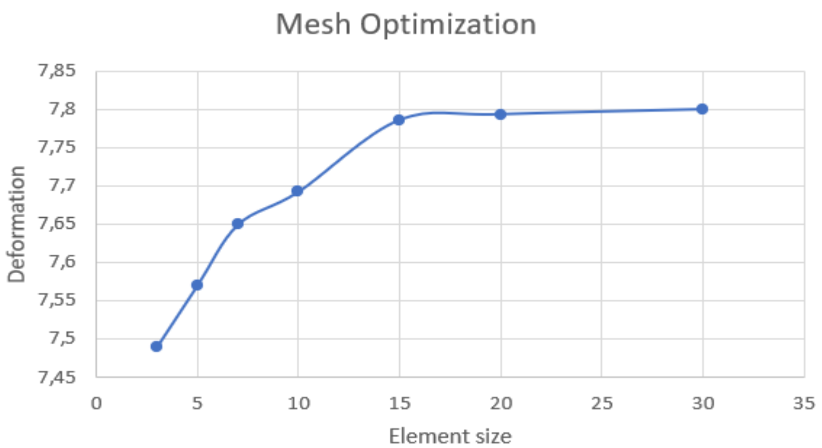

Figure 73: Mesh optimization

The element quality is a parameter that also should be considered. This parameter provides information about the mesh quality. Considering both points, for design optimization a mesh of 20 mm will be used, to not spend too much time on simulations. Once the optimal design is selected a simulation with a 5 mm element size mesh will be performed, to obtain a more accurate result. In the next figure, the element quality of the 20 mm element size mesh is shown. Most of the elements are close to 1, indicating that is a good mesh.

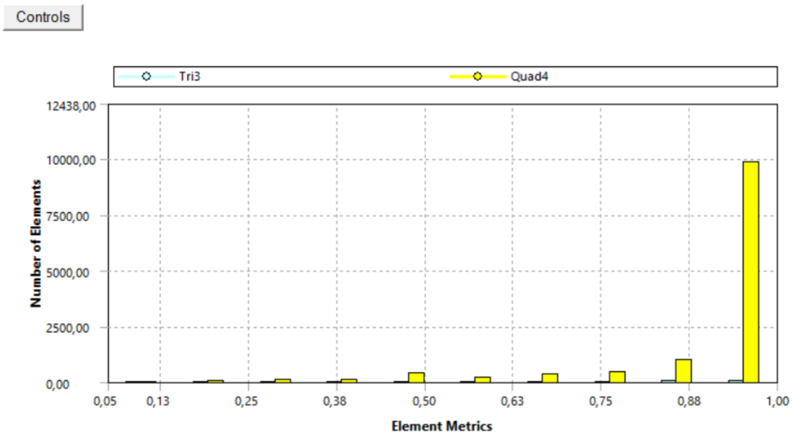

Figure 74: Element quality

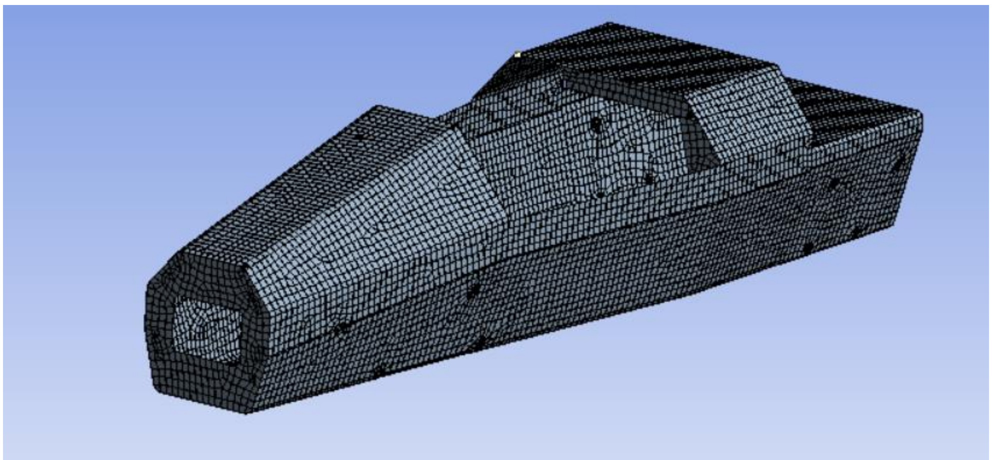

Figure 75: Monocoque mesh

The different parts of the monocoque should be identified, in order to specify the material of each part of the chassis.

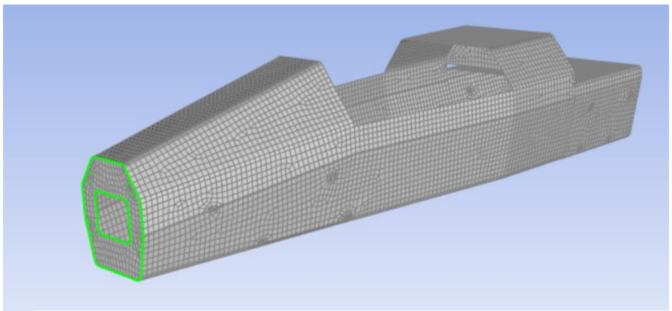

Figure 80: Front Bulkhead

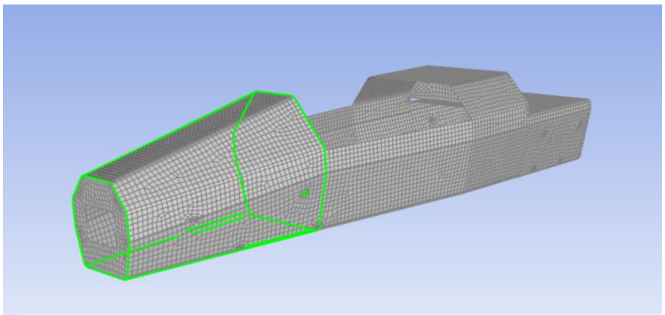

Figure 79: Front

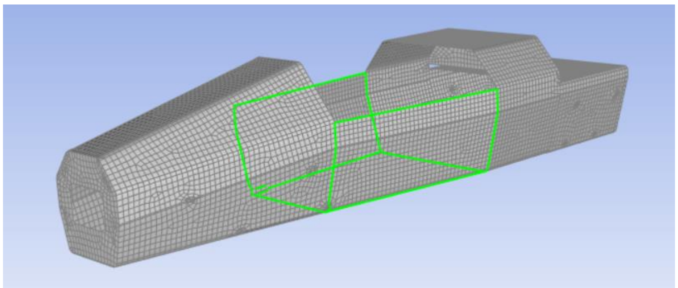

Figure 81: Side Impact

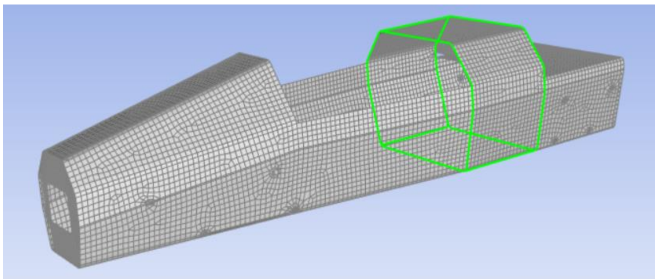

Figure 78: Main Hoop Bracing Support

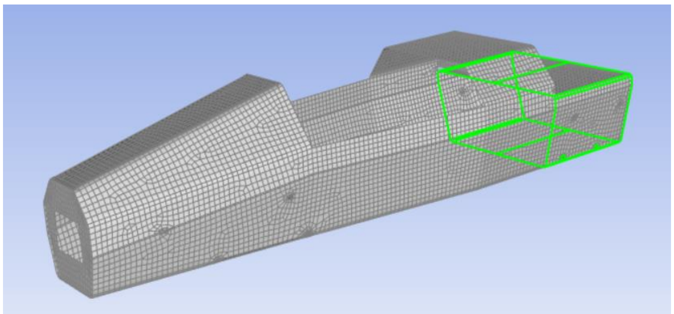

Figure 77: Rear

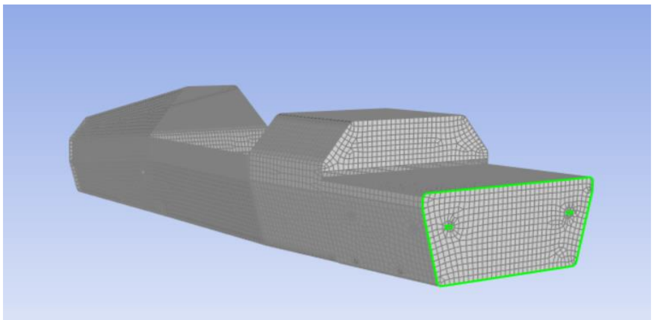

Figure 76: Rear Bulkhead

5.3 SANDWICH STRUCTURES

Each part of the chassis has different sandwich configurations, to fulfil the stiffness demanded by the rules. This will be considered the base case.

- Front: [45º- Biaxial/4x0º UD/45º- Biaxial] with 20 mm thick, 1/4" cell size Aluminium Honeycomb core

Ply	Orientation	Fabric
1	± 45º	Biaxial
2	0º	UD
3	0º	UD
4	0º	UD
5	0º	UD
6	±45º	Biaxial

Table 13: Front ply configuration

- Side Impact: [45º- Biaxial/4x0º UD/45º- Biaxial] with 20 mm thick, 1/4" cell size Aluminium Honeycomb core

Ply	Orientation	Fabric
1	± 45º	Biaxial
2	0º	UD
3	0º	UD
4	0º	UD
5	0º	UD
6	±45º	Biaxial

Table 14: Side Impact ply configuration

- Main Hoop Bracing support: [45º- Biaxial/2x0º UD/45º- Biaxial] with 20 mm thick, 1/4" cell size Aluminium Honeycomb core

Ply	Orientation	Fabric
1	± 45º	Biaxial
2	0º	UD
3	0º	UD
4	0º	UD
5	0º	UD
6	±45º	Biaxial

Table 15: Main Hoop Bracing Support ply configuration

- Rear: [45º- Biaxial/4x0º UD/45º- Biaxial] with 20 mm thick, 1/4" cell size Aluminium Honeycomb core

Ply	Orientation	Fabric
1	± 45º	Biaxial
2	0º	UD
3	0º	UD
4	0º	UD
5	0º	UD
6	±45º	Biaxial

Table 16: Rear ply configuration

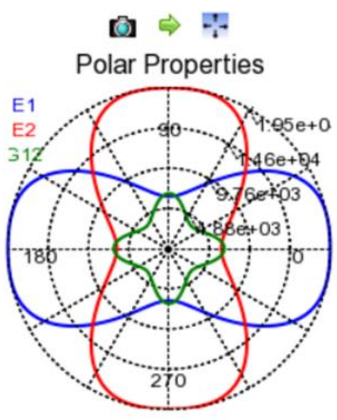

Figure 83: Front polar properties

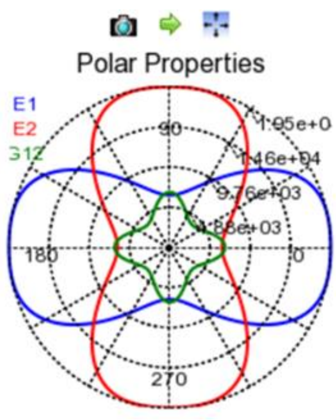

Figure 82: Side Impact polar properties

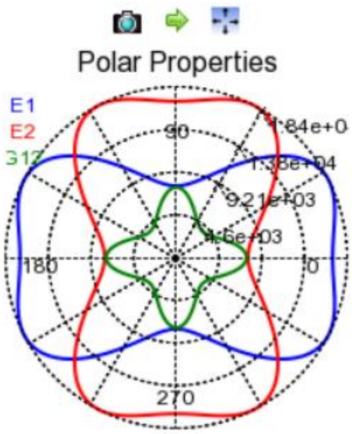

Figure 85: Main Hoop Bracing Support polar properties

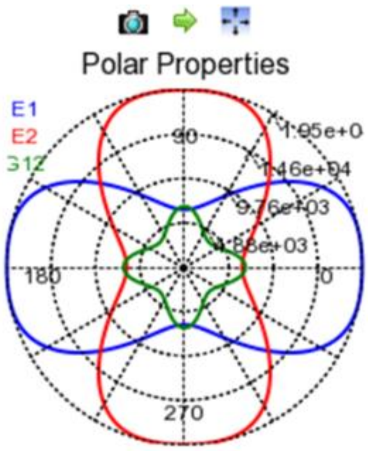

Figure 84: Rear polar properties

It is important to emphasize that 0º degrees represents the axis along the car from the top to the bottom. In the next figures, it would be shown clearly, in this case the Z axis is the one along the car. The fibre orientation will be determined with some rosettes established on Ansys. UDs are oriented along the axis of the car to improve the stiffness from front impact and bending stiffness.

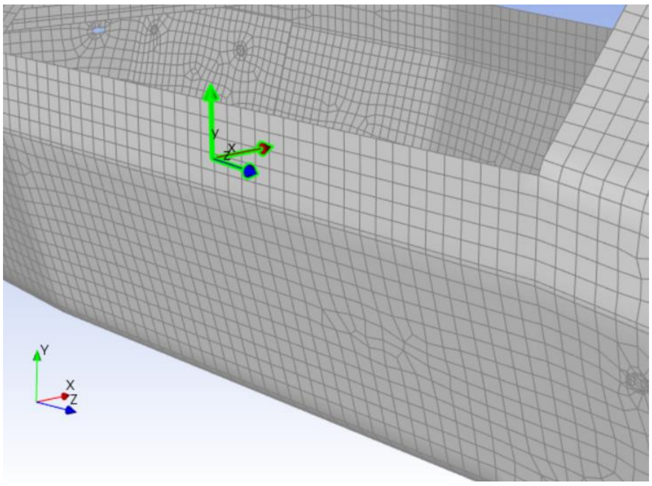

Figure 86: Rosettes

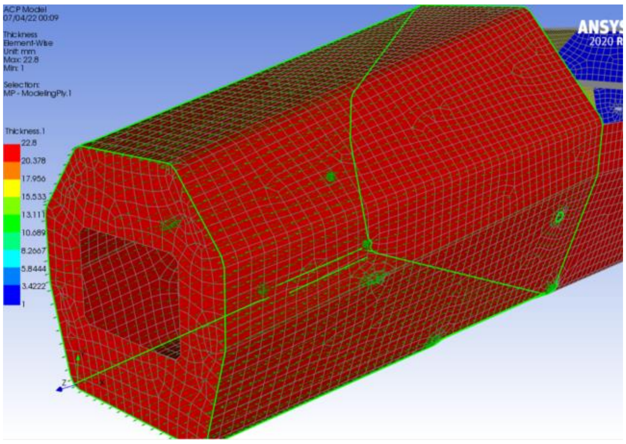

Figure 87: Fibre direction on the front

5.4 ANSYS SIMULATION FOR BASE CASE

The process to carry out the test that will provide the data to calculate the torsional stiffness of the chassis is:

1. First, the rear part must be fixed.
2. Afterwards, two loads are applied on the front hubs to create a torque on the direction of the axis along the car.
3. The maximum deformation on the X axis should be measured. This maximum deformation is mostly located on the top of the front hoop

The load applied is 1750 N because is the force produce by the shock absorbers at their maximum displacement. This data was obtained from the Dynamics department of the team.

