Tampere University of Applied Sciences

Design and Manufacturing of a Formula Student Composite Chassis

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ABSTRACT

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The purpose of this thesis was to design and manufacture a new chassis for Tampere Formula Student's formula-style competition vehicle. The development of a new vehicle concept necessitated a corresponding revision of the team's plans, prompting the need for a fresh chassis design. The opportunity was used to steer away from the traditional space frame opting instead to introduce a new composite chassis concept that would serve as the foundation for future development.

Data from various departments, mainly including suspension and powertrain, was used in the creation of a comprehensive 3D-model of the chassis, accommodating the driver and all the necessary systems. Design decisions for each section of the chassis were made through a process of comparing and evaluating options. The model was developed from the outside in, starting from the outer shell and incorporating material based on the structural properties required for each location. A modular powertrain mounting system was developed utilizing machined aluminium components.

Three distinct panel lay-ups were designed and tested to acquire their properties for use in structural equivalency calculations. A monocoque structure using a foam core sandwich panel configuration was selected. The final structure was constructed using carbon fibre prepreg and PMI foam core material.

Various tooling types and manufacturing methods were compared and assessed. The chosen manufacturing method involves a multi-stage out-of-autoclave cure with carbon fibre prepreg tooling serving as a negative mould. Manufacturing stage was documented in detail highlighting potential issues and considerations. Suggestions are provided for improving the utilization of material data, exploring different core materials and optimizing the roll hoops and front bulkhead area of the chassis.

Key words: composite, chassis, monocoque, formula student

CONTENTS

ABBREVIATIONS AND TERMS

TAMK	Tampere University of Applied Sciences
FRP	Fibre reinforced plastic
CFRP	Carbon fibre reinforced polymer
TFS	Tampere Formula Student
FSG	Formula Student Germany
Autoclave	Pressurised oven
UD	Unidirectional
Twill	A type of fabric weave
SES	Structural equivalency spreadsheet
IAD	Impact attenuator data form
CSI	CSI Composite Solutions and Innovations Oy
PU	Polyurethane
CAD	Computer-aided design

1 INTRODUCTION

The goal of this thesis is to design and manufacture a composite chassis suitable to be used in competition by Tampere Formula Student. It needs to be well suitable for the team’s use case and have emphasis on opening new development paths in the future. The need for a new chassis concept roots in the team’s recent efforts in raising their competitiveness to the top level of competition. While tubular space frames can and have in the past been used in the top level of formula student, a composite structure creates certain benefits like freedom of shape design and performance related improvements, such as weight and stiffness. The most important accomplishments of this work are the creation of a base chassis concept for future development and the documentation of its manufacturing.

This work documents the development cycle of a functional prototype for a composite chassis structure. Most of the focus is on design aspects, such as the layout and modelling the structure. Design choices and options are discussed during the process. Material properties for several composite lay-ups and arrangements are acquired through laboratory testing. The work also focuses on the manufacturing aspects of composite structures and documents the manufacturing stages of the prototype including needed tooling and preparations.

In the beginning there is an introduction to the basics on composite materials and structures as well as a brief look into the ruleset of Formula Student and the competition in general. The design and 3D modelling chapters document the considerations behind the design and highlight some of the supporting tools and methods utilized in the development. Manufacturing methods and tools are introduced in the sixth chapter with extra highlights for possible problem areas and future improvements in the manufacturing process.

1.1 Formula SAE and Formula student

Formula SAE is a design competition organized by the Society of Automotive Engineers International. The idea bases on challenging students to design, fabricate and compete with a self-built formula style racing car. The competition includes a series of static and dynamic events that are judged and scored accordingly. (Formula SAE n.d.)

Over the years the nature of the competition has gained international popularity amongst universities and students. Events have spread from North America to many continents including Asia, Europe, South America and Australia. The competitions have evolved into a worldwide series of events that share a similar ruleset. Most competitions outside Europe use the Formula SAE rules, while European events usually fall under the FS rules updated by Formula Student Germany. According to Formula Student Germany, there are 22 competitions organized around the world, even though not all of them are counted towards the world ranking list (Formula Student Germany / Competitions n.d.).

Like Formula SAE, Formula Student Germany is an international design competition for university level students. The competition has several disciplines that challenge the students to further educate themselves by learning about building and manufacturing as well as the economic aspects of the automotive industry. Judging is done by industry professionals from motorsport, automotive and supplier industries. (Formula Student Germany / Concept n.d.)

Several organizers in Europe have adopted the FSG format into their own competitions. These include, but are not limited to: Formula Student Austria, Formula Student East in Hungary, Formula Student Netherlands and Formula Student Alpe Adria in Croatia. Many organizers have a part in creating the rules but they are hosted by FSG. In recent years even some of the competition documents, mainly regarding chassis structure and crash safety, have been hosted and reviewed on the FSG site while being reviewed by other organizers too.

1.2 Tampere Formula Student

The formula student team at Tampere University of Applied Sciences was founded in 2006 as a student led project. Currently the team is operated as an association that consist of students from Tampere UAS and Tampere University. The team was rebranded from Tampere UAS Motorsport to Tampere Formula Student in 2019 to create a more accurate image of what the team represents: not a racing team, but a design competition team that consist of both UAS and university students.

The team has built a new competition vehicle every year since 2008, except for 2020, when the development was cut short by Covid-19. Season 2023 marks the 15th Formula Student vehicle built by students at TAMK and will create a solid base concept for following years.

1.3 Race car design

Designing a well performing race car is a task not easily achievable. With any design project it is best to start with an assessment of usable resources and assign them accordingly when the project goes on. Resources include time, budget, engineering, past experience and facilities, and certain resources can sometimes be substituted for another (Milliken 1995, 367).

The design work should start with a proper consideration of project objectives, that include such things as performance, handling, structure, tires, adjustable features, driver accommodations and safety. Constraints must also be assessed, as they are the main limiting factor in most race vehicle designs. Vehicle rules and competition rules form most of the constraints, but some practical things, such as component availability can also create limits. (Milliken 1995, 368)

2 Composite materials

Technological development leans heavily on advances in material technology. Without adequate materials, even the best designs are of no use as the final limitation on advancement lies on materials. Even with the modern advancements of composite materials, they are not in any way a new idea. Many naturally occurring materials, such as wood, are considered composite materials. Wood has cellulose fibres in a lignin matrix: the cellulose fibres have high tensile strength while being flexible and the lignin joins the fibres. Proper research in composite materials began in the early 1960s as aerospace, energy and civil construction industries had an increasing demand for stronger and stiffer materials. (Chawla 2012, 3).

The advantages of composite materials are highlighted in certain applications that can implement the flexibility of tailor-made materials to the design task at hand. In aerospace, automotive and marine applications the performance of the design can be raised to a new level by making composites fit its needs. With all industries increasing their focus on energy efficiency, the use of composites has increased in the search of lighter yet stiff and strong solutions. Figure 2.1 illustrates the relative differences in material properties for traditional monolithic and composite materials. (Chawla 2012, 4)

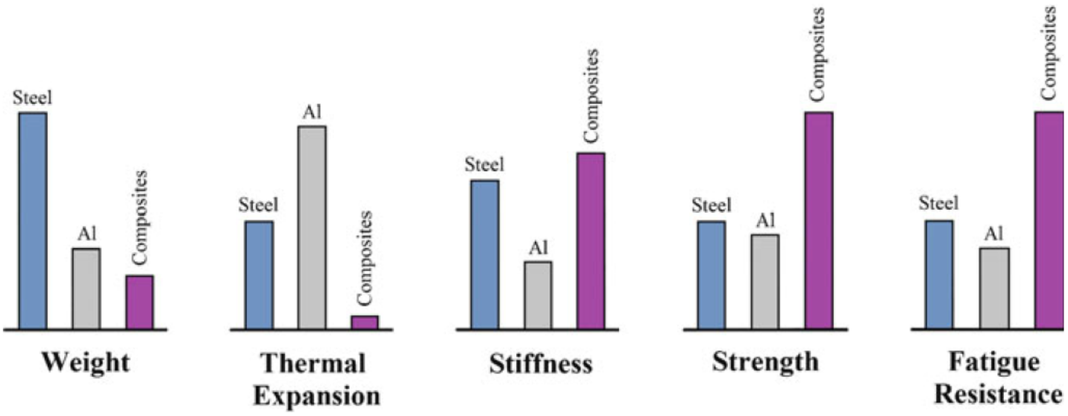


Figure 2.1. Material properties compared between composites and monolithic materials. (Chawla 2012, 4)

2.1 Fibres and matrix

Fibres are sold in either short or long form. Short fibres are mostly used in mats and felts or injection moulding. Long fibres are used either as is or in woven fabrics. Fibres consist of thousands of filaments and can be made from various materials, such as carbon, aramid, glass, boron and silicon carbide. Formed fibre reinforcements can be split into three categories: unidimensional, bidimensional and multidimensional. Unidimensional includes unidirectional fibres in tape, tow or yarn form. Bidimensional includes both woven and nonwoven fabrics, such as felts or mats. Multidimensional includes fabrics that have more than two distinct fibre orientations. (Gay 2003, 4–5)