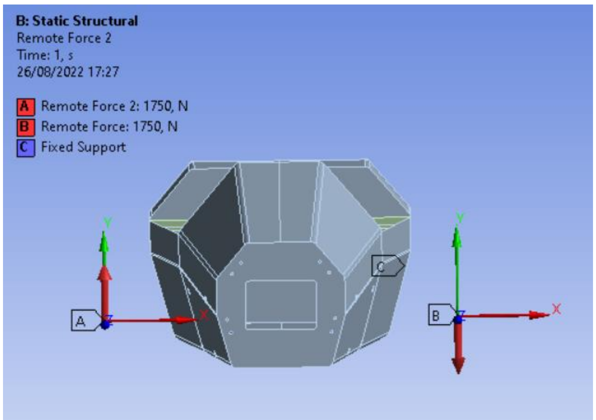

Figure 88: Remote force applied

To calculate the torsional stiffness the following formula must be followed:

$$\text{Torsional Stiffness} = \frac{M}{\theta}\ [\text{Nm/º}]$$

M=2*F*b

$$\theta = \text{arctg}\left(\frac{x_{max}}{h}\right)$$

M= Bending moment applied	θ = Angle rotated at point of maximum displacement
F=force applied [1750 N]	b=distance between where the force is applied at Z axis of the chassis [0.5 m]
h=height between the force is applied and the point of maximum deformation [475 mm]	x_{max}= maximum deformation in X direction.

F =1750 N	h= 475 mm	b= 0.5 m

Base case

For the base case the maximum deformation is 6,4089 mm. The torsional stiffness is 2264 Nm/º. This torsional stiffness is lower than the one on the current chassis (3000 Nm/º). A design optimization will be made to reach a higher torsional stiffness with the lowest weight incrementation.

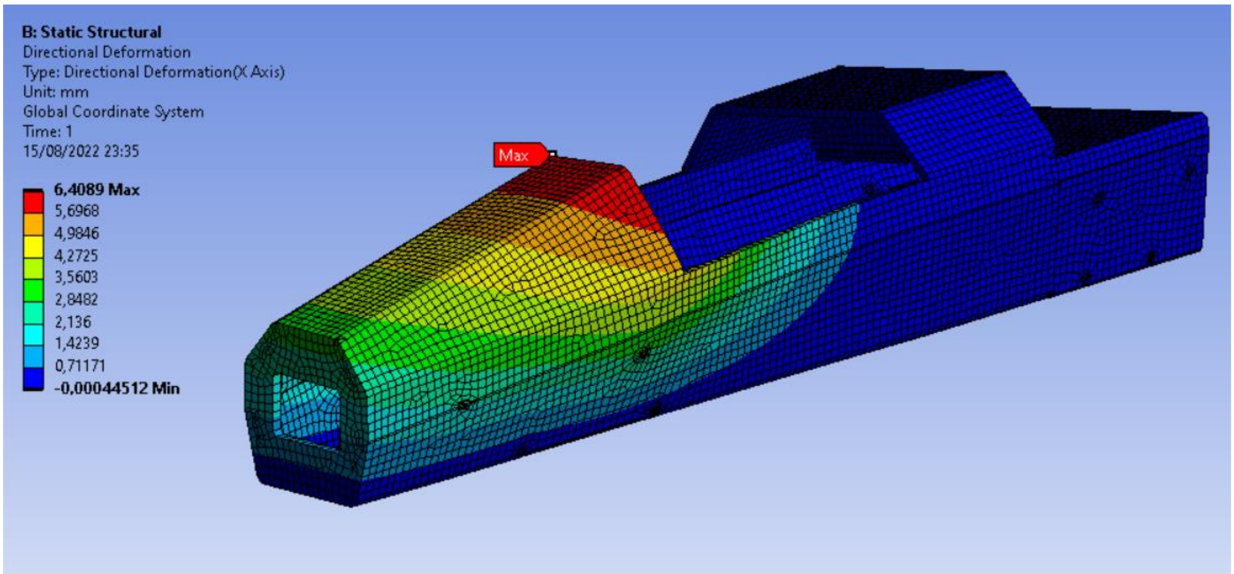

Figure 89: Base case maximum deflection

5.5 DESIGN OPTIMIZATION

The optimization design will be mainly based on the torsional stiffness of the chassis. Torsional stiffness is important to the dynamic vehicle performance. A chassis with a good torsional stiffness allows the suspension to perform as designed. As the design optimization is based on the torsional stiffness only the front and the side impact will be changing the plies configuration. The core will be the same for every iteration.

First iteration

Ply	Orientation	Fabric
1	± 45º	Biaxial
2	±45º	Biaxial
3	0º	UD
4	0º	UD
5	0º	UD
6	0º	UD
7	±45º	Biaxial
8	±45º	Biaxial

Table 17: First iteration ply configuration

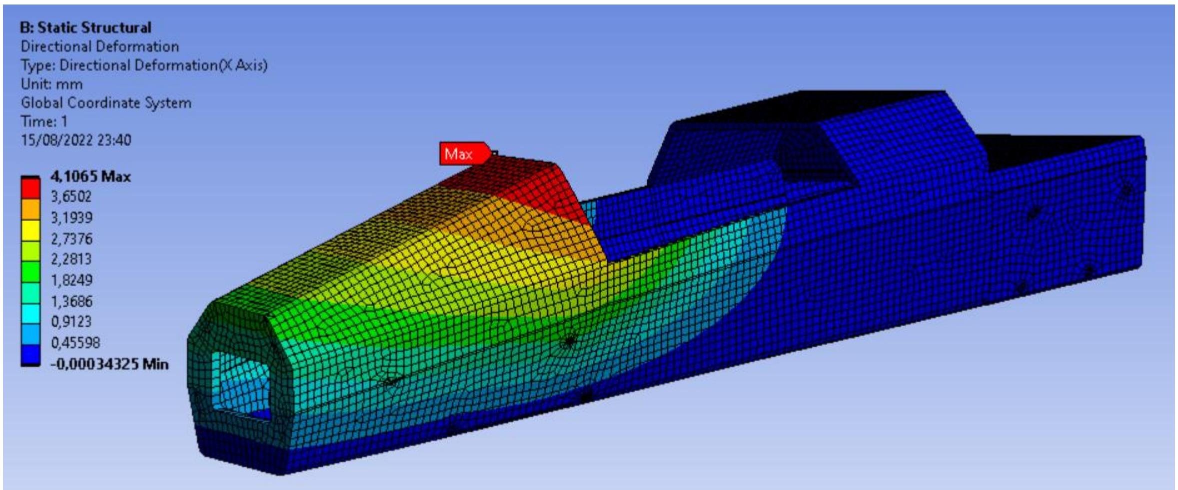

Figure 90: First iteration maximum deformation

Second Iteration

Ply	Orientation	Fabric
1	± 45º	Biaxial
2	±45º	Biaxial
3	0º	UD
4	0º	UD
5	0º	UD
6	±45º	Biaxial
7	±45º	Biaxial

Table 18: Second iteration ply configuration

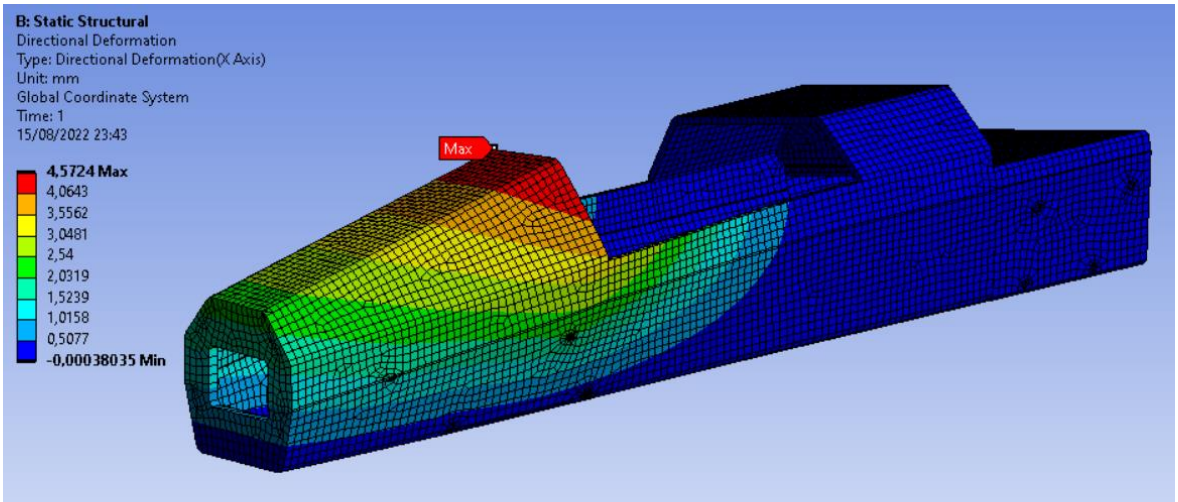

Figure 91: Second iteration maximum deformation

Third Iteration

Ply	Orientation	Fabric
1	± 45º	Biaxial
2	0º	UD
3	0º	UD
4	0º	UD
5	0º	UD
6	0º	UD
7	0º	UD
8	±45º	Biaxial

Table 19: Third iteration ply configuration

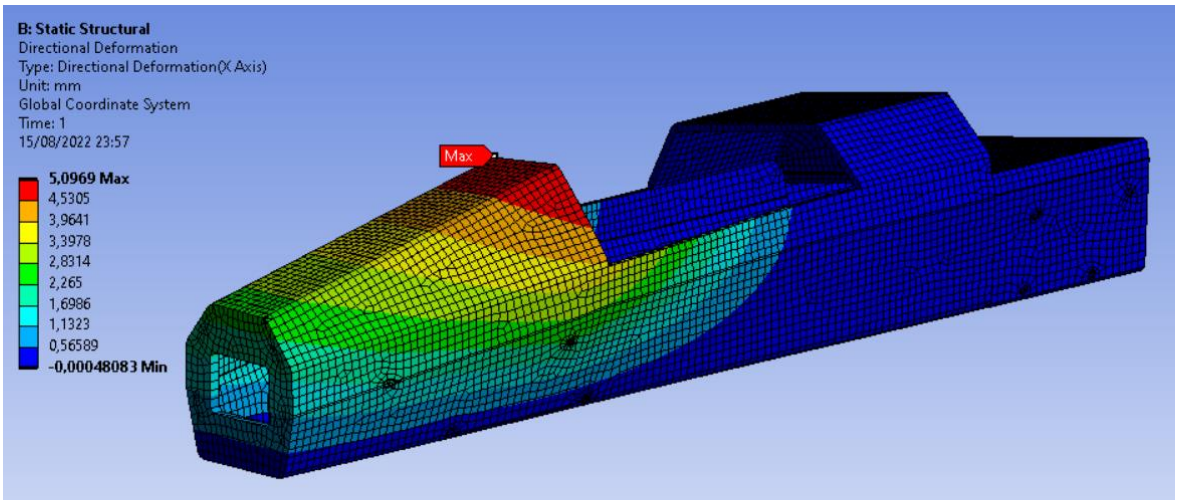

Figure 92: Third iteration maximum deformation

Fourth Iteration

Ply	Orientation	Fabric
1	± 45º	Biaxial
2	90º	UD
3	0º	UD
4	0º	UD
5	0º	UD
6	0º	UD
7	90º	UD
8	±45º	Biaxial

Table 20: Fourth iteration ply configuration

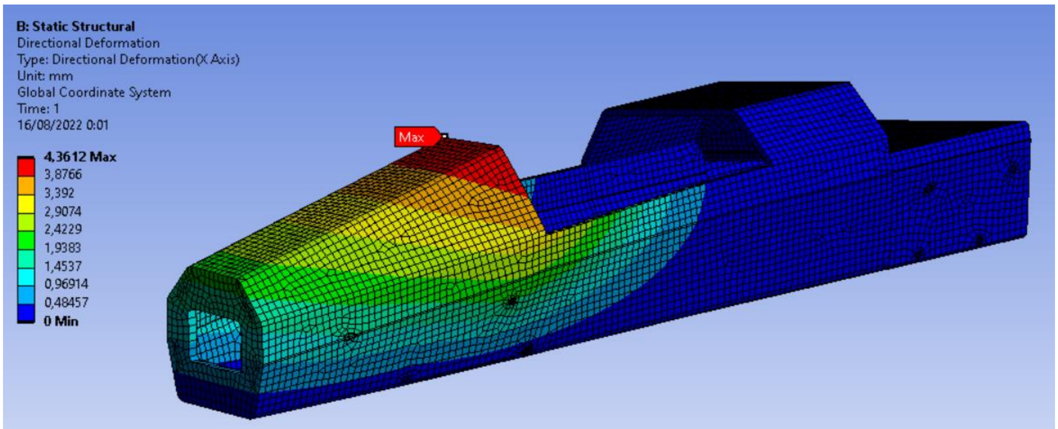

Figure 93: Fourth iteration maximum deformation

Fifth Iteration

Ply	Orientation	Fabric
1	± 45º	Biaxial
2	90º	UD
3	0º	UD
4	0º	UD
5	0º	UD
6	90º	UD
7	±45º	Biaxial

Table 21: Fifth iteration ply configuration

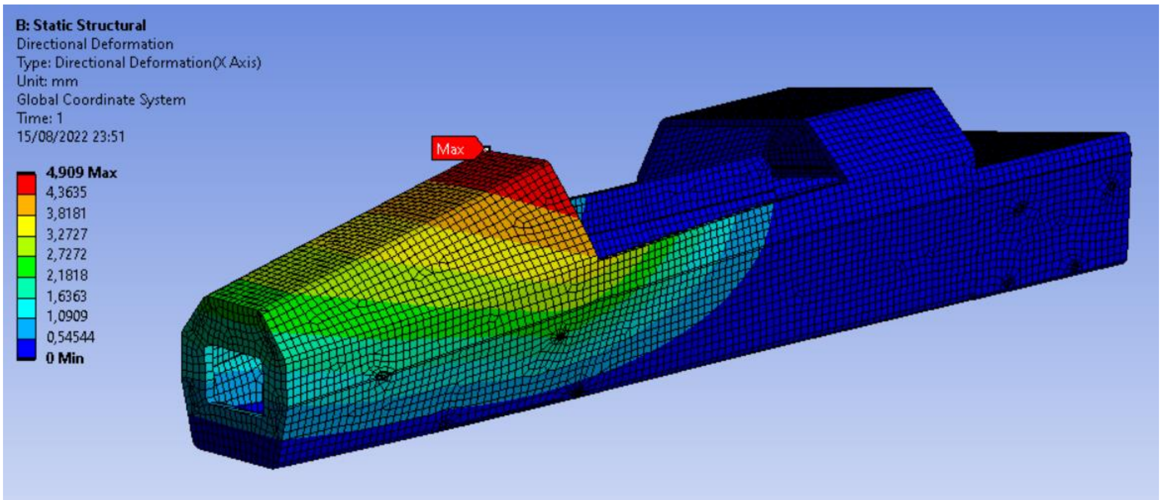

Figure 94: Fifth iteration maximum deflection

5.5.1 RESULTS CONCLUSIONS

Iteration	Torsional Stiffness [Nm/º]	Total weight [kg]	Ply configuration
First	3533	52,9	[2x±45º/4x0º/2x±45º]
Second	3174	49,5	[2x±45º/3x0º/2x±45º]
Third	2846	52,9	[1x±45º/6x0º/1x±45º]
Fourth	3326	52,9	[1x±45º/1x90º/4x0º/1x90º/1x±45º]
Fifth	2955	49,5	[1x±45º/1x90º/3x0º/1x90º/1x±45º]

Table 22: Results conclusions

The second iteration is the one which provides a better torsional stiffness than the current chassis with the lowest weight incrementation compared to the base case.

The total weight of the chassis has been calculated considering that each carbon fibre tape has a 300 g/m^2 areal weight and the ratio epoxy resin/carbon fibre is for 100g of fibre 130 g of epoxy resin and hardener must be applied. Also considering the weight of the front hoop and main hoop that is 6,5 kg.

5.6 OPTIMAL DESIGN TEST

To determinate the final properties of the optimal design, a 3-point bending test was carried out in Ansys. It is complex to know in Ansys the maximum tested force. The maximum deflection is 2,96 mm with a force of 6200 N applied. By Von-Mises the equivalent stress will be known and will be compared to the skin stress to check if the composite will break. In this case the skin stress is 60 MPa and the equivalent stress is 62 MPa, meaning that the panel will break, and the force applied will be the last force before breaking.

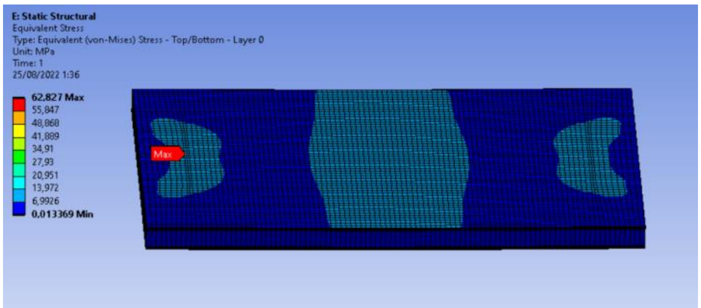

Figure 96: Von-Mises criteria for the optimal design

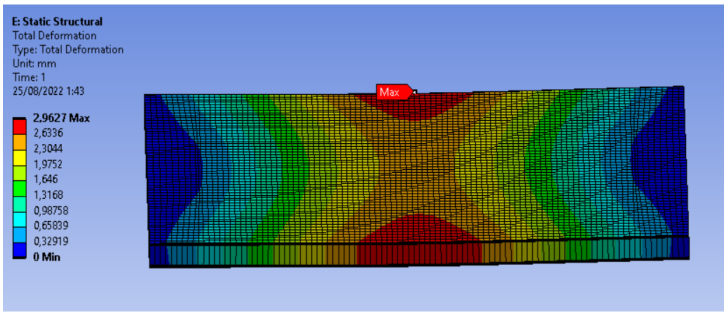

Figure 95: Optimal design bending test on Ansys

It is important to check that the new design fulfils the stiffness requirements. This will be verified with the SES. As it can be appreciated on the figure below, it satisfies the stiffness equivalency. Side Impact structure is the most restrictive part of the chassis. The front part that corresponds to the Front Bulkhead Supports and the Front Hoop Bracing, has the same layers configuration as the Side Impact, due to this, it is assume that the front part also fulfils the FS Rules, as well as the Front Bulkhead. For the Rear part and the Main Hoop Bracing Support there is not a specific stiffness required.

Figure 2: Load Deflection Curve for vertical Side impact structure

Enter values for minimum and maximum load/deflection in linear-elastic region.
Gradient must be >= that of two baseline steel tubes

x_1 (mm)	0	y_1 (N)	0	Gradient (N/mm)	3444
x_2 (mm)	1,8	y_2 (N)	6200		

##

Enter value for force at panel failure (max 12.7 mm deflection) or maximum tested force.

y_{max} (N) **6000** (>= bending strength of two baseline side impact tubes)

Enter value of absorbed energy, must be >= that of two baseline tubes

Energy (J) **40,626**

Enter details of test setup, panel core and skin thicknesses below

l (mm)	400	Panel Support Span
h (mm)	275	Panel Height (should be 275mm)
b (mm)	20	Core Thickness
t_1 (mm)	1,8	Inner Skin Thickness
t_2 (mm)	1,8	Outer Skin Thickness
I (mm^4)	117889	Second moment of area
E (GPa)	**39,0**	Skin modulus of elasticity
σ_{UTS}(MPa)	**60**	UTS of skins

Figure 97: Optimal design SES

For the different test total, deformation and equivalent stress will be shown. Following the formula of composites, it is known that σ_{eq} is 60 MPa. It must be ensured that the equivalent stress of Von Mises is lower than 60 MPa. As it is the final design a mesh with a 5 mm element size will be used in order to provide more accurate results.

5.6.1 TORSIONAL TEST

- The maximum deflection is 5.0563 mm on the top of the front hoop, achieving a final torsional stiffness of 3316 Nm/º.
- The maximum stress is located on the intersection of the front part and top point of the side impact. It is lower than 60 MPa, so the composite will not break, ensuring that the chassis will not break if a torque of 1750 Nm is applied.

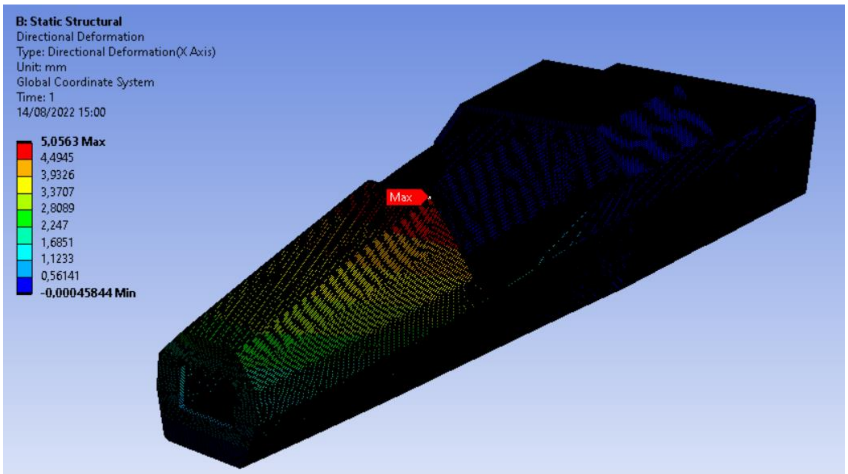

Figure 98: Torsional test maximum deflection

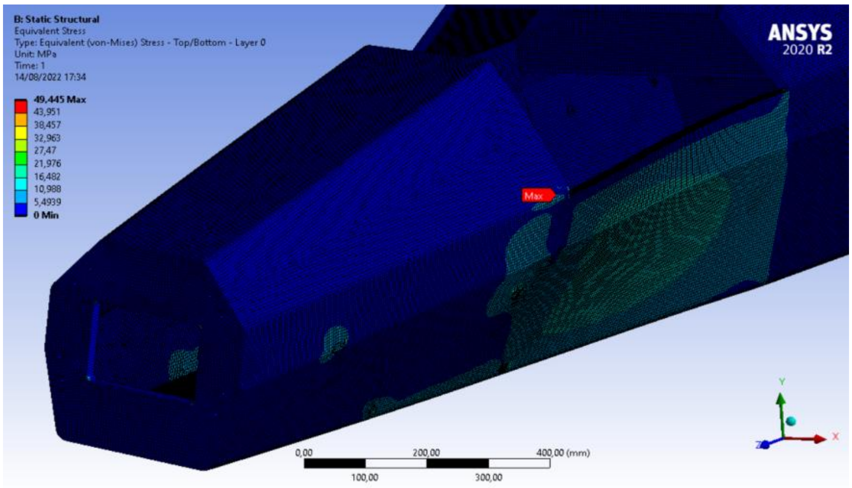

Figure 99: Torsional test von-Mises criteria

5.6.2 LATERAL IMPACT

For the lateral impact front bulkhead and rear part have been fixed and a 7.5 KN load is applied on the side impact. This load is the shear strength that the side impact must resist. The results are:

- A maximum deflection of 2,0484 mm on the top of the side impact structure.
- Von Mises stress is 21,685 MPa, quite lower than the maximum stress admitted, 60 MPa. The maximum stress is located on the intersection of the main hoop bracing supports and the top surface of the side impact.

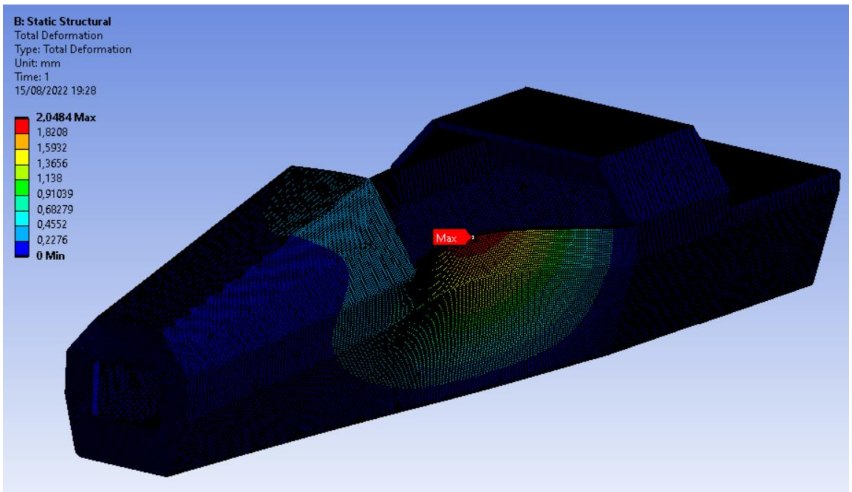

Figure 100: Lateral impact maximum deflection

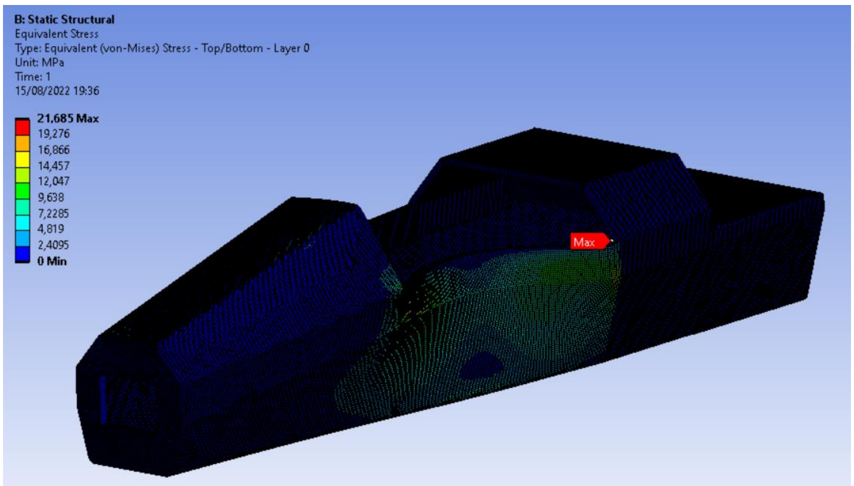

Figure 101: Lateral Impact von-Mises criteria

5.6.3 FRONTAL TEST

For the frontal test a load of 20 KN (8g, considering that the weight of a standard formula student car is 250 kg) was applied on the front bulkhead with the rear part fixed. The results are the following ones:

- The maximum deflection is 1.3538 mm
- The maximum stress is lower than 60 MPa

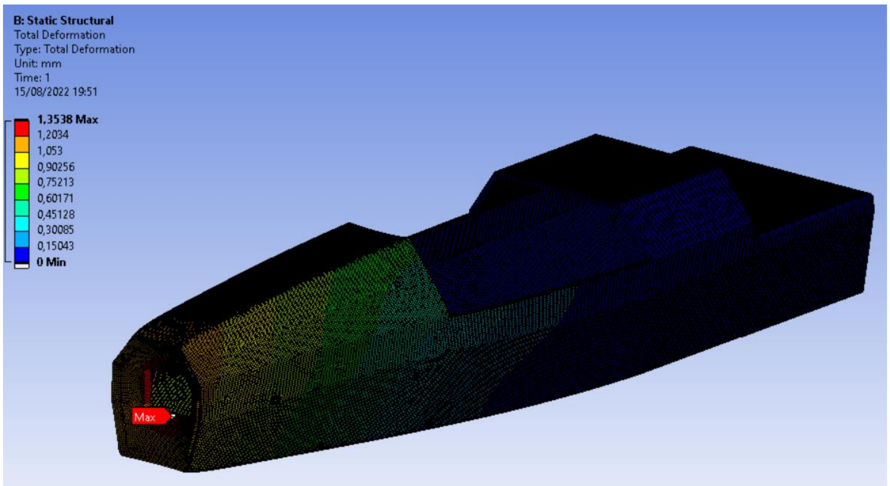

Figure 102: Frontal test maximum deflection

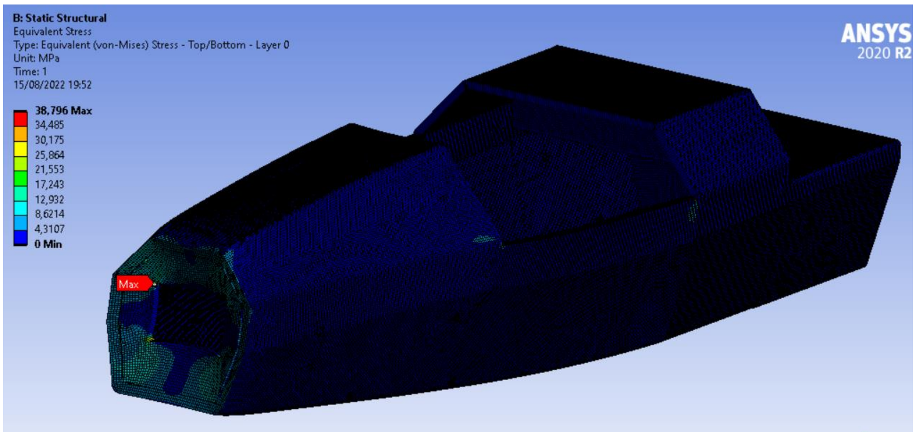

Figure 103: Frontal test von-Mises criteria

Test	Load applied	Maximum stress [MPa]	Max allowable stress [MPa]	Maximum deformation [mm]
Torsional	1750 Nm	49,445	60	5,0563
Lateral Impact	7,5 KN	21,685	60	2,0484
Frontal	20 KN	38,796	60	1,3538

Table 23: Optimal design test results

6. MANUFACTURE PROCESS

6.1 CUT AND FOLD

Cut and fold process is the manufacture process selected, due, mainly, to economic reasons. Cut and fold technique consists of manipulating the panel by removing a strip of skin from one face of the sandwich composite, allowing the panel to be folded to create specific angles and a desired structure. After the strip of skin is removed, adhesive is applied to the exposed core. The component is then clamped until the adhesive cure is complete [15]. In this case, a structural adhesive will be used in order to ensure the shape of the panel.