Typical requirements of fibres are a high modulus of elasticity and ultimate strength, which should be retained in handling and fabrication. The fibres should also have low variation in properties for individual and a regular arrangement in the matrix. Matrices need to work well in binding and protecting the fibres while being able to transfer stresses to the fibres using adhesion and/or friction. They also need to have chemical compatibility with the fibres for the entire working period. (Altenbach 2004, 6)

2.2 Fibre reinforced polymers

2.2.1 Polymers

Fibre reinforced polymers constitute of a polymer resin used with fibre fillers. Resins can be divided into two basic classes: thermosets and thermoplastics. The most commonly used group are thermosetting resins, which include epoxy, polyester, vinyl ester and polyamide matrices. Popular thermoplastics include polyethylene, polyether-ether-ketone and polystyrene. (Altenbach 2004, 5)

The matrix material is chosen to fit the reinforcement and use case. Polyester resins are often used due to their cost effectiveness. While epoxy is multiple times more expensive than polyester variants, it is very popular in certain applications, such as aerospace (Altenbach 2004, 5). Epoxy is chosen over polyester in use cases where mechanical properties and curing properties need specific control.

2.2.2 Reinforcement

One of the easier ways of classification for composites is by the reinforcement type, illustrated in figure 2.2. The main classes are fibre reinforced and particle reinforced composites, which are then split to smaller classes. Particle reinforced composites are split between randomly oriented and preferably oriented particles. Fibre reinforced composites are classified into two main classes: continuous fibre reinforcement and discontinuous fibre reinforcements. Continuous fibre reinforcements include long fibres that are classified by their orientation, such as unidirectional, bidirectional and spatial orientation. Discontinuous fibres have two classes of short fibres that are split between random orientation and preferred orientation fibres.

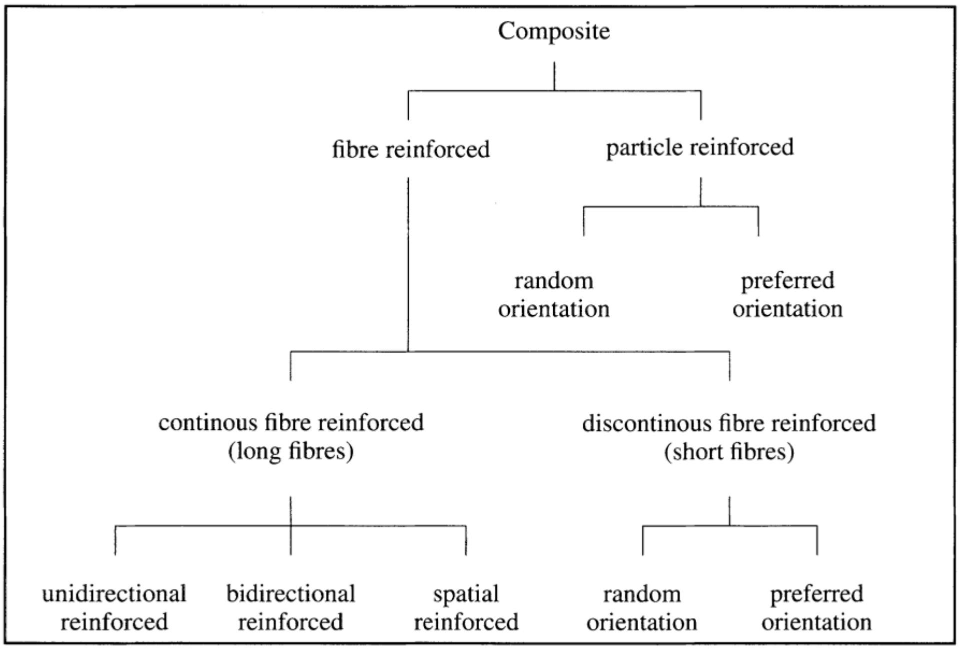


Figure 2.2. Classification of composites (Altenbach 2004, 4).

Fibre reinforced composites are usually preferred to other types of composites due to fibrous forms being stronger and stiffer than any other form. The fibres are strong only in fibre direction, which means that the fibre material needs to be arranged in multiple orientations or the result is a material that has little to no reinforcement transverse to the fibre direction. (Chawla 2012, 5)

Glass fibre is a common reinforcement material, as it offers good material and weight properties for a relatively economic cost. Performance orientated and weight conscious applications tend to choose other reinforcements than glass since it is not very stiff compared to some advanced high modulus fibre, such as carbon or boron.

Carbon fibre is a commonly used reinforcement in motorsport and aerospace applications due to its high stiffness to weight ratio. Carbon fibres are created by heating and crystallizing precursor fibres, such as polyacrylonitrile and rayon (Chawla 2012, 24). Carbon fibre as a term is used to describe a family of fibres that have different properties depending on the manufacturer and method. The process usually includes the same essential steps, but the execution of those stages makes the difference.

2.2.3 Prepreg

Pre-impregnated fibres, prepregs are usually in the form of a thin sheet of unidirectional or woven fibre/polymer composite that is shipped with the polymer matrix already applied to the fibres. In figure 2.3 can be seen that the material is shipped with protective, easily removable protective films on both surfaces of the material to prevent it from sticking to itself.

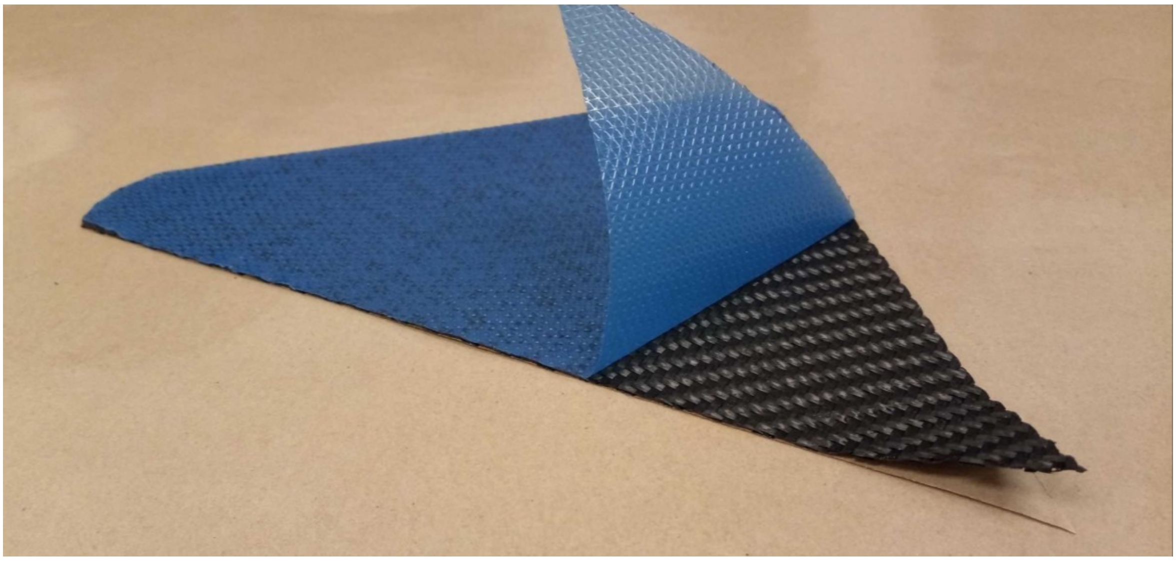


Figure 2.3. Off cut of 2x2 Twill weave prepreg fabric with the protective films.

The resin is in a partially cured state and has a self-adhesive tack for easy lay-up and handling. Rolls of prepreg material are stored in a freezer and have a limited working life, as the resin slowly cures in room temperature. The material or fabric is very stable to handle, as the resin and films keep the fibres firmly in position. The stability makes prepregs very easy to cut, either by hand or with a computer-controlled cutter, such as the one in figure 2.4, to create accurate plies with intricate features.

Figure 2.4. CNC cutting prepreg at CSI Composite Solutions and Innovations.

Prepregs are conventionally designed to be cured in an autoclave to ensure best possible resin flow and surface finish, but recent years have shown an increasing amount of out-of-autoclave prepregs needing only a proper vacuum and an oven to cure. The oven needs to have sufficient ramp control for good results, and all steps in the lay-up must be done carefully to ensure good quality laminate while avoiding pinholes and other imperfections.

2.3 Composite structures

One of the advantages of composites is that they can be manufactured in many ways, shapes and sizes. Manufacturing methods include, but are not limited to

- Hand lay-up
- Filament winding
- Pultrusion
- Resin transfer moulding
- Vacuum infusion
- Film stacking
- Thermoforming
- Injection moulding

As mentioned before, long fibre reinforcements maintain optimal material properties only in the fibre direction. This creates both opportunities and difficulties in designing structural composite parts: a lot of plies are needed to cover all possible fibre orientations, but the load paths can be studied, and the orientations optimised for actual load cases. In a design engineering perspective, utilizing composite materials essentially means creating a different material for each application (Chawla 2012, 4).

Sandwich structures are a way to create very lightweight yet very stiff structures by combining a light core material between two skins. Core material is often either a polymer foam or a honeycomb that’s either metallic or non-metallic. While metallic honeycombs are less expensive and have better structural features, non-metallic honeycombs, such as bonded sheets of polyamide, are not sensitive to corrosion and create good thermal insulation (Gay 2003, 60).

3 Limitations

3.1 Rules

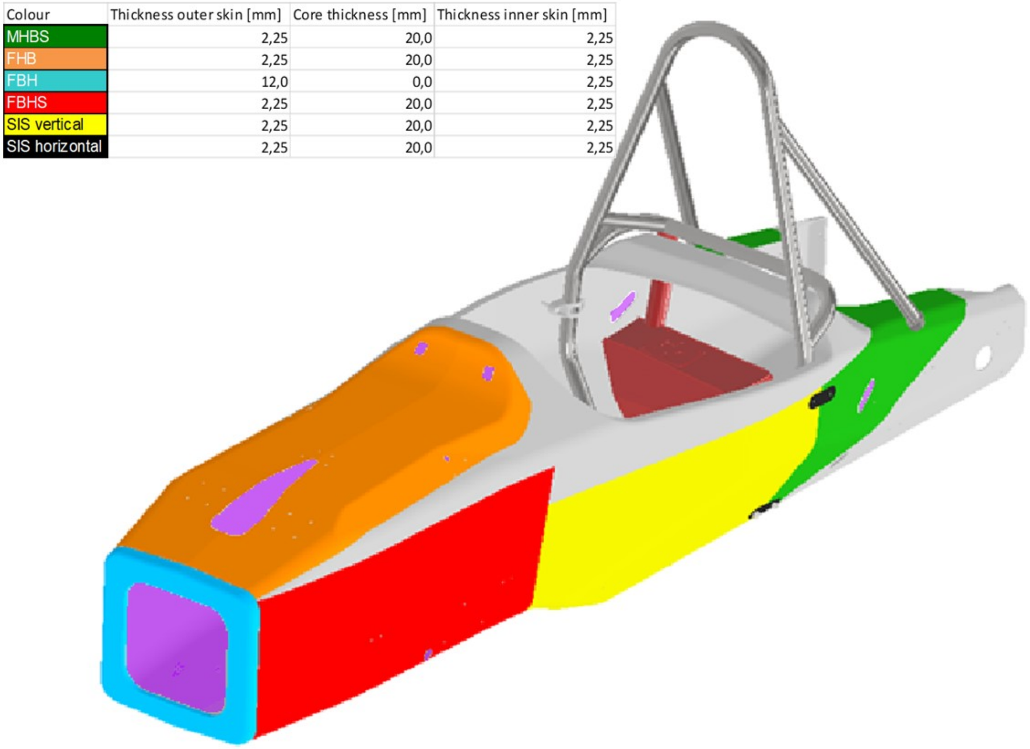
Most formula student competitions in Europe use the ruleset published by Formula Student Germany. The document gives limits and some guidance to all teams competing under the rules. Most of the rules are related to safety features, but there are also rules to create a balanced competition for the teams.

Chassis rules are extensive, as the chassis is the main protection for the driver in an event of an accident. The section includes things such as minimum tube sizing, structure location and crash protection equipment. Teams are expected to build a well-engineered chassis that meets all the requirements set by the organizers. Guidance is also given to the teams that wish to build their chassis out of alternative materials, such as composites.

Teams using alternative materials in their chassis construction must create physical test panels that are compared to the baseline tube chassis designs for stiffness, shear and yield values. The panels must be marked permanently and brought into competition for the scrutineers to compare them to the actual built chassis. (FS Rules v1.1 2023, 29)

3.2 Structural Equivalency Spreadsheet

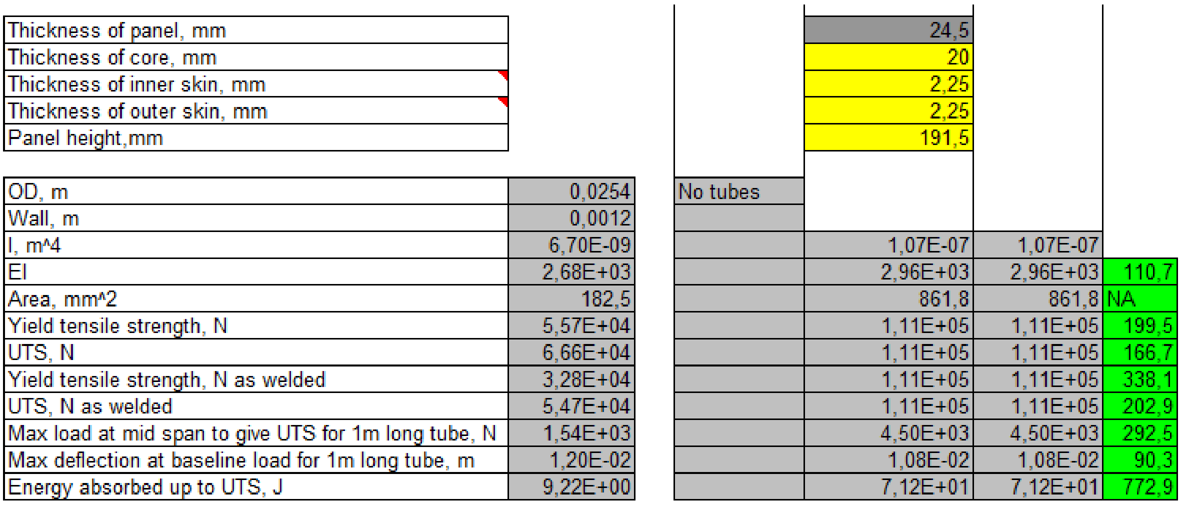
The structural equivalency spreadsheet, later referred to as SES, is a document that is used to convey all the necessary information on chassis design from the teams to the scrutineers and competition officials. The document is submitted months before competition and inspected by experts. The spreadsheet includes pictures and tables of the used chassis materials, data of tested panels, as well as information on the whole primary structure and its components. Alternative materials are listed, and their lay-up is specified. Figure 3.1 shows the structural lay-ups of the chassis and is included in the chassis pics sheet (Appendix 1) dedicated for pictures and material listing of the chassis.



Colour	Thickness outer skin [mm]	Core thickness [mm]	Thickness inner skin [mm]
MHBS	2,25	20,0	2,25
FHB	2,25	20,0	2,25
FBH	12,0	0,0	2,25
FBHS	2,25	20,0	2,25
SIS vertical	2,25	20,0	2,25
SIS horizontal	2,25	20,0	2,25

Figure 3.1. Chassis lay-ups on the Chassis pics sheet of the SES.

Each chassis structure and area have a separate tab on the SES where equivalency to a baseline design is shown (FS23 SES v1.0 2023). The sheets, shown in figure 3.2, have dedicated yellow cells to fill in necessary information on the panel, which includes panel height, skin and core thickness and information on which test panels the material data is derived from. Full sheet that includes pictures of the structure can be seen in appendix 2.



Thickness of panel, mm			24,5		
Thickness of core, mm			20		
Thickness of inner skin, mm			2,25		
Thickness of outer skin, mm			2,25		
Panel height,mm			191,5		
OD, m	0,0254	No tubes			
Wall, m	0,0012				
I, m^4	6,70E-09		1,07E-07	1,07E-07	
EI	2,68E+03		2,96E+03	2,96E+03	110,7
Area, mm^2	182,5		861,8	861,8	NA
Yield tensile strength, N	5,57E+04		1,11E+05	1,11E+05	199,5
UTS, N	6,66E+04		1,11E+05	1,11E+05	166,7
Yield tensile strength, N as welded	3,28E+04		1,11E+05	1,11E+05	338,1
UTS, N as welded	5,47E+04		1,11E+05	1,11E+05	202,9
Max load at mid span to give UTS for 1m long tube, N	1,54E+03		4,50E+03	4,50E+03	292,5
Max deflection at baseline load for 1m long tube, m	1,20E-02		1,08E-02	1,08E-02	90,3
Energy absorbed up to UTS, J	9,22E+00		7,12E+01	7,12E+01	772,9

Figure 3.2. Main hoop bracing structure equivalency data (FS23 SES v1.0 2023).

Each test panel has its own sheet to input material data. The sheets also include a baseline tube test to check test rig compliance. Test data is inserted into the yellow cells and the document has formulas for calculating structural data, such as skin modulus of elasticity and absorbed energy before failure. Pictures of the test setup are also necessary. Test data of the main structural panel shown in figure 3.3, taken from Appendix 3.