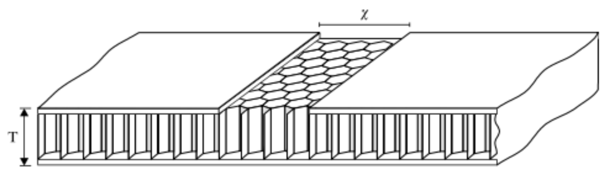

Figure 104: Folded panel

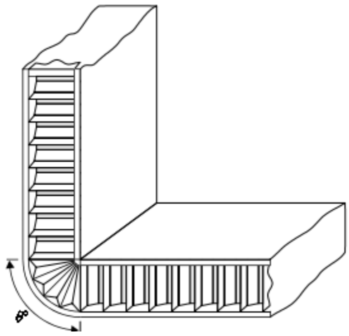

Figure 105: Strip of skin removed

The advantages and disadvantages of cut and fold method compared to steel spaceframe are:

Advantages	Disadvantages
Specific strength and stiffness increase	More complexity in terms of manufacturing
Less heat transfer to chassis	
Introducing composites into the team	
A lower weight could be reach with a design optimization	

Table 24: Advantages and disadvantages of cut and fold compared to steel spaceframe

The advantages and disadvantages of cut and fold compared to a monocoque with a moulded carbon tub are:

Advantages	Disadvantages
Cheaper than a moulded chassis	Unknown properties when bent
	Complex aerodynamic shapes cannot be developed

Table 25: Advantages and disadvantages of a cut and fold compared to a monocoque with a moulded carbon tube

6.2 MANUFACTURE PROCESS

The next steps should be followed when manufacturing:

1. Laminate the "unfolded" plate of each part of the chassis. The laminate process will be the same as they one explained on Chapter 4. Each plate would be oversized to achieve the proper final dimensions to make the manufacture process easier (no complex shapes) and to provide a better finish cutting the edges. In the following table, the dimensions of each part of the chassis are attached.

Part	Dimensions [mm]
Front	1100 x 950
Side Impact	850 x 650
Main Hoop Bracing Support	1200 x 470
Rear	1150 x 500

Table 26: General manufacture dimensions

2. Cut. Once the composite has cured, the sandwich will be cut to final dimensions before being folded. To achieve an accurate cut, two options will be considered: laser and waterjet.
    - <u>Laser cut</u>: It is a manufacture technique that consist of cutting or engraving a material by laser. The process involves cutting the material with a powerful, high-precision laser that focuses on a small area of the material. The main disadvantage of this method is that the material can reach temperatures of 140 ºC. This can affect to the final properties of the skin (carbon fibre and epoxy resin) due to the sudden increase in temperature. Even though is a method that provides an accurate and fast cut, it would be discarded because of how it could negatively affect the skin of the sandwich.

- Water jet: Water jet cutting is a manufacturing process that uses high pressure jets of water provided by pressurizing pumps that deliver a supersonic stream of water to cut and shape various types of materials [16]. In this case, the finish will not be better than laser cut, but the material will not be subjected to high temperatures.

Even for water jet cut or laser cut, to cut the part, a .dxf file will have to be done. This dxf file will define the trajectory that the machine has to follow in order to cut the piece. An example of a .dxf file will be attached on the following image.

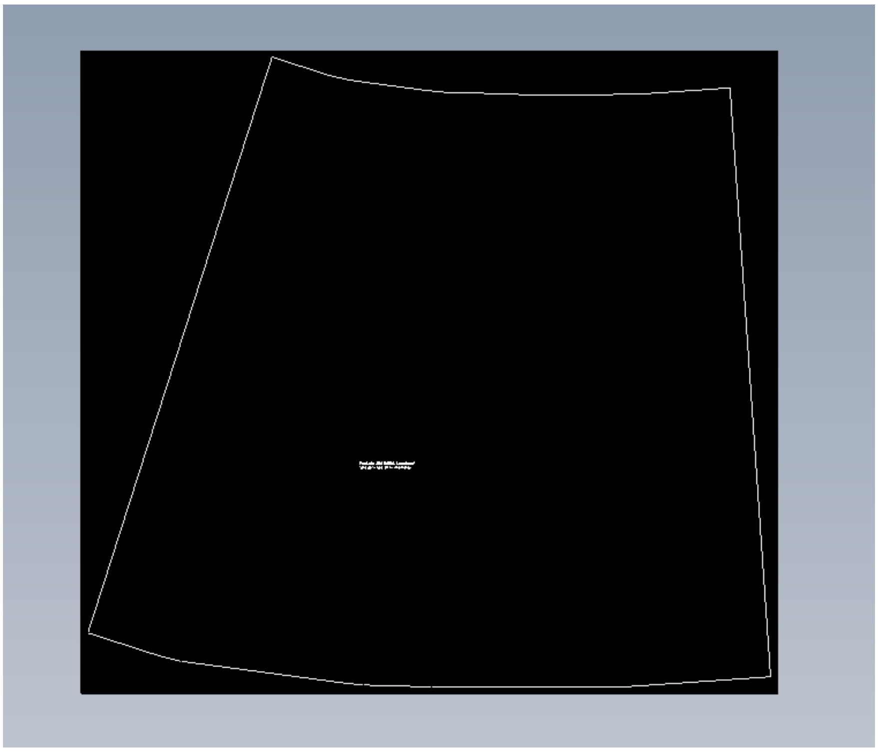

Figure 106: Dxf file

3. Remove the strip of the skin required to reach the angle of bending.

   The strip of the skin removed will depend on the angle of bending. In the next table, the angle of bending required, and the strip removed for each part of the monocoque will be shown.

Part	Angle [º]	Strip removed [mm]
Front	75/15/40/50	30/6/16/20
Side Impact	75/15	30/6
Main Hoop Bracing Support	75/15/40/50	30/6/16/20
Rear	75/15/90	30/6/36

Table 27: Strip to remove on each part

The strip removed has been calculated following the next formula.

$$x = \frac{2\pi * T * \theta^{º}}{360}$$

Equation 10: Strip of skin for the angle required

There are different tools to remove the strip of skin. Two tools or machines will be considered: rotary tool and milling machine.

- Rotary tool: a rotary tool such as Dremel, is a good starting point for cutting carbon fibre. For this method, a cutting wheel design for metal would work but it would not be enough if a lot of work has to be done because it would degrade easily. It is recommended to get a diamond or tungsten carbon. These would last longer, and it would provide a smooth cut because it would not get stack with the resin while cutting. In this case, it is difficult to reach with accuracy the strip of skin that is removed for folding the panel, so this technique could be discarded.

- Milling machine: a milling machine is a machine tool used to perform machining work by chip removal, by means of the movement of a rotating tool with several cutting edges. If more accuracy is required a CNC (computer numerical control) milling machine could be used. A diamond pattern burr router or a polycrystalline diamond cutter is required.

To ensure that the folding process correctly develops a CNC milling machine will be required for more precision.

Figure 107: Rotary Tool

Figure 108: Milling machine

4. Fold. To fold each part, every cut groove must be filled. It can be filled by:
    - Structural adhesive such as using 3M Scotch-Weld Structural Epoxy AdhesiveEC-9323 B/A adhesive, due to its resilient behaviour. It has a full curing time of 14 days at room temperature (23 ºC) or 2 hours at 65 ºC.
    - Epoxy resin with glass bubbles or microballoons, such as 3M Glass Bubbles S60. Compared to the adhesive structural, glass bubbles have a higher shear strength (42 MPa compared to 36-40 MPa from the structural adhesive) and microballoons because of their spherical shape are easier to fill on any cut groove. [17]

Once the filler was set and the panel was placed into its proper position a carbon tape will be applied to reinforce the area. Lastly a "vacuum bag" process will be followed.

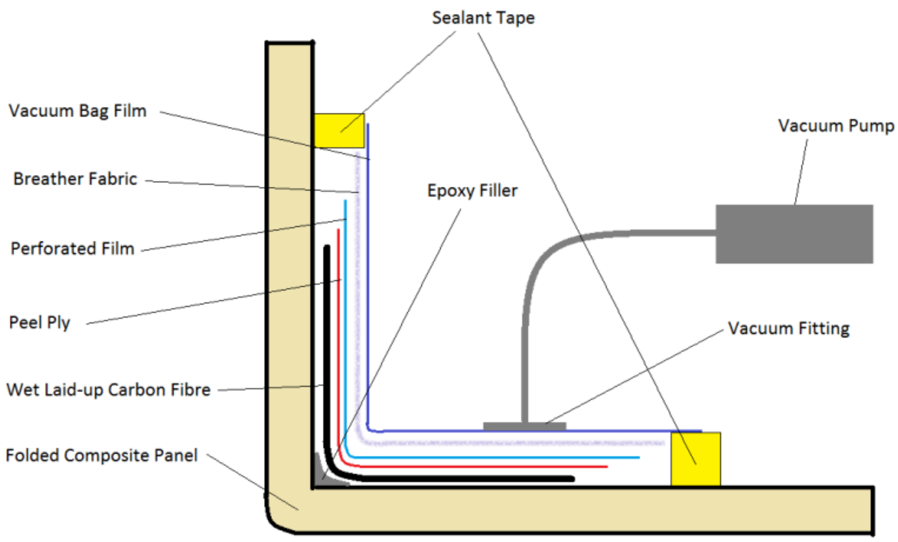

Figure 109: Folding process

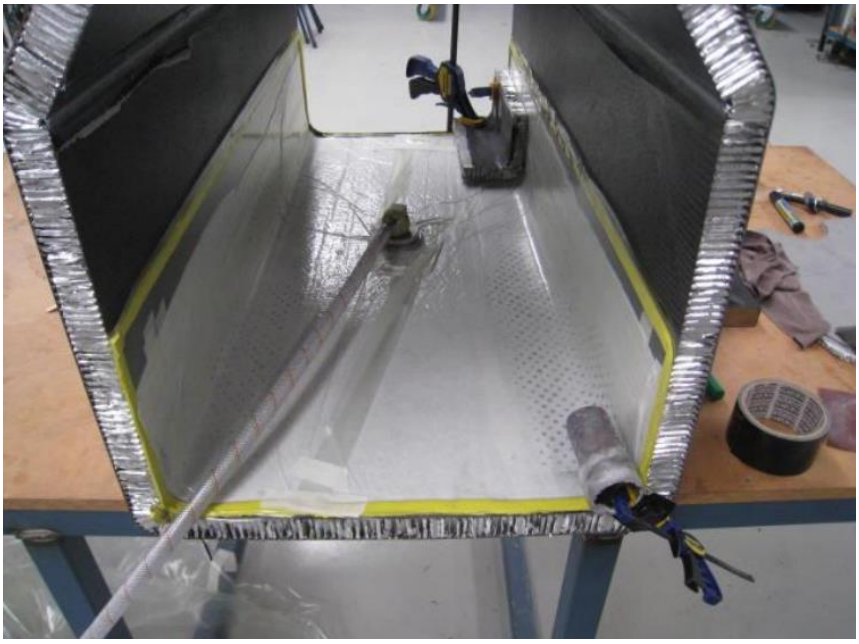

Figure 110: Folded panels

7. FINAL CHARACTERISTICS

Laminate process	Wet lay-up with a vacuum bagging cured process
Skin ply configuration	Front: [2x±45 Biaxial/3x0 UD/2x±45 Biaxial] SI: [2x±45 Biaxial/3x0 UD/2x±45 Biaxial] MHBS: [1x±45 Biaxial/2x0 UD/1x±45 Biaxial] Rear: [1x±45 Biaxial/4x0 UD/1x±45 Biaxial]
Core	Aluminium honeycomb with 20 mm thick and 1/4" cell size
Torsional Stiffness [Nm/º]	3316
Weight [kg]	49,5
Manufacture technique	Cut and fold with a CNC milling machine process to remove the skin

Table 28: Final characteristics

8. BUDGET

Thanks to the attached drawings with the unfolded parts, the surface to laminate for each part is known. The following table shows the required area of each type of fibre for each part and in total.

Parts	Total Area $[m^2]$	Biaxial 45 plies	UD 0 plies
Front	2,1	16,8	12,6
Side Impact	1,1	8,96	6,6
MHB Support	1,13	9,04	6,78
Rear	1,1	9,2	6,9
TOTAL $[m^2]$		43,84	32,88

Table 29: Carbon fibre square metres required

For the lay-up material two supplier have been chosen: Easy Composites and Castro Composites. The epoxy resin and the Biaxial 45º plies will be bought in Easy Composites while the UD 0º plies will be bought in Castro Composites.

In the case of the Biaxial 45 plies, 43,84 square metres are needed. The supplier provides plies with 1.27 meters of width and the length the client whish. In this case, for reaching the 26 square meters needed, the length should be 34.5 metres. To ensure, 40 metres will be bought. This has a cost of 814€.

On the other hand, 32,88 square metres of UD 0º plies are required. The supplier provides plies with 0,63 meters of width and a maximum length of 25 metres. For reaching the 42.6 meters required, the length should be 52,2 metres. Two rolls of 25 meters and a roll of 5 metres will be bought. This has a cost of 1083,79€.

Finally, in the case of the epoxy resin, the carbon fibre weight must be measured. The areal weight of both fibre is 300g/m^2 . This led to a total weight of 18,7 kg. Following the mix ratio by weight (100g resin /30 g hardener), 18,7 kg of resin and 5,6 kg of hardener (26,65 kg in total), will be required. The supply offers 1kg or 5kg kit size (resin+hardener). 30 kg of this kit will be bought. This has a cost of 576,6 €

Lay-up material	**Cost [€]**
Biaxial	814
UD	1083,79
Epoxy resin	576,6
TOTAL	**2474,39**

Table 30: Lay-up material cost

For the aluminium honeycomb a plate of 2500 x 1250 mm has a cost of 155,1 €. 5,43 square metres are required. Two plates of 2500 x 1250 mm are required with a cost of 310,2 €.

Core	**Cost [€]**
Aluminium honeycomb	**310,2**

Table 31: Core budget

Lastly, for the fold process a CNC milling machine will be required. The cost per hour of a CNC milling is 42,5 €. This data was taken from the cost report of the team. The time that will take to remove the skin is unknown. 5 hours' time will be estimated.

Manufacture process	**Cost [€]**
CNC milling machine	**212,5**

Table 32: Manufacture process budget

	Cost [€]
Lay-up material	2474,39
Core	310,2
Manufacture process	212,5
TOTAL	**2997,09**

Table 33: Total cost

9. CONCLUSIONS AND FUTURE WORKS

9.1 CONCLUSIONS

The conclusions drawn from this work are:

- After the design optimization, the value of torsional stiffness is 3316 Nm/º, higher than the previous chassis (3000 Nm/º), meaning that the design in terms of stiffness is optimal.
- The weight of the monocoque is 49,5 kg, 5% heavier than the steel spaceframe chassis. The design in terms of weight must be optimize and the manufacture process will play a key role for reducing weight.
- It has been demonstrated that cut and fold manufacture process offers a low cost (2997,09 €) compared to a steel spaceframe (10.000 €) or a monocoque with a carbon moulded chassis. With the facilities that the team has currently, the manufacture of a carbon fibre monocoque chassis is possible.