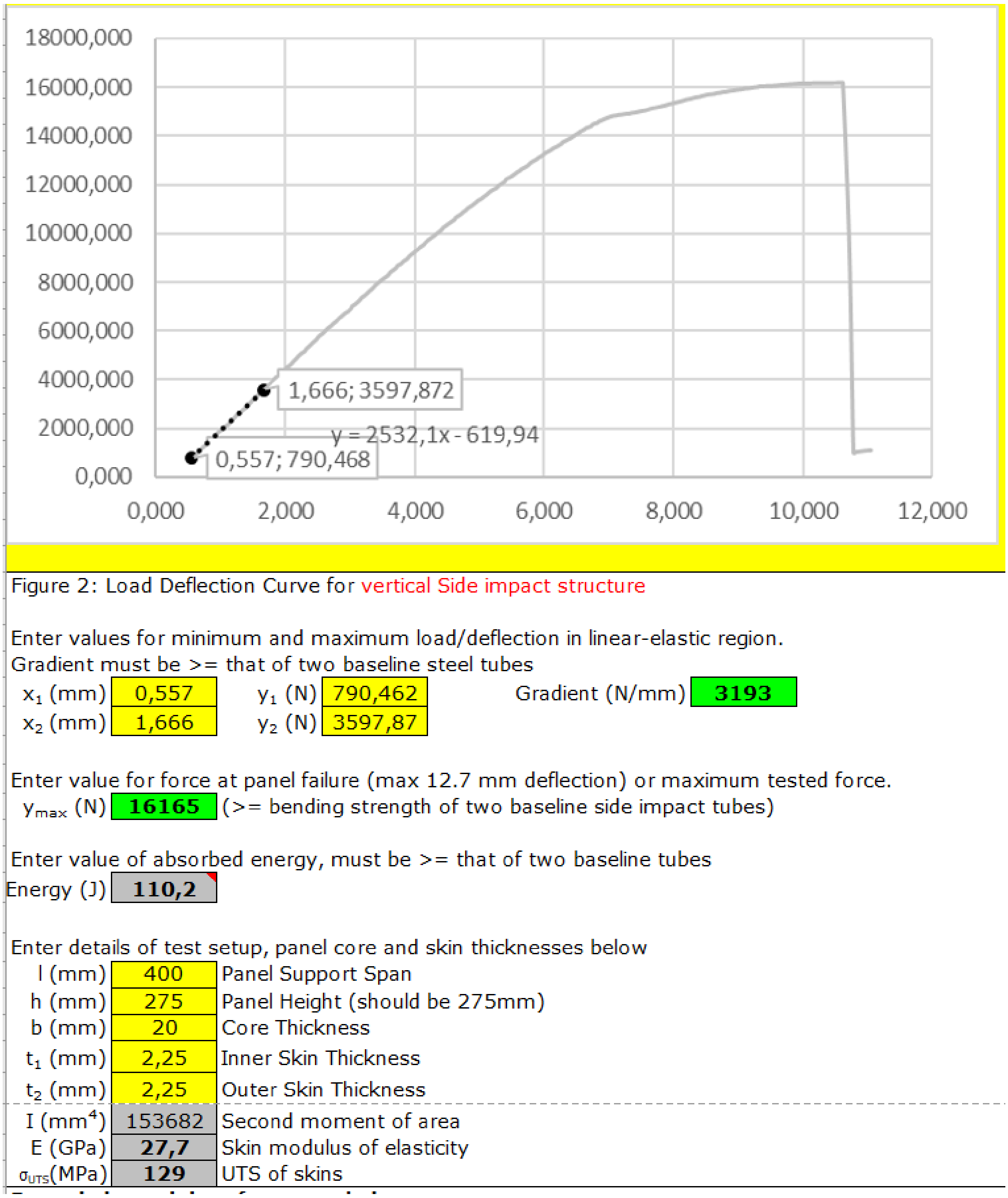


Figure 2: Load Deflection Curve for vertical Side impact structure

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

x_1 (mm)	0,557	y_1 (N)	790,462	Gradient (N/mm)	**3193**
x_2 (mm)	1,666	y_2 (N)	3597,87		

Enter value for force at panel failure (max 12.7 mm deflection) or maximum tested force.
y_{max} (N) **16165** (>= bending strength of two baseline side impact tubes)

Enter value of absorbed energy, must be >= that of two baseline tubes
Energy (J) **110,2**

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)	2,25	Inner Skin Thickness
t_2 (mm)	2,25	Outer Skin Thickness
I (mm^4)	153682	Second moment of area
E (GPa)	**27,7**	Skin modulus of elasticity
σ_{UTS}(MPa)	**129**	UTS of skins

Figure 3.3. Test panel test data in SES (FS23 SES v1.0 2023).

4 Design

4.1 Conceptualizing

The team starts their season with conceptualizing workshops, which are usually held in the beginning of the fall semester before new members are recruited into the team. These workshops start with reflecting on previous seasons achievements, goals and how the team has done overall. New goals and targets are set for the upcoming season, and they construct the overall direction for the season. With goals set, the team moves on into brainstorming new design ideas and systems. The goals and their feasibility are then evaluated in relation to the set targets and available workforce.

The ideas and systems chosen for development affect existing systems and departments as well, so it will usually take until early October before the design work of key components such as chassis, can be properly started. This season, however, was a bit different. Since the team did not finish the monocoque for the 2022 season, there was now a complete unbuilt car that needed some changes. It was decided that improvements to suspension kinematics were necessary, so the chassis was also due for changes. This opened new possibilities for development, as the chassis shape and therefore also the moulds would need to be revised. First thing was to rethink if the half monocoque half spaceframe was optimal.

4.2 Chassis type

There are several different options when it comes to the design of a monocoque chassis for formula student. Some teams have created aluminium sandwich panel chassis’ that are assembled from flat and bent panels with rivets and adhesive. The usual route is to build fibre reinforced plastic skins that incorporate some sort of core material, usually either honeycomb or structural foam. The structure can also be a so called half monocoque or full monocoque, which means that some part of the chassis may be spaceframe or other separate structure that is attached to the front half of the chassis.

Half monocoques are most often used by teams with combustion engines, since they can be difficult to package and create large amounts of radiant heat into the chassis. Some teams have also used the same (at least in shape if not lay-up) composite chassis for CV and EV powertrains with a different rear portion, which saves design and manufacturing efforts while also cutting costs.

First iteration in the development of the monocoque chassis was created as a combination of a half- and full monocoque, as it integrated the entire primary structure, which is the ruleset mandated portion of the chassis, into a single structure. A tubular space frame was added in the rear to accommodate suspension pick up points and powertrain mounting. As the season 2022 went on and the design of the vehicle continued, it became apparent that the rear portion of the chassis would be quite tightly packaged. Having a bulkhead in the middle of the engine compartment meant that the space to work on the powertrain was limited, and removing the tubular rear frame would be a common task for maintenance purposes.

The compromise with added mountings and complexity would have led to more work for the team, both in the manufacturing phase as well as during competition season in the form of increased maintenance workload. Rear chassis compliance was also a true concern with all the bolted connections and limited triangulation of the tubes, which was a result of all the powertrain components needing space for moving, maintenance and pass throughs.

When it came clear that all the suspension kinematics were subject to change, it was decided that a full monocoque is more suitable for the team’s needs. A full monocoque simplifies manufacturing and maintenance with the added benefit of rigidity, while being roughly the same weight if not lighter than a combination of composites and tubing. At an early stage it was acknowledged that engine removal would become necessary for most maintenance work, so a lot of thought was given to make it as straightforward as possible while maintaining the structural rigidity and integrity of the chassis.

4.3 Structural design

Design of the structural aspects was mainly based on equivalency to mandated tubular structures. This is very straightforward with the structural equivalency spreadsheet Excel file that is supplied and updated yearly by Formula Student Germany. The ruleset mandates specific size composite test panels that are tested on a material test machine and compared to calculated stiffness values of certain cross section tubes.

Most structural panel choices were made from the knowledge of previously tested panels. For the first iteration in 2022, a set of panels was tested to determine a combination of core & skin thickness that is adequate for different parts of the chassis. For the second iteration a new panel was developed that had mostly unidirectional fibres with a surface layer from twill. A second UD panel was made with a size variation for harness mount testing and a third panel with the previous twill skins was also tested with new markings, in case it was fit for some areas.

4.3.1 Structural testing

The FSG rules mandate a series of structural tests to determine actual physical properties for all members of a vehicle's primary structure. A three-point bend test and a punch test were performed on all structural panels. An additional pull-out strength test was needed on one panel to show equivalency for safety harness mounting.

The three-point bend test shown in figure 4.1 was performed on a 275x500mm panel to determine its stiffness and on most occasions it's failure point. The test was done on a 400-millimetre support span and a cylindrical press tool with a minimum radius of 50mm.

Figure 4.1. Three-point bend test.

The punch test shown in figure 4.2 was performed with a 25mm punch on a support under the panel that has a 32mm hole. The data is used to determine shear strength values for the panels. The shear values are utilized in calculations to determine pull-out force for mountings and breaking point for certain structures under a shear load.

Figure 4.2. Punch test.

The safety harness mountings were tested with the same material testing machine using a 400x400 mm panel shown in figure 4.3. The sample was supported by a steel ring with a diameter of 250 mm, as the rules mandate the minimum distance from the load application point to the support edges as 125 mm (FS rules v1.1 2023, 41). Testing was done with all the hardware used to attach the safety harness, including the eye bolt, insert in the panel and a circular steel backing plate under the retaining nut.

As the panel lay-up has most of the reinforcements oriented between plus and minus degrees from the zero orientation, the structure is much stronger in that direction. This compared with a thin 2mm backing plate led to the plate bending easily and pulling through the lower skin. While the test yielded a passing result of 22,8 kN with the minimum being 19,5 kN, a thicker backing plate should help to achieve a higher factor of safety for the mounting.

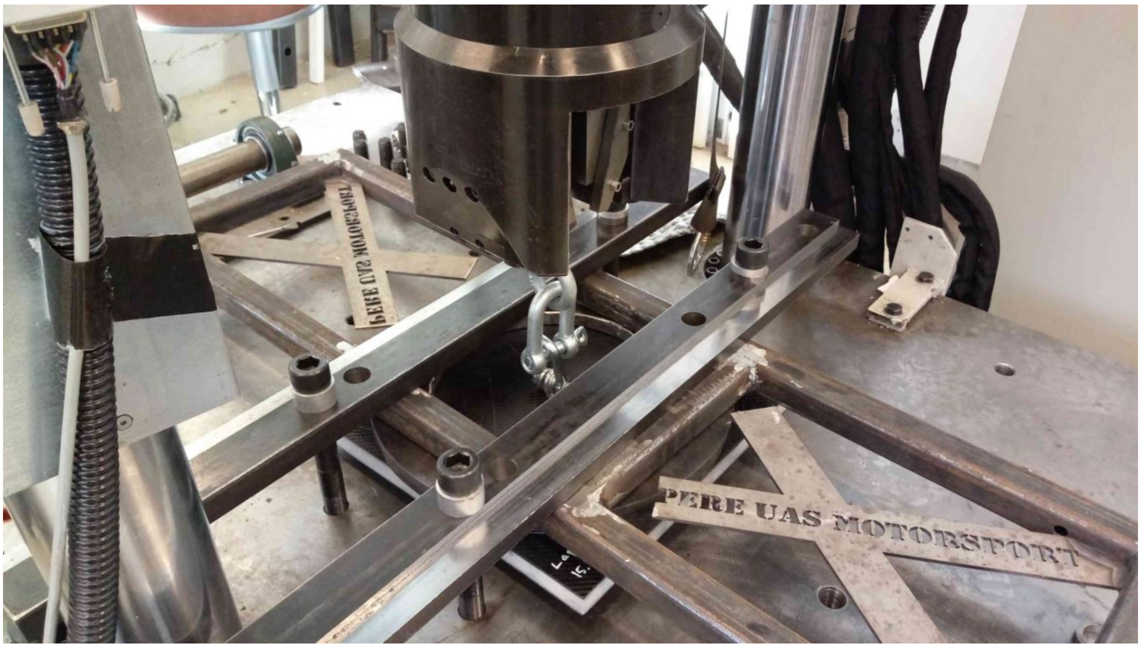


Figure 4.3. Safety harness mounting test.

4.3.2 Main structural panel

Fibre orientation and lay-up were mildly optimized for the loads in the chassis. The front bulkhead and roll hoops create stiffer areas that are connected with composite panels, so most of the dynamic loads in the chassis would be somewhat longitudinal. For every panel the zero direction, which is the reference for the fibre orientation, spans a longer distance than the 90-direction. This led to optimizing the fibre orientation for bending in the longer direction.

For most structural areas a UD heavy panel was created. The structure consists of two skins with a 416g 0/90 Twill layer and 6 layers of 300g UD oriented in 15/-15/0/15/-15/0 degrees. The panel has a 20mm Rohacell PMI foam core and the skin fibre orientations are mirrored from the centreline of the panel. The panel has a peak shear force of 17,7 kN and a skin shear strength of 72,5 MPa. Three-point bend test yields a skin modulus of elasticity of 27,7 GPa and an ultimate tensile strength of 129 MPa. The SES calculates skin modulus from the tests without considering the core material properties, so skin modulus is actually a combination of the properties present in the actual composite panel.

4.3.3 Front bulkhead

The front bulkhead area is a bit special as it has a required perimeter shear strength to accommodate for heavy frontal impacts. The shear force is determined from a punch test and the lower peak force is chosen for bulkhead shear force calculations.

A few panels with thick skins and varying core thicknesses were tested in 2022 for the first iteration, but it was quickly noticed that a panel with as thin as a 10mm foam core is not up to the task, since core deformation leads to the outer skin shearing prematurely and yielding a low shear force. This led to two options: find another core material that doesn’t deform in the same way, or use a monolithic composite panel in the front bulkhead.

Since the testing was done in the spring of 2022 with the competition season closing in quickly, a decision was made to test a CFRP only panel. While the shear force is a deciding factor, the panel also needs to fulfil the three-point bend test requirements for the front bulkhead. The panel stiffness needs to be equivalent to a minimum of two 25x2mm steel tubes. The bending requirement meant that the structure was built with quite a heavy lay-up, especially since the first iteration chassis had a taller front bulkhead and needed to show equivalency to an extra diagonal support tube.

The result is a 14,2mm thick monolithic panel that has 32 layers of 416g twill fabric alternating between 0/90 and -45/45 orientation. This panel has a peak shear force of 140 kN yielding a 125,4 MPa skin shear strength. The modulus of elasticity for the panel is 58,4 GPa.

4.3.4 Additional structures

The chassis has a few areas that are not considered a part of the primary structure in the rules and therefore are not subject to equivalency requirements. These areas were all built with a twill only panel and simple 0/90 and -45/45 fibre orientations. Modelling the first iteration had shown that varying the skin thickness between areas, especially those that are split in the middle of a flat surface cause complications in the design and manufacturing of the chassis. All skins are currently 2,25mm thick, apart from the front bulkhead and rear bulkhead mounting area.

The “non-structural” panel is constructed with a skin that has three 416g Twill layers in 0/90 orientation and two layers with -45/45 orientation in between the others. Core is the same 20mm Rohacell PMI foam all around, except for the front floor, where a 10mm core was opted to add room on the inside.

Powertrain mounting area has a monolithic 4,5mm skin, as the core is reduced in those areas. This creates a solid flange for attaching the powertrain mounting plate to the chassis with M8 fasteners. A solid structure is also built for mounting the rear chassis supporting CFRP plate to the rearmost surface of the chassis. The flange has thickness of 9,25mm for added stiffness and bolt tear out strength, as the edge distance from the bolt holes is small.

5 3D CAD modelling

Modelling the chassis started with the vehicle's kinematic points, which were designed for optimal vehicle dynamics in a separate software. After the kinematic points were located into the model, a representative driver and powertrain components were roughly positioned. As seen in figure 5.1 the driver was at first represented by a sketch with dimensions derived from the rulebook and later a 3D model was added for better understanding of the space available.

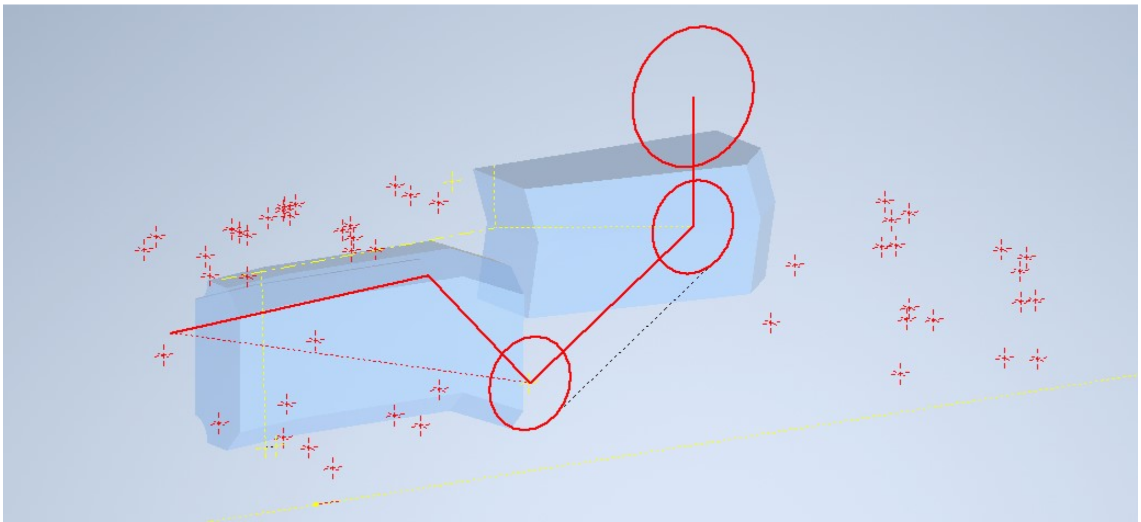


Figure 5.1. Base of the CAD design with templates and kinematic points.