With an optimal manufacture process, the implementation of the monocoque chassis will be profitable to improve the performance of the prototype.

9.2 FUTURE WORKS

For future works:

- Design optimization in order to reduce weight. Try different manufacture process and new plies configuration and core. If it is possible, the use of prepreg and autoclave or oven for the cured process will be ideal to obtain a proper stiffness-weight ratio.

- Design justification considering aerodynamics. Aerodynamics plays a key role in the performance of the car. Proposing different shapes of the chassis improving car aerodynamics. A simulation in Ansys Fluent will be useful.
- Inserts implementation. To ensure the bolded attachment to the monocoque inserts are required. Inserts could affect to the stiffness of the chassis so the position of each insert must be studied.

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ANNEX I: SUSTAINABLE DEVELOPMENT GOALS

The Sustainable Development Goals are the building plan to achieve a more sustainable for the future of society. These 17 goals are all interconnected, and we should achieve them all by 2030.

Figure 111: Sustainable Development Goals

It is clear, that carbon fibre has significantly changed many of the products we use every day, improving their mechanical properties. The manufacturing process of this material is very complex and unique to each supplier. The manufacture process has 4 steps (stabilizing, carbonizing, treating the surface and sizing). In the stabilizing process, 200- 300 ºC of temperature are reached for 30-120 minutes, and in the carbonizing process the fibres are heated to a temperature between 1000 ºC and 3000ºC. Because of this, there are some points to consider in terms of sustainability:

1) High energy demand due to this heat intensive process
2) The industrial ovens have the potential to emit some dangerous pollutants such as NH3, HCN…
3) Currently, the recycling process of these materials are inefficient and quite expensive

Because of this, many companies are working on reducing these energy demands or trying to replace this fibre for another one of vegetal origin.

This type of fibre of vegetal origin are called Flax fibre. One of the companies that are implementing flax fibre into competition vehicle is “Bcomp”. [18]

“Bcomp” wants to make an impact and be a part of the solution for cleaner mobility. Thanks to this flax fibre they affirm:

1) 85% reduction of the cradle-to-gate CO2 footprint thanks to the use of sustainable material
2) 50% reduction in weight therefore increasing energy efficiency and range of vehicles
3) 70% reduction in the use of plastic

The characteristics of the plant are in line with the Sustainable Development Goals 14 (Life Below Water) and 15 (Life on Land) in particular, and it does not compete with food production (SDG n° 2) thanks to its action as a rotational crop.

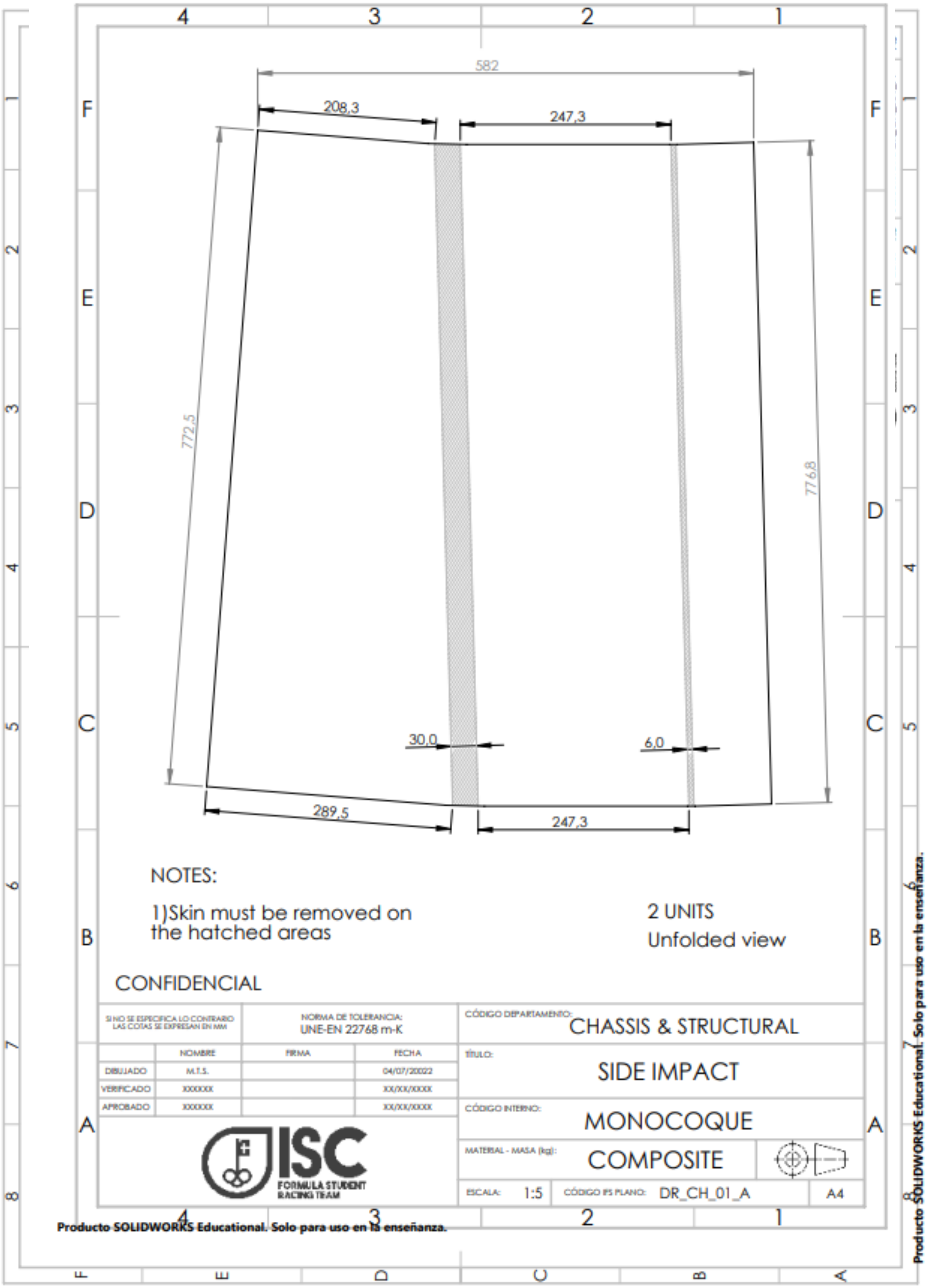
We can see this flax fibre is involved in many projects in motorsport:

1) McLaren F1 MCL-35 seats
2) Porsche Cayman 718 GT4 CS MR with natural fibre bodywork