5.1 Preliminary design

Some of the design phases were done twice during the project as the chassis got significant changes in the fall of 2022 after the team decided that suspension kinematics were to be updated. The newer iteration took all the information gathered when designing the previous season's unbuilt composite chassis and streamlined the model. A simplified mock-up was drawn with extruded features and placed in the Inventor workspace that the team uses to design the vehicle and all its components, see figure 5.2. Based on previous design experience it was determined that large curvatures and complex shapes in the chassis would create problems in the manufacturing and mould making phase. The previous design was not very suitable for simple moulds, as it lacked draft angles in key positions and had some difficult shapes for the positive mould machining phase.

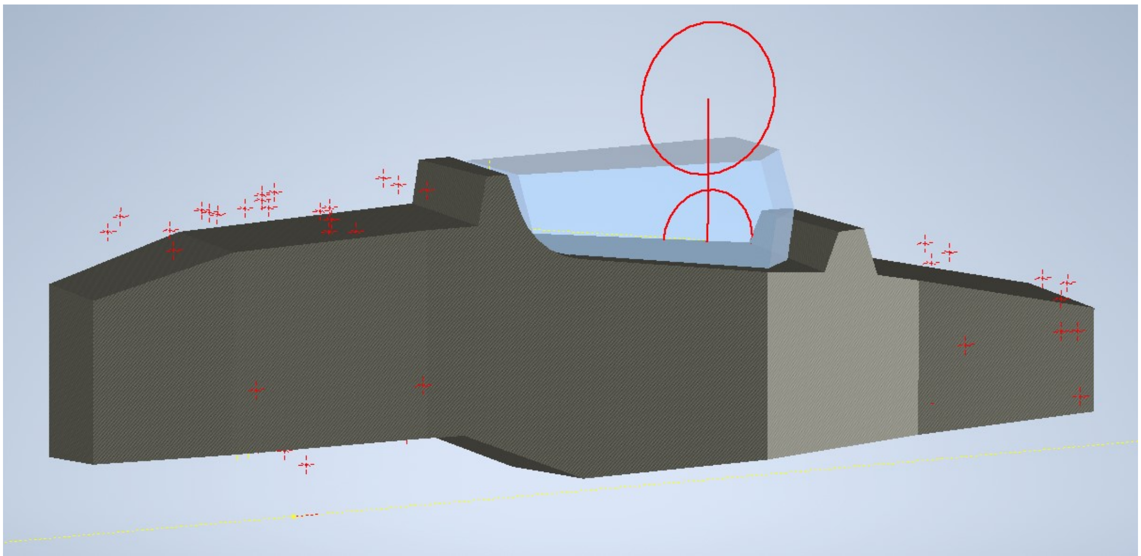


Figure 5.2. Early mock-up of the shape

5.1.1 Driver position

Driver position was mostly designed during the first iteration of the chassis and was improved in the second phase. Previous vehicles had shown that there was need for additional room for drivers' arms, so the steering wheel was moved upwards in relation to the drivers' hips. Previous tube chassis vehicles also had quite a low front ground clearance, as there was no hybrid system and the front lower suspension arms were mounted in the sides of the chassis instead of the underside. Due to those reasons, the composite chassis has a raised front section also affecting drivers' legroom. The rules dictate certain measurements for the cockpit opening and internal cross sections, as well as a specific driver template to ensure minimum legroom.

The chassis was extended forward for the second iteration, as there was a concern about fitting taller drivers in the vehicle. Initial testing for suitable position updates were done in the team's ergonomics test rig and then applied to the chassis in CAD. For visualizing the usable space in the chassis, a CAD study was done to insert a human driver in the cockpit. The work was done in Siemens NX, as the package offers a module for adding and moving mannequins in the modelling space. The differences in legroom between iterations can be easily compared in figure 5.3.

The steering wheel was also moved rearwards and up in relation to the drivers' hips to offer an improved arm position. The tube frame design had issues with the old position, as the steering wheel was so far forward it was hitting the drivers' legs when turning. The closer position also allows for a better elbow angle, which helps with steering force input. Space for drivers' arms was also added in the cockpit sides, since there has been an issue of elbows hitting the chassis with some drivers. This was not properly addressed in the first iteration but was revised for the second iteration. See figure 5.3 for comparison.

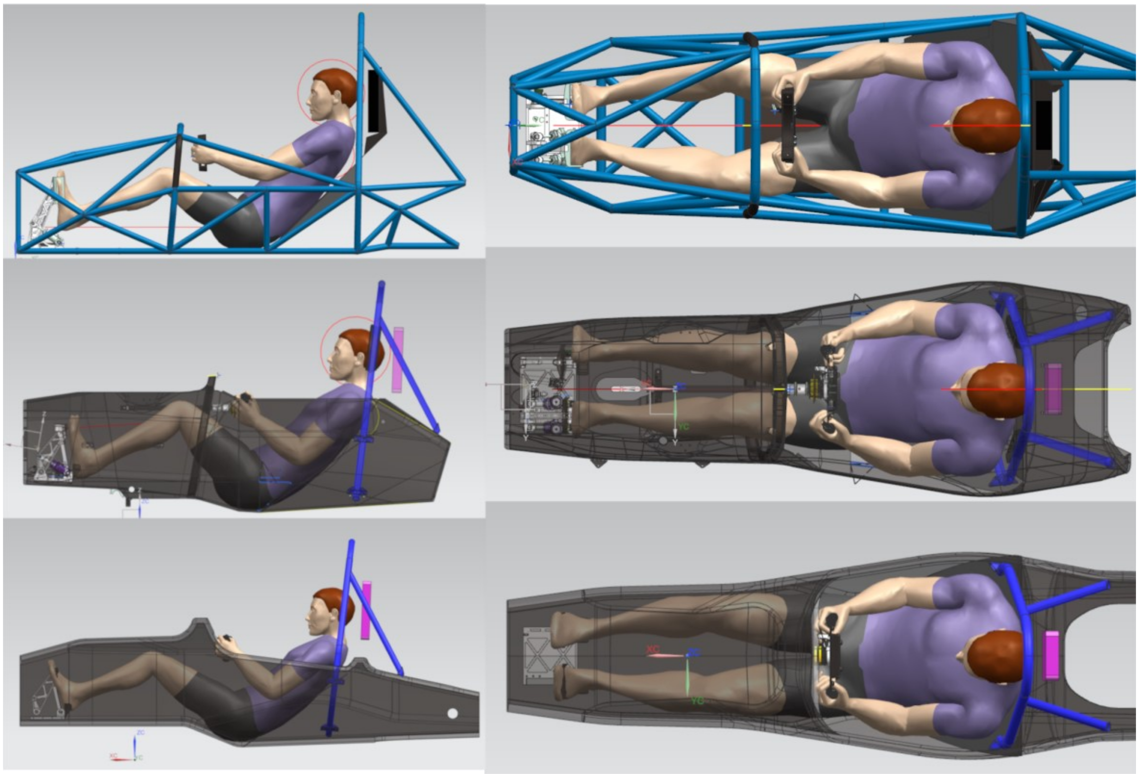


Figure 5.3. Comparison of chassis versions for ergonomic position.

5.1.2 Powertrain

Powertrain location was completely revamped from the first iteration, as the choice was made to pivot from a rear tubular spaceframe to a full monocoque. The engine and drivetrain were moved down for a lower centre of gravity. Internal combustion powertrain creates several challenges for the chassis, as the engine needs cooling and exhaust, as well as sufficient space for maintenance and assembly in case the powertrain needs to be extracted from the vehicle.

The current powerplant is a turbocharged single cylinder Yamaha engine seen in figure 5.4. It is mostly based on the 2014-2017 YZ450F motor but includes several components, such as the crankshaft and flywheel from the enduro variant WR450F. Single cylinder engines are quite notorious for vibration, which poses some issues on chassis design and creates additional stress on the structure. Many discussions on engine mounting were had with experienced teams during the 2022 season, as there were some concerns on reliability. The team decided to continue with rigid engine mounts and lower chassis failure risk by designing the powertrain mounting to be as rigid as possible. This turned out to be a successful route, as the chassis had no issues with the maintained vibrations during or after the competition season.

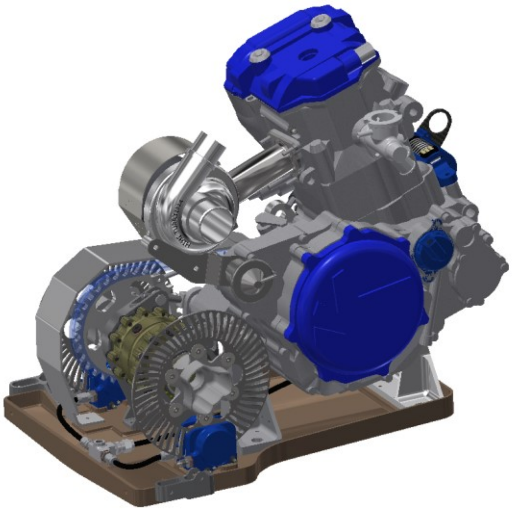


Figure 5.4. Engine and drivetrain mounted to the removable plate.

5.1.3 Suspension & steering components

Suspension kinematics play the most significant role in the overall chassis dimensions, as most of the design is based on suspension key locations. The kinematic points are not enough to determine component clearance, and therefore chassis design was constantly waiting for some sort of component or assembly. Notable issues were front suspension components on top of the chassis, as seen in figure 5.5, steering rack on the underside and rear dampers, as they needed cut outs on top of the rear chassis.

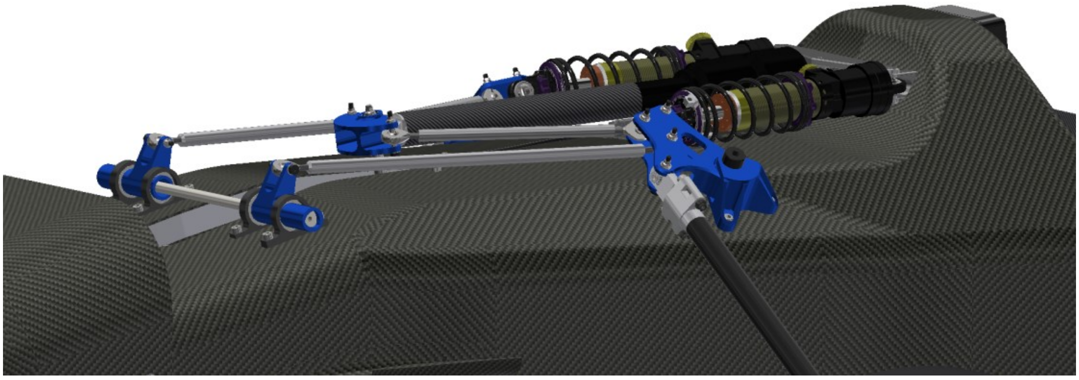


Figure 5.5. Suspension components on top of the chassis.

5.2 Shape design

Chassis shape was designed in a way that makes the widest possible cross sections for the mandated panel areas. Other key factors were sufficient cockpit space, easily manufacturable shapes and best possible space for vital components. The final shape can be seen in figure 5.6.

Figure 5.6. Final composite chassis design.

5.2.1 Front structure

The front portion of the chassis consist of three mandated structures: front bulkhead (FBH), front hoop bracing (FHB) and front bulkhead support structure (FBHS). In addition to those, the front has a “non-structural” floor. The front structure had several key design aspects, but most the care was taken to ensure that the driver and the ruleset mandated template fit well into the vehicle. Other aspects included suspension components that surround the structure and the visual and aerodynamic considerations regarding the shape.

The new vehicle incorporates push rod suspension on both axles of the vehicle, which meant that especially the front bell cranks and dampers would be located quite high up. During the first iteration of the chassis, the dampers, third element and bell cranks were moved up and forwards several times to accommodate needed chassis internal cross section while maintaining visibility for the driver. In the end the cockpit internal cross section was still cramped, and the chassis shape had some compromises.

In the fall of 2022, when the decision was made to upgrade the suspension kinematics, an opportunity arose to investigate rearranging the suspension components and designing the chassis from the beginning. A redesign was chosen to incorporate mounting surfaces and clearances early on. This led to an overall cleaner design in the shape, which would also be easier to manufacture.

While the suspension components needed to be located low enough for visibility, the top of the front hoop needs to be as high as possible, since the steering wheel in no position can be higher than the top of the front hoop. For front hoop bracing only the area that is located in the top 50mm of the hoop is considered part of the equivalent structure, which led to a lot of design work focusing on this area and its structural equivalency.

The front bulkhead outer dimensions were decreased slightly to make it smaller than 350mm in height and width. This meant that the structure only needs to show equivalency to two 25mm*2mm round tubes and the frontal opening could be made larger. The current opening allows the removal of the complete pedalbox assembly, which was not possible in the first iteration and was changed for maintenance purposes. Access through the front bulkhead opening would need the anti-intrusion plate to be removed, so an additional access hole was added on top of the chassis, shown in figure 5.7. Eventually the front anti roll bar was moved on top of the access hole and created problems for maintenance that need to be addressed in future developments.

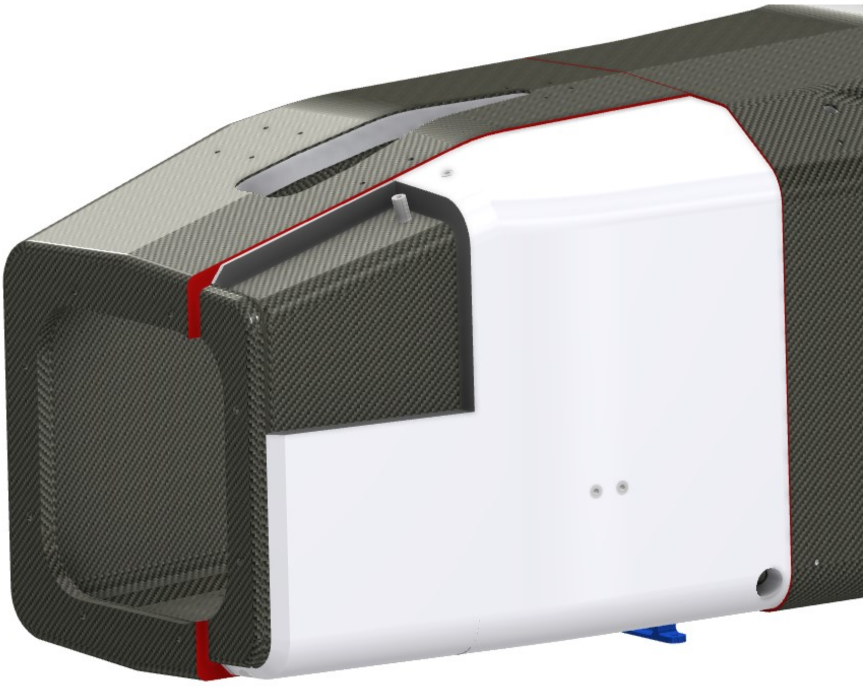


Figure 5.7. Cut-out illustration of the front chassis.

5.2.2 Cockpit and floor

The centre part of the chassis includes the side impact structure (SIS) and the cockpit opening. Cockpit design was most affected by driver position, but some consideration was also made for aerodynamic components. Cockpit opening is the area where the drivers need to have the most amount of space available for comfortable seating arrangements and arm movements

In the first iteration the chassis had a very narrow floor to accommodate large aerodynamic floor tunnels in the sides of the chassis. The ergonomics design test bench doesn’t currently have means to test for different cockpit shapes, so it could not be studied early on. As the 2022 design season went on, the floor on the inside of the chassis got even narrower with the addition of thick core and skins. At that point it was noted that the space may become an issue for some drivers.

Learning from the first iteration, the floor was made wider from the beginning of the second iteration. While the sides were also slightly widened, during the season some drivers had issues with their arms not fitting well enough in the cockpit. The issue can be addressed in the future without changing the outside chassis shape and therefore tooling, as the structure has room for making it thinner in some areas. For drivers it might be beneficial to make the cockpit as wide as physically possible, but some consideration needs to be given for structural and aerodynamic features.

5.2.3 Rear structure

Chassis rear structure has a single mandated composite structure, which is the main hoop bracing support (MHBS). Most design considerations in the rear were focused on the powertrain and its components. The rear portion was left open in the back to make room for engine and exhaust components, and to create a way for easy removal of the powertrain as an assembly.

In the early stages of the second iteration the rear chassis shape changed several times as the damper and bell crank locations were improved over time. At first it seemed difficult to line up all the suspension components so that a neat and well functional package was achievable, but after some iterations a good solution was reached. In the rear the chassis extends to the rearmost suspension mounting locations with a downwards slope to give the powertrain a somewhat open location. Since powertrain maintenance was one of the key factors in the design, the chassis has no integral cross members in the rear. Instead, a separate CFRP rear support panel was designed to work with the aluminium powertrain mounting plate for easy access and proper structural rigidity.