Figure 113: McLaren F1 MCL-35 seats


Figure 112: Porsche Cayman 718 GTS CS MR

ANEXX II: DRAWINGS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247,3
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1)Skin must be removed on the hatched areas
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Unfolded view
CONFIDENCIAL
NORMA DE TOLERANCIA: UNE-EN 22768 m-K
NOMBRE
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FECHA
DIBUJADO
M.T.S.
VERIFICADO
APROBADO
CÓDIGO DEPARTAMENTO:
CHASSIS & STRUCTURAL
TÍTULO:
SIDE IMPACT
CÓDIGO INTERNO:
MONOCOQUE
MATERIAL - MASA (kg):
COMPOSITE
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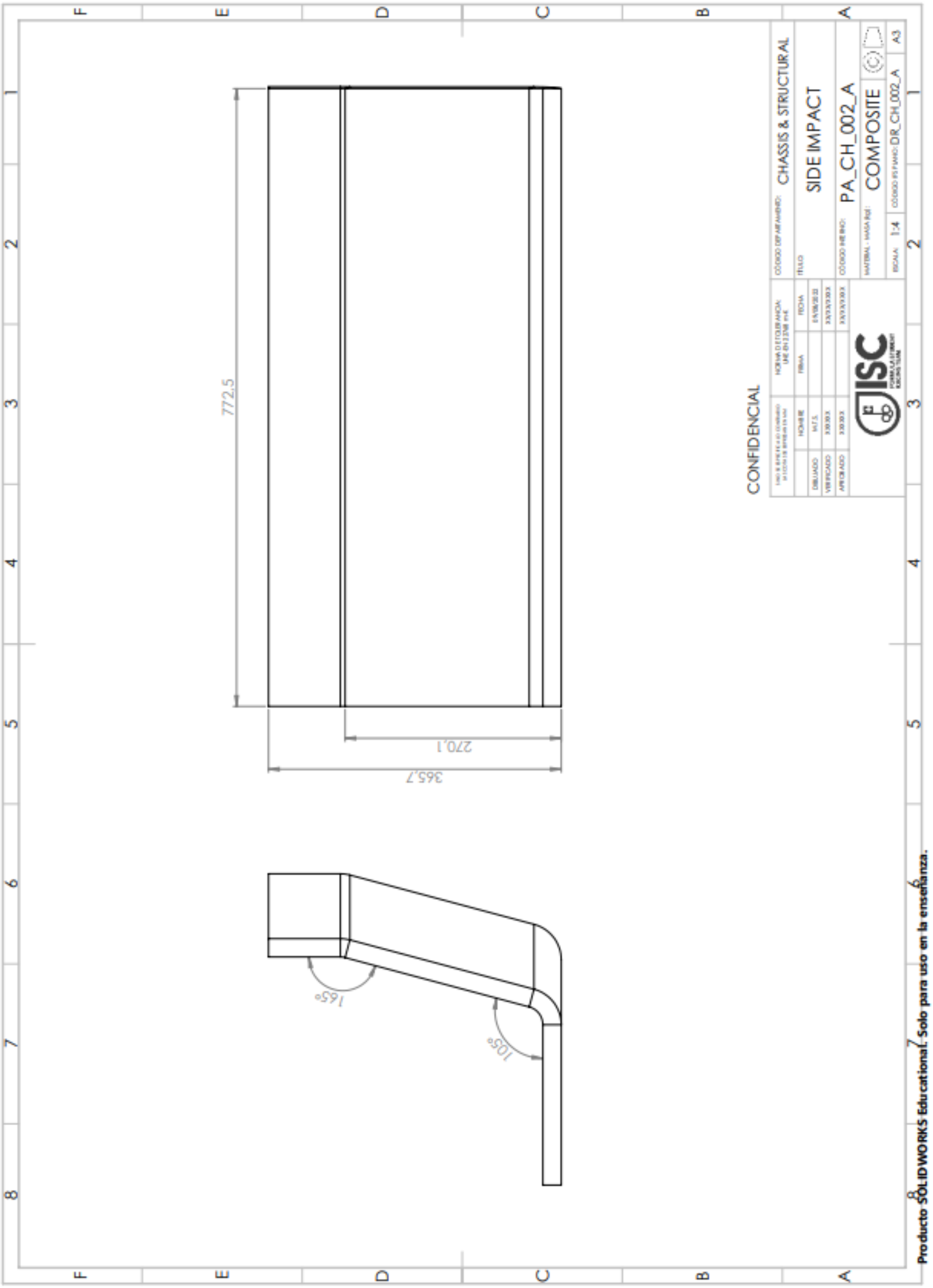
Producto SOLIDWORKS Educational. Solo para uso en la enseñanza.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SIDE IMPACT
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COMPOSITE
DR_CH_002_A
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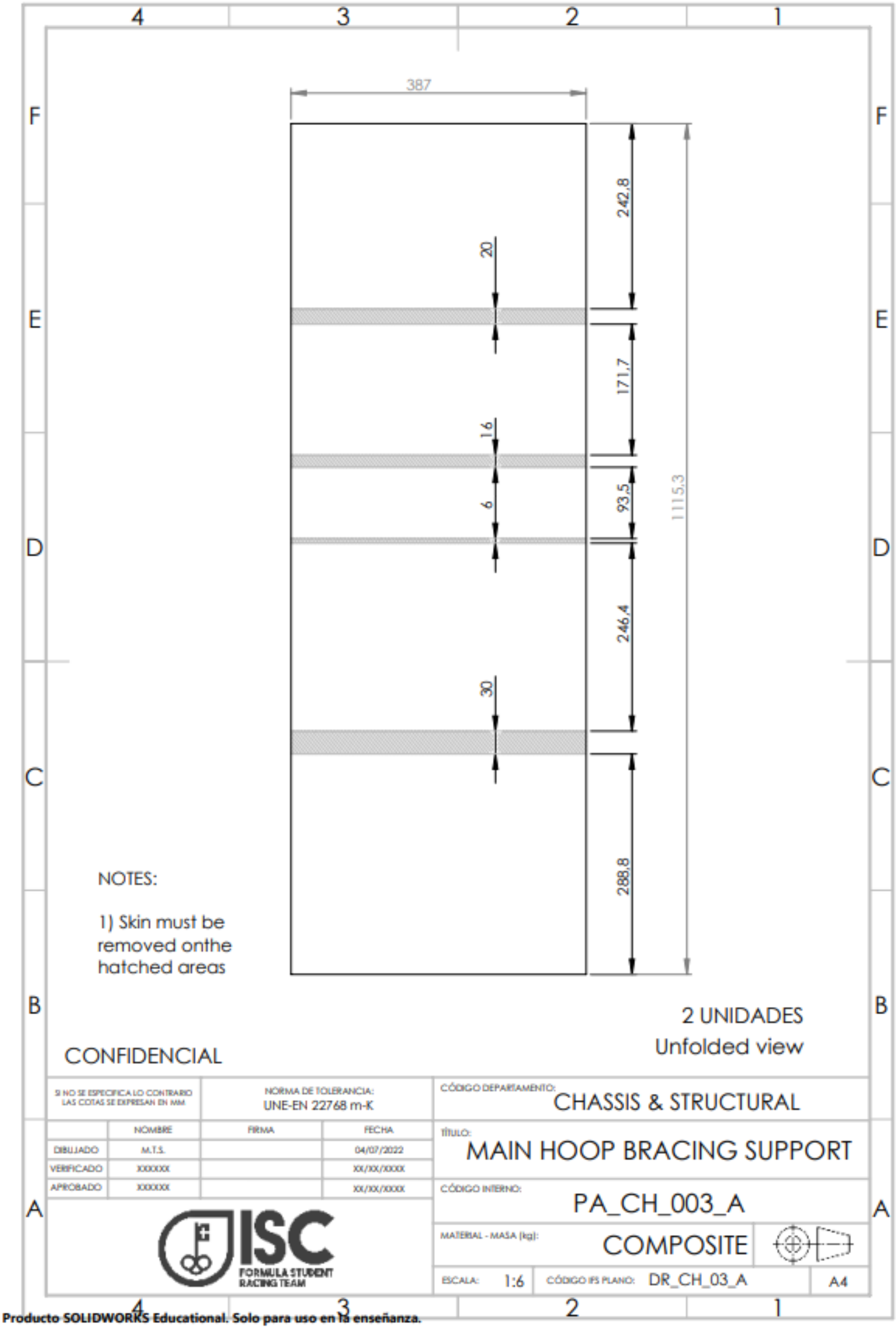
Producto SOLIDWORKS Educational. Solo para uso en la enseñanza.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FIRMA
FECHA
DIBUJADO M.T.S. 04/07/2022
VERIFICADO XXXXXX XX/XX/XXXX
APROBADO XXXXXX XX/XX/XXXX
TÍTULO: MAIN HOOP BRACING SUPPORT
CÓDIGO INTERNO: PA_CH_003_A
MATERIAL - MASA (kg): COMPOSITE
ESCALA: 1:6
CÓDIGO FS PLANO: DR_CH_03_A
A4
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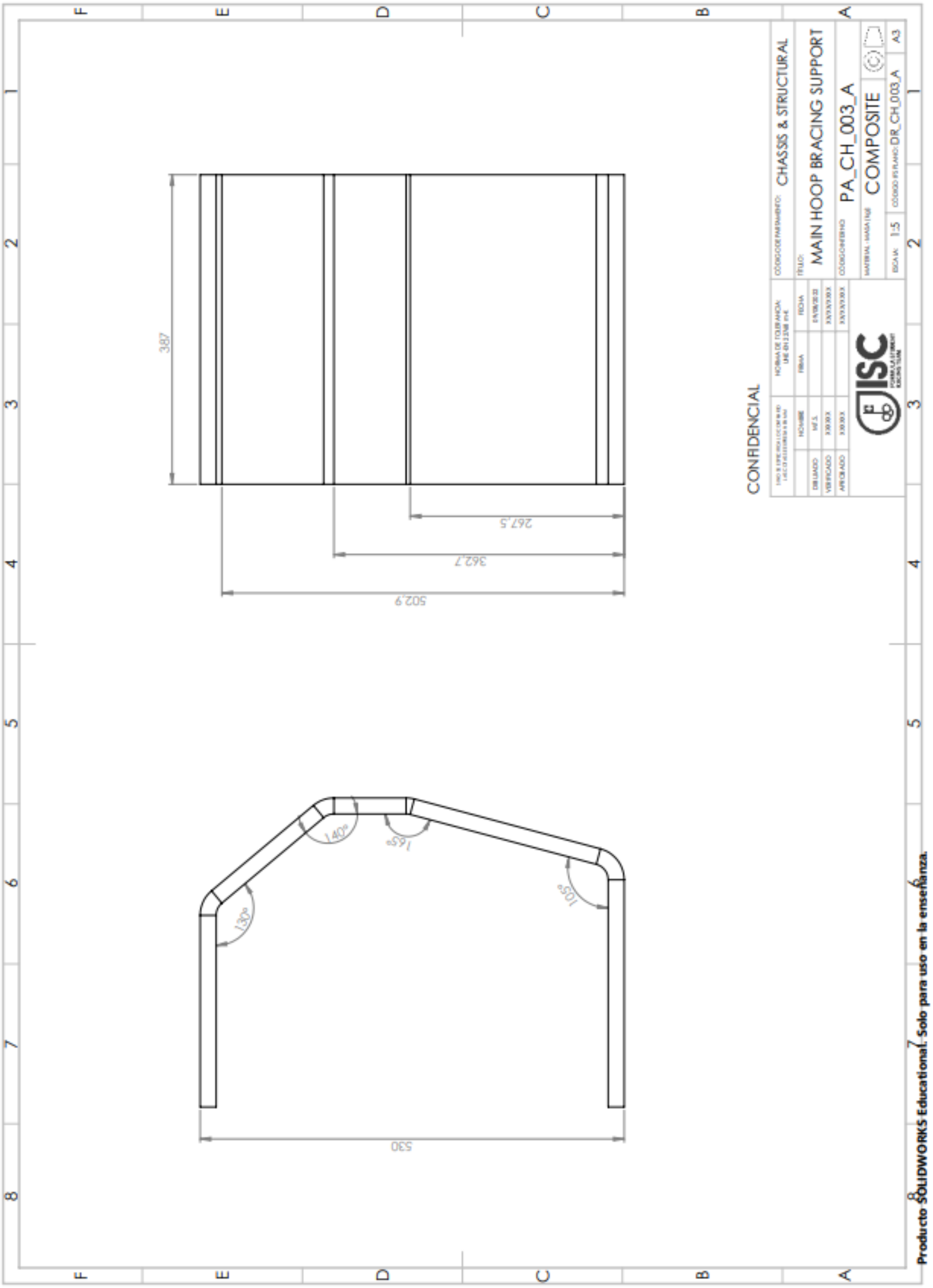
Producto SOLIDWORKS Educational. Solo para uso en la enseñanza.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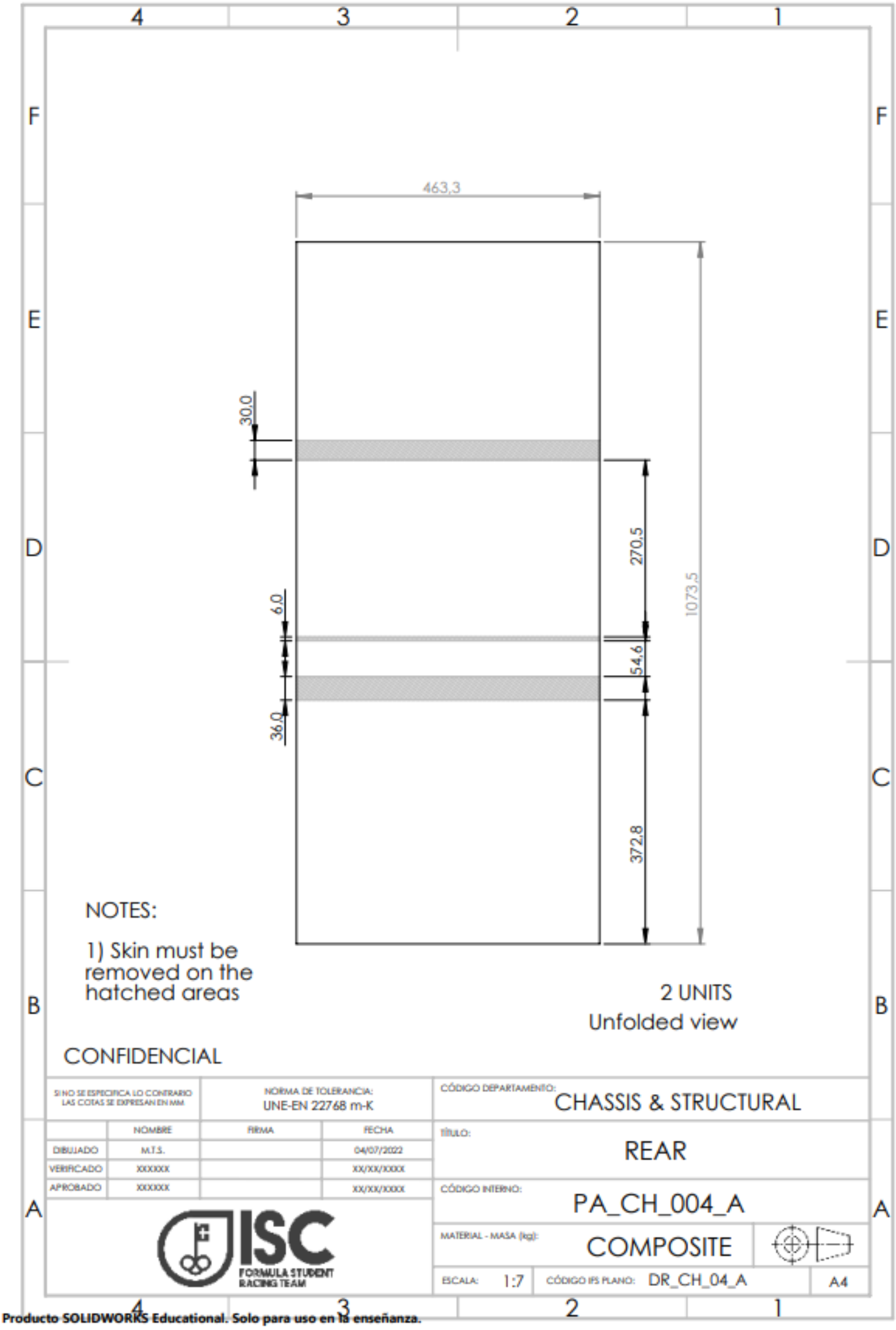
Producto SOLIDWORKS Educational. Solo para uso en la enseñanza.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CÓDIGO DEPARTAMENTO:
CHASSIS & STRUCTURAL
NOMBRE
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M.T.S.
04/07/2022
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APROBADO
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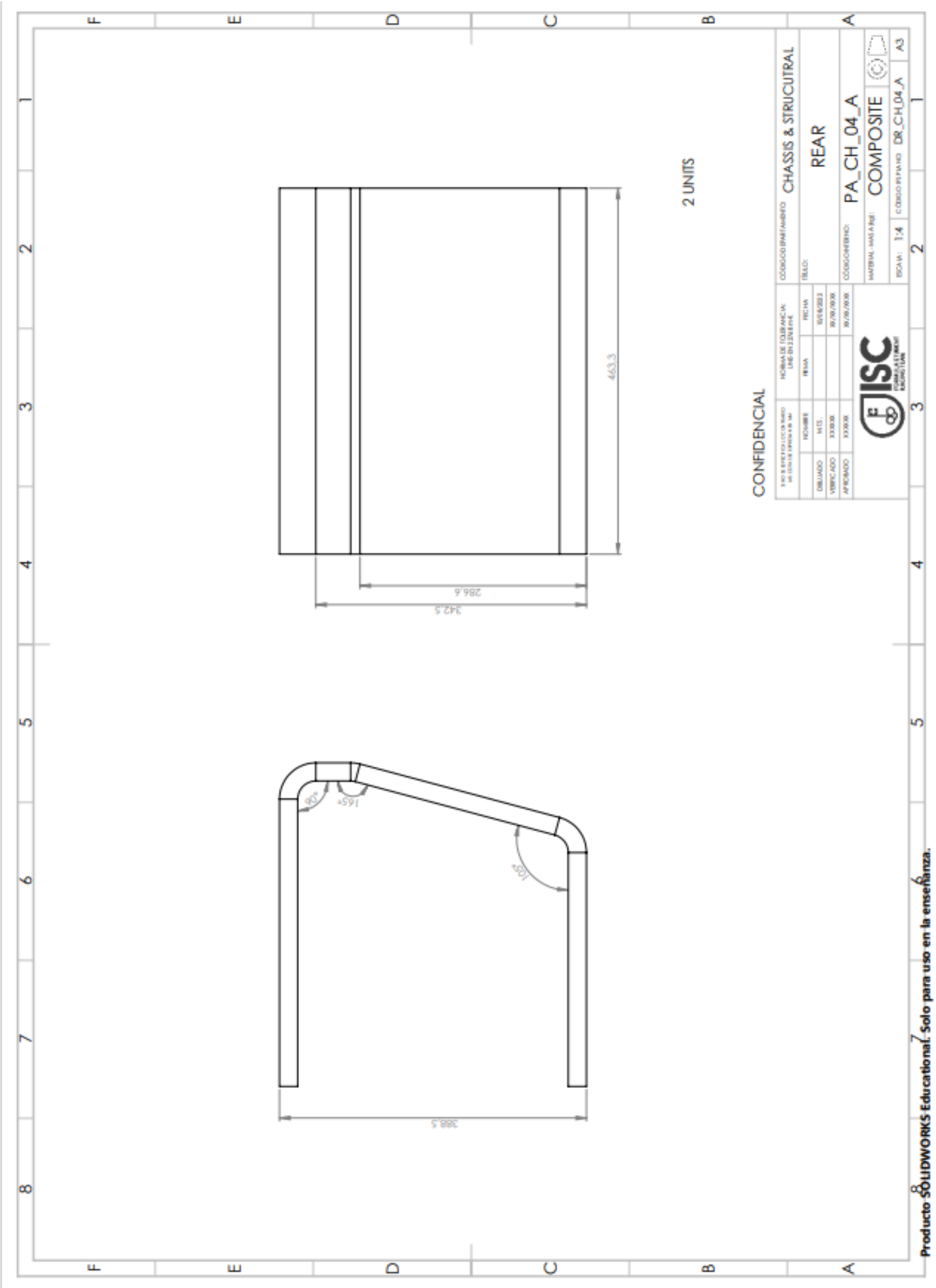
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388.5
165°
90°
105°
Producto SOLIDWORKS Educational. Solo para uso en la enseñanza.

ANEXX III: DATASHEETS

PYROFIL™ MITSUBISHI RAYON CO.,LTD.

PYROFIL DEPARTMENT
1-1-1, Marunouchi, Chiyoda--Ku
Tokyo ,100-8253, Japan
Tel: +81-3-6748-7514/Fax: +81-3-3286-1380
PYROFIL WebSite: www.mrc.co.jp

Typical Properties of Carbon Fiber

PYROFIL™

	Type	Number of Filaments	Filament Diameter	Yield	Tensile Strength			Tensile Modulus			Elongation	Density
			μ m	mg/m	kg/mm2	Mpa	Ksi	ton/mm2	GPa	Msi	%	g/cm3
HT Series	TR 30S 3L	3,000	7	200	420	4,120	600	24.0	234	34	1.8	1.79
	TR 50S 6L	6,000	7	400								
	TR 50S12L	12,000	7	800	500	4,900	710	24.5	240	35	2.0	1.82
	TR 50S15L	15,000	7	1,000								
	TR 50D12L	12,000	7	800	510	5,000	720	24.5	240	35	2.1	1.82
	TRH50 18M	18,000	6	1000	540	5,300	770	25.5	250	36	2.1	1.82
	TRH50 60M	60,000	6	3,200	490	4,830	700	25.5	250	36	1.9	1.81
	TRW40 50L	50,000	8	3,750	420	4,120	600	24.5	240	35	1.7	1.80
IM Series	MR 60H 24P	24,000	5	960	580	5,680	820	29.5	290	42	1.9	1.81
HM Series	MS 40 12M	12,000	6	600	450	4,410	640	35.0	345	50	1.3	1.77
	HR 40 12M	12,000	6	600	450	4,410	640	40.0	395	57	1.1	1.82
	HS 40 12P	12,000	5	430	470	4,610	670	46.0	455	65	1.0	1.85

GRAFIL™

	Type	Number of Filaments	Filament Diameter	Yield	Tensile Strength			Tensile Modulus			Elongation	Density
			μ m	mg/m	kg/mm2	Mpa	Ksi	ton/mm2	GPa	Msi	%	g/cm3
HT Series	34-700	12,000	7	800	490	4,830	700	24.0	234	34	2.0	1.80
		24,000	7	1,600								
	37-800	30,000	6	1,675	560	5,520	800	26.0	255	37	2.1	1.81

NOVEMBER 2013

UNIDIRECTIONAL CARBON FABRIC

24K and 300 gsm (width: 63 cm)

DESCRIPTION

300 gsm UNIDIRECTIONAL 24K CARBON FABRIC suitable for production of composite parts and tools with epoxy, vinyl ester and urethane-acrylic (Crestapol) resins. Ideal for specific reinforcements in certain directions of the composite part or tool.

Supplied covered with a protective and sealing plastic film. Additionally, the fabric yarns are held together thanks to the application of a thin thermoplastic thread on one side of the fabric. This thread is compatible with all thermosetting resins. Roll width: 63 cm.

CHARACTERISTICS

Test Report Nº	12458026-11
Item	SIGRATEX C U300-0/SO
Fiber type	SIGRAFIL C T24-4.8/240-E100
Carbon thread type	24K y 1600 tex
Areal Weight	303 +/-5%
Width	600 +/- 2%
Crimp	Scrimp on one side

TYPE OF SUPPLY

- 300 gsm Unidirectional 24K Carbon fabric x 1 linear m (0.63 m^2), supplied rolled in a cardboard box
- 300 gsm Unidirectional 24K Carbon fabric x 5 linear m (3.15 m^2), supplied rolled in a cardboard box
- 300 gsm Unidirectional 24K Carbon fabric x 25 linear m (15.75 m), supplied rolled in a cardboard box

*This technical data sheet has been created based on our latest knowledge and according to the best information and knowledge currently available. As we are unable to check if our products are used as recommended, we cannot guarantee the results. In spite of this, we will be glad to give an advice.

RESINAS CASTRO S.L.
Pol. Ind. A Granxa, 3ª Paralela
C/Cíes 190, 36400 O Porriño – ESPAÑA
Tlf.: +34 986 342 955 Fax: +34 986 342 520
E-mail: shop@castrocomposites.com
Web: www.castrocomposites.com

easycomposites™ share the knowledge

EPOXY INFUSION RESIN IN2

Key Features

- Ideal For Resin Infusion
- Ultra Low Viscosity Resin
- Outstanding Wetting Abilities
- Good Mechanical Properties
- Choice of Hardener Speed

Product Description

Our IN2 is a high performance epoxy resin that has been specifically formulated for use in resin infusion composites production.

As an infusion resin it is ultra-low viscosity ensuring that is able to quickly infuse through a range of reinforcements. Its excellent mechanical strength makes it ideally suited for use with high performance reinforcements such as carbon fibre and aramids like Kevlar.

The resin also exhibits excellent cured mechanical properies far in excess of many more traditional epoxy resin brands (as can be seen from the technical data sheets). Improved mechanical properties mean stronger, ligher, higher performance parts.

Recommended Uses

This is a high performance low viscosity epoxy resin formulated specifically for use in resin infusion composites production. The resin cures to a clear finish.

This is the same epoxy infusion resin that is included with our Resin Infusion Complete Starter Kit.

When cured the epoxy exhibits good flexural strength making it will suited to the lamination of structural parts. The resin also exhibits very good clarity making it also suitable for use when laminating unpainted carbon fibre composites.

Properties

The table below shows the typical uncured properties:

Property	Units	Resin	Hardener	Combined
Material	-	Epoxy Resin	Formulated Amine	Epoxy
Appearance	-	Clear Liquid	Amber Liquid	Clear Liquid
Viscosity @20 °C	mPa.s.	500 – 800	10 - 20	200 – 450
Density @20 °C	g/cm^3	1.08 – 1.18	1.07 – 1.13	1.12 – 1.18

How to Use

IN2 is a chemical product for professional use. It is essential to read and understand the safety and technical information before use.

Follow the guidelines for safe use outlined in the SDS which include the use ofappropriate hand and eye protection during mixing and use.

Mix Ratio

Mix Ratio 100:30 by Weight

IN2 Epoxy Laminating Resin should be mixed with AT30 FAST or AT30 SLOW Hardener at a ratio of 100 parts of resin to 30 part sof hardener, by weight. FAST and SLOW hardeners can be blended to achieve pot-life and demould times anywhere between those stated. However, you must still maintain the correct overall ratio of resin to hardener to ensure a proper cure.

Failure to do so will result in a poor or only partial cure of the resin, greatly reduced mechanical properties and possibly other adverse effects. Under no circumstances add 'extra hardener' in an attempt to speed up the cure time; epoxies do not work in this way.

Our IN2 Infusion Resin is available with a choice of two hardener speeds; 'FAST' which has a pot-life of 9-14mins and 'SLOW' which provides a pot-life of 80-100mins. As standard we recommend using IN2 Infusion Resin with the SLOW hardener, especially for larger infusion projects. For small projects where you are confident of the infusion time, use of the FAST hardener greatly reduces the demould time.

Mixing Instructions

IN2 is a highly reactive (fast curing) resin system. Only weigh out and mix as much resin as you can use within the pot life.

Weigh or measure the exact correct ratio of resin and hardener into a straight sided container. Using a suitable mixing stick begin to mix the resin and hardener together to combine them completely.

Spend at least one minute mixing the resin and hardener together, paying particular attention to the sides and base of the container. Remember: Any resin that has not been thoroughly combined with hardener will not cure.

Once you have finished mixing in one container, it is good practice to transfer the mixed resin into a second container and undertake further mixing of the resin using a new mixing stick. Doing so will eliminate the risk of accidentally using unmixed resin from the bottom or sides of the container.

Pot-Life / Working Time / Cure Time

IN2 is a highly reactive resin system and once the resin has been mixed with the hardener, the reaction will start to give off heat (exotherm) which will further accelerate the cure of the resin, especially when the resin is in the mixing pot.

Transfer the resin from the mixing pot onto the part as soon as possible to extend the working time and avoid the risk of uncontrollable rapid cure in the mixing pot.

As with all epoxies, the pot-life/working time will vary significantly depending on the ambient temperature, the starting temperature of the resin and hardener and the amount of resin mixed.

IN2 can be used in ambient temperatures between 15°C (59°F) and 30°C (86°F). For best results, an ambient temperature of at least 20°C (68°F) is recommended. Ensure that both resin and hardener containers are within this temperature range before use.

During an infusion, you can reduce the chance of the resin 'gelling' in the pot by mixing small quantities at a time and topping up the resin jug as the resin is drawn into the laminate. Once the resin is in the laminate, it is much less likely to exotherm and gel before you want it to.

The table below gives an indication of pot-life and cure times:

	Pot-Life @ 25 °C	Gelation @ 25 °C	Demould Time @ 25 °C
AT30 SLOW*	80 - 100mins	8 - 11hrs	18 - 24hrs
AT30 FAST*	9 - 14mins	2 - 4hrs	6 - 8hrs

*Fast and slow hardeners can be blended to achieve pot-life and demould timesanywhere between those stated above.

	25 °C	60 °C	100 °C	Full Cure at 25°C
Cure Time	24hrs	6hrs	3hrs	7 Days

Full Cure / Post-Cure

As with most epoxy systems, where parts cure in normal ambient temperatures, full cure is not reached for several days. Although parts will be handleable after the listed demould time (at 25°C), full mechanical properties will take at least 14 days to develop in (at 25°C). Where possible, avoid exposing the cured resin to full service rigours for at least this time.

As with many post-cure cycles for resins, the post-cure cycle for our IN2 Epoxy Resin is not too sensitive and a range of different post-cure cycles will produce good results, specifically improved mechanical performance and elevated HDT/operating temperature. Post-curing parts that will be used at or exposed to elevated operating temperatures (such as vehicle bonnets/hoods in direct sunlight, engine-bay parts, car interior parts etc.) is strongly recommended to prevent distortion of the parts when they are put into service and experience these higher temperatures.

Where possible, parts should be post-cured still inside the mould to reduce distortion and improve surface finish (i.e. reduce 'print-through'). When post-curing parts in the mould, it is important to post-cure them without demoulding at all (i.e. don't demould and then put them back into the mould) otherwise you can get some strange patterns on the surface where some areas are post cured in direct contact with the mould surface and others are not.

A simple and very effective post-cure cycle with the IN2 Epoxy Infusion Resin is as follows:

CYCLE #1 SUITABLE FOR MOST SITUATIONS

- 24hrs at room temperature
- 6hrs at 60°C

If you're encountering any surface finish issues (faint print-through) then you can experiment with a slower 'ramp rate' which sometimes improves things:

CYCLE #2 SUGGESTED FOR SUBTLE IMPROVEMENTS TO SURFACE FINISH

- 24hrs at room temperature
- 2hrs at 40°C
- 2hrs at 50°C
- 5hrs at 60°C

If you need to push the HDT of the finished part higher then you could increase post-cure up to a maximum of 80°C as follows:

CYCLE #3 SUGGESTED FOR HIGHEST POSSIBLE HDT/OPERATING TEMPERATURE

- 24hrs at room temperature
- 2hrs at 40°C
- 2hrs at 50°C
- 2hrs at 60°C
- 2hrs at 70°C
- 4hrs at 80°C

These are all just suggestions. Most situations just call for option #1; 6hrs at 60°C. Many customers also find that they can dispense with the 24hrs cure at ambient and simply load newly infused parts into the oven to begin the cure however this is something that you would need to experiment with yourself. A cure at ambient temperature before post-cure is generally favoured with most resin systems.

Mechanical Properties

Cured Resin Properties

	Units	AT30 SLOW	AT30 FAST
Colour		Pale yellow	Pale yellow
Machinability		Excellent	Excellent
Density 25°C	g/ml	1.08 – 1.12	1.08 – 1.12
Hardness 25°C	Shore D/15	84.5 – 88.5	86 – 90
Maximum Tg	°C	92 – 98	75 – 81
Water absorption (24h RT)	%	0.12 – 0.20	0.22 – 0.27
Water absorption (2hr 100°C)	%	0.58 – 0.70	0.95 – 1.00
Flexural strength	MN/m^2	112 – 124	95 – 109
Maximum strain	%	5 – 7	4 – 6
Strain at break	%	6 – 8	7 – 9
Flexural modulus	MN/m^2	3150 – 3550	2500 – 3100
Tensile strength	MN/m^2	65.5 – 73.5	67.0 – 75.0
Elongation at break	%	6 – 8	5 – 7

Transport and Storage

Resin and hardener should be kept in tightly seal containers during transport and storage. Both the resin and hardener should be stored in ambient conditions of between 10°C (50°F) and 25°C (77°F).

When stored correctly, the resin and hardener will have a shelf-life of 12 months. Although it may be possible to use the resin after a longer period, a deterioration in the performance of the resin will occur, especially in relation to clarity and cure profile.

Pay particular attention to ensuring that containers are kept tightly sealed. Epoxy hardeners especially will deteriorate quickly when exposed to air.

Disclaimer

This data is not to be used for specifications. Values listed are for typical properties and should not be considered minimum or maximum.

Our technical advice, whether verbal or in writing, is given in good faith but Easy Composites Ltd gives no warranty; express or implied, and all products are sold upon condition that purchasers will make their own tests to determine the quality and suitability of the product for their particular application and circumstances.

Easy Composites Ltd shall be in no way responsible for the proper use and service of the product, nor for the safeguarding of personnel or property, all of which is the duty of the user. Any information or suggestions are without warranty of any kind and purchasers are solely responsible for any loss arising from the use of such information or suggestions. No information or suggestions given by us shall be deemed to be a recommendation to use any product in conflict with any existing patent rights. Before using any of our products, users should familiarise themselves with the relevant technical and safety datasheets provided by Easy Composites Ltd.

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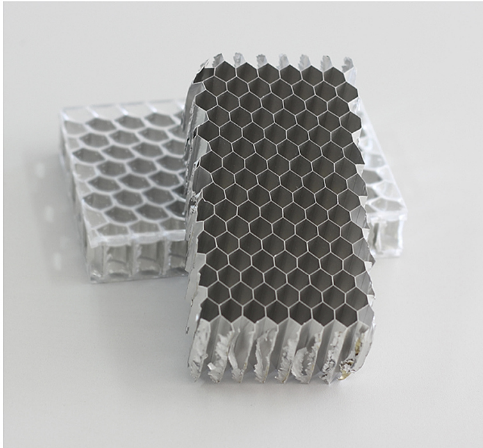
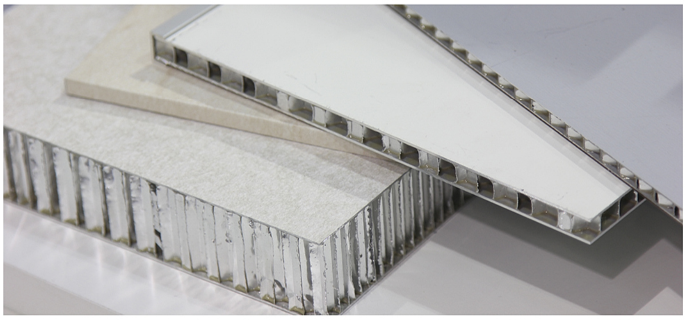
Ficha Técnica

ALUCOAT es una compañía española que produce núcleo de nido de abeja de aluminio de alta calidad, **aluNID®**, que tiene una amplia variedad de aplicaciones.



Nuestro núcleo de nido de abeja de aluminio se adapta a los requerimientos del cliente y puede ser suministrado en diferentes condiciones. **aluNID®** ofrece soluciones en colaboración con los clientes y trabaja junto a pequeñas y grandes empresas tanto a nivel nacional como internacional.

aluNID® se utiliza por tanto en sectores tan diversos como en el de la construcción y arquitectura, transportes (ferroviario, naval…), en la industria y diferentes aplicaciones comerciales gracias a su composición y propiedades únicas en el sector.



Propiedades

- •Ligero
- •Resistente y rígido en compresión y cizallamiento
- •Incombustible
- •Reciclable
- •Conductor eléctrico y térmico
- •Buena planicidad
- •Resistente a la corrosión

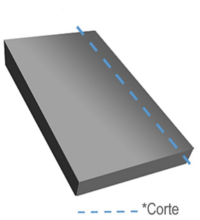
Propiedades Mecánicas

Ejemplo de referencia para su pedido:

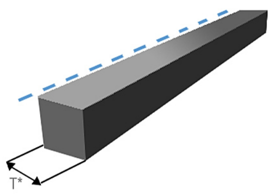
aluNID® 3000	-	O 1/4”	-	56	-	L1500-W3000	-	P	-	T10	-	B	-	EX
Aleación		Tamaño de Celda		Densidad		Dimensiones Expandidas		Perforado		Espesor		Tolerancia de corte		Expandido

Se suministra de 3 maneras:

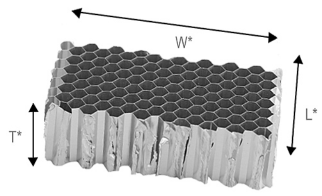
Bloques no expandido(BLQ)



No expandido en loncha (NEX)



Expandido en plancha (EXP)



* T = Espesor, L = Longitud, W = Ancho

ALUCOAT diesgnation	ø inch	ø mm	Foil µm	Density kg/m3	Compressive Strength Plain Strength Mpa	Compressive Strength Stabilised Strength Mpa	Crush Strength Mpa	Plate Shear In L direction Strength Mpa	Plate Shear In L direction Strength Mpa	Plate Shear In W direction Strength Mpa	Plate Shear In W direction Strength Mpa
aluNID® 3000	1/4	6,35	50	56	2,2	3,50	0,90	1,65	327	0,97	172
aluNID® 3000	3/8	9,52	50	40	1,2	1,95	0,50	1,10	214	0,64	107
aluNID® 3000	1/2	12,7	50	29	0,70	0,95	0,30	0,70	143	0,43	68
aluNID® 3000	3/4	19,1	50	20	0,35	0,60	0,15	0,40	90	0,28	40
aluNID® 3000	1/4	6,35	70	80	4,15	4,30	1,65	2,70	511	1,50	284
aluNID® 3000	3/8	9,52	70	54	2,00	2,60	0,85	1,60	312	0,95	163
aluNID® 3000	1/2	12,7	70	40	1,20	1,50	0,50	1,10	214	0,65	107
aluNID® 3000	3/4	19,1	70	27	0,60	0,85	0,25	0,65	131	0,40	61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3M Advanced Materials Division

3M™ Glass Bubbles S60

Introduction

3M™ Glass Bubbles S60 are high-strength polymer additives made from a water-resistant and chemically-stable soda-lime-borosilicate glass. The S60 product can be used in a variety of industries and applications, such as automotive; injection molding; transportation; and oil and gas– wherever a low density filler with intermediate crush strength is required. These hollow glass microspheres can be used as a low-density filler material ideal for plastic and rubber parts created from injection molding, extrusion processes and/or other vigorous processing equipment (Banbury mixers, etc.).

3M glass bubbles S60 help to reduce weight; reduce noise, vibration and harmonics; reduce thermal expansion; and contribute to cost savings. They are ideal additive materials in the automotive, truck, rail and aerospace industries.

Formulating Information

Flow properties: 3M glass bubbles S60 will remain free flowing for at least two years from the date of manufacture when stored in the original, unopened container in accordance with the recommended storage conditions. (See storage recommendations at right).

Material Description (Not for specification purposes.)

Property	3M™ Glass Bubbles S60
Shape	Hollow spheres with thin walls
Composition	Soda-lime-borosilicate glass
Color, unaided eye	White, powdery

Typical Physical Properties (Not for specification purposes.)

Property	3M™ Glass Bubbles S60
Crush strength, 90% survival by volume (psi)	6,000
True density (g/cc)	0.60
Packing factor (bulk density to true particle density)	60%
pH (at 5 wt% loading in water)	9.5
Average diameter (microns)	30
Softening point (°C)	600
Flotation (volume % <1.0 g/cc density)	92%
Volatile content (by weight)	0.5%

3M Advanced Materials product realization process and manufacturing sites are aligned to ISO 9001 Quality Systems. Test data is generated by following documented procedures and test methods.

Glass bubble breakage: Breakage may occur if the product is severely processed. To minimize breakage, minimize exposure to high shear processes and point contact shear such as gear pumps and 3-roll mills. When adding to an extrusion process, the material should be added downstream of the feed hopper via a side stuffer or top feeder (similar to adding glass fiber). Contact 3M technical service or your equipment vendor for assistance if breakage is suspected.

Packaging

3M glass bubbles S60 are available in the following packaging sizes:

Gallon: 2 lb/.9 kg

Small Box: 125 lb/56.7 kg

Large Box: 850 lb/38.6 kg

Bulk Bag: 1,000 lb /454 kg

Bulk Trailer: 38,000 lb/17,237 kg

Product Storage, Handling and Safety

Storage: Ideal storage conditions include unopened cartons in a dry and temperature-controlled warehouse. Extended exposure of 3M™ Glass Bubbles S60 boxes to high humidity and/or conditions susceptible to condensation may result in some amount of "caking" of the glass bubbles.

To minimize the potential for caking and thereby maximize storage life, the following suggestions are offered:

1. Carefully re-tie opened bags immediately after use.
2. If the polyethylene bag is punctured during shipping or handling, seal the hole as soon as possible or insert the contents into an undamaged bag.
3. During hot and/or humid months, store boxes in the driest, coolest space available.

If controlled storage conditions are unavailable, carry a minimum inventory, and process on a first in/ first out basis.

Handling: Due to the low weight and small particle size of 3M glass bubbles S60, dusting may occur while handling and processing. To minimize the dusting potential during handling, consider the following:

- Do not open glass bubbles packages until ready to use.
- Upon opening, have local exhaust ventilation near the opening to pull away airborne particles. (Dust collection equipment may be required – check local OSHA and other applicable regulations.)
- Remove glass bubbles with a suction "wand" (with slight positive pressure aeration) and transfer to a closed mixing tank inside fully contained piping. If a closed mixing tank is not available, use dust collection equipment as close as practical to the point of entry. Pneumatic conveyor systems have been used successfully to transport glass bubbles without dusting from shipping containers to batch mixing equipment. Equipment vendors should be consulted for recommendations.
- Static eliminators should be used to prevent static buildup.

Safety: For worker protection, please consider the following:

- Use safety glasses with side shields for eye protection.
- An air-purifying respirator suitable for particulates may be selected for protection after an optional exposure assessment is performed for your specific application. (For additional information about personal protective equipment, refer to the product Safety Data Sheet.)
- Use with appropriate local exhaust ventilation/dust collection in the work area.
- Refer to the 3M™ Glass Bubbles Safety Data Sheet for additional safety information.

Additional Information

3M glass bubbles are supported by global sales, technical and customer service resources, with fully-staffed technical service laboratories in the U.S., Europe, Japan, Latin America and Southeast Asia. Users benefit from 3M's broad technology base and continuing attention to product development, performance, safety and environmental issues.

For additional technical information on 3M glass bubbles in the United States, call 3M Advanced Materials Division, **800-367-8905**. For other 3M global offices, and information on additional 3M products, visit our web site at: **www.3M.com/glassbubbles**.

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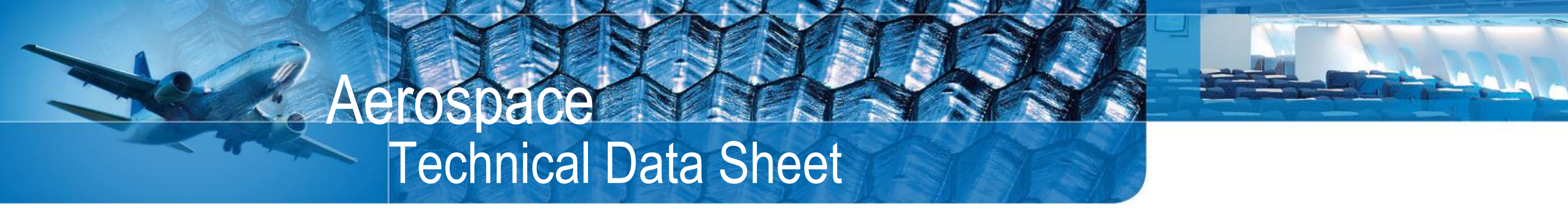


3M™ Scotch-Weld™ EC-9323 B/A

Two Part Structural Adhesive

Product Description

3M™ Scotch-Weld™ Structural Epoxy Adhesive EC-9323 B/A is a two component epoxy paste adhesive which cures at room temperature or with mild heat to form a tough, impact resistant structural bond. It has an excellent adhesion to a wide variety of substrates such as metals, glass, ceramics and plastics, incl. GFRP and CFRP. Once cured it provides extremely high shear and peel strength over a wide temperature range, with outstanding resistance to harsh environments and chemicals commonly encountered in aerospace applications.

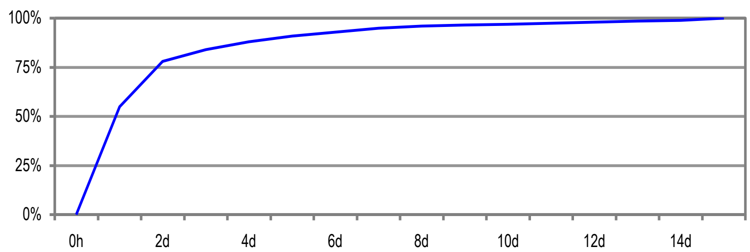
Key Features

- Toughened system providing extremely high shear and peel strength
- Wide service temperature range
- Outstanding environmental resistance
- Full room temperature processing

Product Characterization

The following technical information and data should be considered representative or typical only and should not be used for specification purpose

General Properties	Part B	Part A
Colour	Off-white	Red-orange
Base	Modified epoxy	Modified amine
Consistency	Thixotropic paste	Slight gel
Density	1.18 g / cm³	1.06 g / cm³
Solids	100 %	100 %
Viscosity [(a)]	700 Pas	18 Pas
Mix ratio by weight (by volume)	100 : 27 wt. (100 : 30 vol.)	
Work life [(b)] / Open Time at 23 ± 2 °C	150 minutes / 20 minutes	
Strength build-up at 23 ± 2 °C	(see chart below)	



Handling strength[(c)]	4-5 hours	
Full cure cycle	14 days at room temperature	
Packaging	Cans and pails	

[(a)] *Brookfield RVF Spindle 7, 2 rpm* [(b)] *50 g of mixed adhesive* [(c)] *Time to reach 1 MPa Overlap Shear Strength*

Product Performance

The following data show typical values obtained with Scotch-Weld™ EC-9323 B/A on unprimed, sulfochromic etched, 2024 T3 aluminium. The samples have been cured for 15 days at room temperature, if not stated otherwise. To control the bond line thickness, approximately 1 wt. % of glass beads, 90 – 150 µm diameter were added to the adhesive.

Mechanical Properties		Test Temperature	Cured for 15 days at 23 °C	Cured for 2 hours at 65 °C
Overlap Shear Strength EN 2243-1		-55 °C	38 MPa	42 MPa
		23 °C	36 MPa	40 MPa
		80 °C	22 MPa	22 MPa
		120 °C	4 MPa	4 MPa
		150 °C	2 MPa	-
Overlap Shear Strength EN 2243-1	Stainless steel	23 °C	-	27 MPa
	CFRP, GFRP epoxy matrix resin	23 °C	-	28 MPa [d]
	PMMA	23 °C	-	3 MPa [d]
Floating Roller Peel Strength EN 2243-2		-55 °C	120 N / 25 mm	90 N / 25 mm
		23 °C	170 N / 25 mm	190 N / 25 mm
		80 °C	145 N / 25 mm	145 N / 25 mm
Impact Resistance ANFOR NF 76-115		23 °C	17,4 kJ / m²	32,2 kJ / m²

[d] Substrate Failure

Environmental Ageing

The following data show typical values obtained with Scotch-Weld™ EC-9323 B/A after 750 hours exposure to different media and environments to determine the aging resistance. The samples have been cured for 15 days at room temperature.

Mechanical Properties	Environment	Test Temperature	Results
Overlap Shear Strength EN 2243-1	Demineralized water at 23 ± 2 °C	23 °C	34 MPa
	Gasoline super at 23 ± 2 °C	23 °C	36 MPa
	Engine oil (20W40) 23 ± 2 °C	23 °C	36 MPa
	Hydraulic fluid skydrol 500B at 23 ± 2 °C	23 °C	37 MPa
	JP4 fluid at 23 ± 2 °C	23 °C	36 MPa
	5 % Salt spray at 23 ± 2 °C	23 °C	34 MPa
	Hot / Wet 70 °C, ≥ 95% R.H.	23 °C	33 MPa
	Dry heat at 120 ± 2 °C	23 °C	35 MPa

3M™ Scotch-Weld™ Structural Epoxy Adhesive EC-9323-150 B/A

Scotch-Weld™ EC-9323-150 B/A is a product modification of Scotch-Weld™ EC-9323 B/A. There are no significant differences in terms of performance. It contains 1 wt % of glass beads 90 – 150 µm diameter for bond line thickness control. Slight differences can be observed in density and viscosity.

Handling, Application, Storage

Precautionary Information

Refer to product label and Material Safety Data Sheet (MSDS) for health and safety information before using this product. For MSDS visit our website www.3M.com/msds.

Instructions for use

While this information is provided as general application guideline based upon typical conditions, it is recognized that no two applications are identical due to, among other things, differing assemblies, methods of heat and pressure application, production equipment and other limitations. It is therefore suggested that experiments be run, within the actual constrains imposed to determine optimum conditions for your specific application and to determine suitability of product for particular intended use.

Process step	Instruction
Surface preparation	The strength and durability of a bonded joint are dependent on proper treatment of the surface to be bonded. An acclimated, thoroughly cleaned, dry, grease-free surface is essential for maximum performance. Cleaning methods which will produce a break free water film on metal surfaces are generally satisfactory. At the very least, joint surfaces should be cleaned with a good proprietary degreasing agent and mechanically abraded, e.g. with 3M Scotch-Brite™ 7447. Abrading should be followed by a second degreasing treatment, e.g. with 3M 08984 Adhesive Cleaner. Optimum processing temperature for substrates and adhesive is around room temperature of 23 °C.
Application	This product consists of two parts. Combine Part B and Part A in a separate container just prior to application in the proportions specified. **Note**: Mix ratio deviations above +/- 5 % have significant influence on material performance. Mix both components thoroughly until a uniform colour is obtained. **Important:** Be careful when mixing quantities larger than 100 grams, because exothermic reaction may occur. Apply adhesive to parts to be bonded before the work life expires, e.g. by spatula. **Note:** Work life depends to some extent on mixed quantity and the shape of the container. Use of a shallow container will minimize the quantity impact. In order to obtain optimum mechanical performance, the joint components should be assembled and clamped as soon as the adhesive has been applied and before end of the open time. A fixation of the joint and an even contact pressure throughout the joint area during cure will ensure optimum performance. Maximum shear strength is obtained with 0.10 – 0.20 mm bond line thickness. Close the containers after use to protect the material against humidity.
Curing	Once mixed, Scotch-Weld™ EC-9323 B/A will gel in 3 hours, build up handling strength in 4-5 hours and fully cure within 14 days at room temperature. **Note:** Lower temperature will slow down the reaction times. Curing time can be accelerated by mild heat. Following times and temperatures will result in a full cure: ▪ 14 days at 23 ± 2 °C ▪ 2 hours at 65 ± 2 °C ▪ 15 minutes at 100 ± 2 °C **Note:** The curing temperature may have influence on the final product performance.
Cleaning	Excess uncured adhesive can be cleaned with ketone type solvents. After cure the adhesive can be removed mechanically. **Note**: When using solvents, extinguish all ignition sources, including pilot lights, and follow the manufacturer's precautions and instructions for use.
Storage and Handling	Store the product at room temperature. Shelf life is minimum 12 months from date of shipment in the original unopened containers. The specific expiry date is mentioned on the product label.

Important notice: All statements, technical information and recommendations in this data sheet are based on tests 3M believes to be reliable, but the accuracy or completeness of those tests is not guaranteed. All technical data and information should be considered typical or representative only and should not be used for specification purposes. Given the variety of factors that affect the use and performance of a 3M product, some of which are uniquely within the user's knowledge and control, it is essential that the user evaluate the 3M product before use to determine the suitability of the 3M product for the intended use and method of application. All questions of liability relating to the 3M product are governed by the terms of the sale subject to, where applicable, the prevailing law.

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Automotive and Aerospace Solutions Division
European Aerospace Laboratory
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