The first iteration had shown that the structure between the cockpit opening and the rear powertrain opening must remain narrow with the current engine and driver position. The area in question is where the safety harness shoulder belts would be attached to, and in that case would need to be equivalent to the rules mandated shoulder harness bar (SHB) structure. The area was shaped in a way that will give it adequate resistance in bending loads when the harnesses are mounted in that location. The previous structure had shown the difficulties in testing the panel for harness loads, as the area would need to be moulded to the actual shape to withstand a harness load of 13kN. For that reason, it was decided at an early stage that the shoulder harness would mount to a steel tube attached to the main hoop, since showing equivalency for the steel tube is very straightforward. Future development work includes this area and testing the harness mounting panel.

5.2.4 Other chassis components

In addition to the previously mentioned composite structures, the chassis has a few other components, such as the roll hoops, a bolt on rear bulkhead for structural rigidity and an aluminium powertrain mounting plate for easy removal of the powertrain as a unit.

The rules allow the front hoop design a few options: it must be made out of steel or aluminium and it must have a closed cross section. Equivalency must be shown to a 30mm*2mm round steel tube, and a welded aluminium construction must have proof of proper heat treatment. The current chassis concept includes suspension components that are mounted directly to the hoop and therefore it also needs to be very accurately manufactured. Front hoop was eventually designed as a solid machined aluminium part to achieve the highest possible accuracy and avoid aluminium welding. The construction is shown in figure 5.9, where the red area marks an area that per the rules is not part of the hoop, but an additional support for the chassis and suspension mounts. Options were discussed to create a partially machined channel shaped aluminium hoop that would have a plate welded to create a closed cross section, but those developments were left for following seasons to streamline manufacturing.

Main hoop and its bracings are mandated by the rules to be a steel tube construction. All primary structure tubes have a minimum wall thickness, cross sectional area and area moment of inertia. With those parameters the tubing choice is usually very straightforward: pick the lightest option that is equivalent to the rules. The team has been sponsored by SSAB for years, so the tubing is acquired from them. The steel members of the chassis, as seen on the right in figure 5.9, were made from SSAB Form 220 cold drawn steel tube and laser cut to shape. The final assembly for the steel hoop and its mountings was done on the finished composite chassis to ensure accurate positioning of all tubes and mounting features.

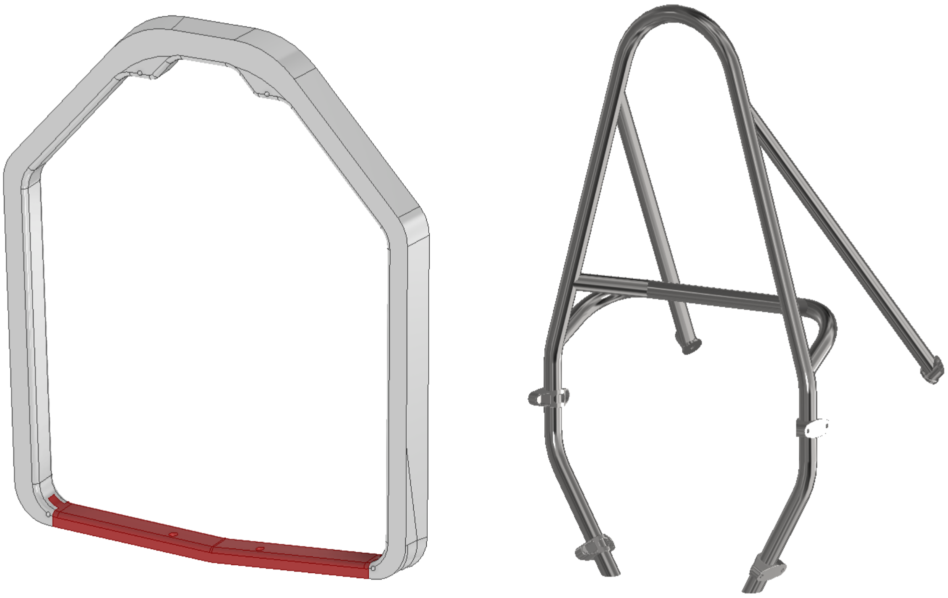


Figure 5.9. Aluminium front hoop and steel main hoop with bracings on the right.

A mounting plate was designed for powertrain, rear dampers and rear brake components. The goal was to create a simple method that ties the package together and supports the open floor structure. The construction, as seen in figure 5.10, is machined from a solid aluminium plate (pink) and has attachments for engine mounts (green), brake calipers, differential mounts and rear damper mounts (yellow). Attaching the plate to the chassis is done with six M8 thru bolts located near the engine and damper mounts to minimize compliance.

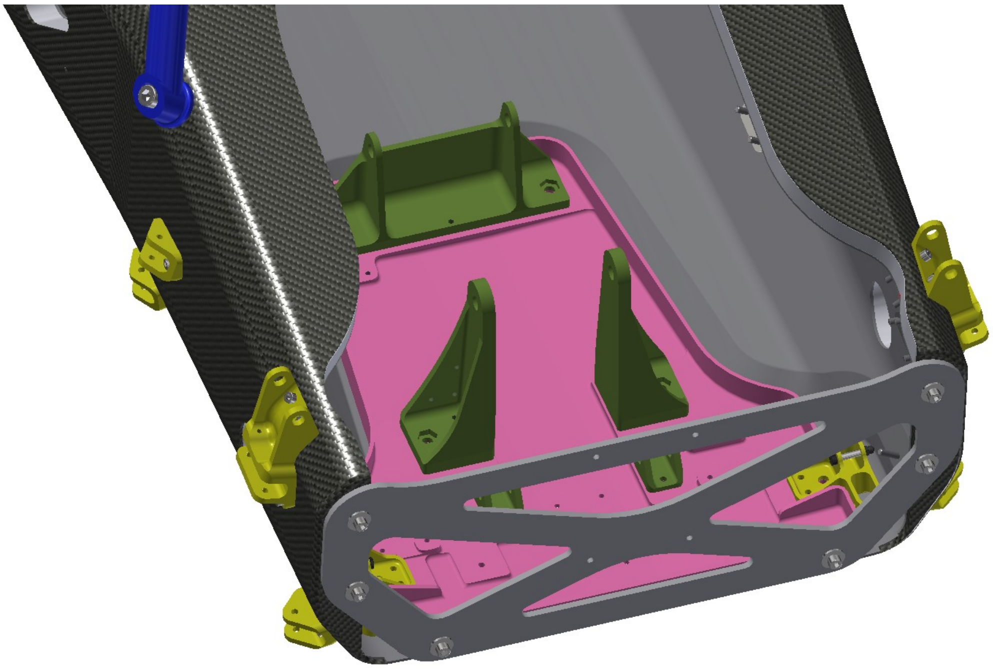


Figure 5.10. Powertrain mounting plate inside the chassis.

6 Manufacturing

Manufacturability plays a large role in the design of composite parts, as complexity and part shape can create problems for mould design and other manufacturing phases. Like cast parts, most shapes need to have sufficient draft angles for easy removal from their moulds after curing. If the design does not allow sufficient draft angles or where complex shapes are present, the mould can be split into smaller sections to help with demoulding. However, multi-part moulds are usually more labour intensive and therefore more expensive to produce. Dividing the mould into several pieces increases the risk of the mould warping or mould dimensions being less accurate.

6.1 Materials

6.1.1 Prepreg carbon fibre

Typically, pre-impregnated reinforcements need an autoclave for curing. However, there are some constraints regarding the use of an autoclave. The largest issue is the fact that there are very few industrial sized autoclaves in Finland, especially ones that are available for the teams use in a reasonable timeframe. This led to prioritizing out-of-autoclave -type materials over traditional choices. Out-of-autoclave prepregs usually have longer cure times and therefore also limit the teams manufacturing schedule, as the available high temperature oven is normally in high utilization.

For the team’s use case prepreg material makes the most sense from a manufacturing point of view. It is easy and accurate to position into the moulds and there are no issues regarding resin flow, as the resin is already included with the reinforcements. A fully enclosed mould creates serious issues for resin infusion and wet lay-up, most notably in holding the fibres in place during lay-up and secondly making the resin flow and stay in the correct locations.

In the spring of 2022, the team had issues acquiring prepregs, as global demand had driven everyone’s stocks low. Back then a decision was made to acquire materials through EasyComposites, as they had both the component and tooling prepregs in stock. Test panels made in early 2022 proved that EasyComposites' product was of good quality and yielded good results, which also led to them being the material supplier of choice for the 2023 season.

For the outer layer and other parts where twill type fabric is dominant, a 416 g/m^2 2x2 Twill was chosen, more specifically XPREG XC110. For unidirectional fibres the product was chosen from EasyComposites' autoclave cure line-up, XPREG XC130. While it is a different resin system, the two are fully compatible (EasyComposites n.d.). An autoclave cure fabric would typically leave pinholes when cured in a normal oven, but since the UD fibres are not used as surface plies, it made no difference.

6.1.2 Core

Core material was chosen mainly on the grounds of manufacturability. At an early stage it was determined that there was a need for an easily workable and malleable material. Different foams as well as some honeycomb core materials, such as Nomex and aluminium were considered. Due to the need of accurate trimming and additional potting compounds for core splicing, it was decided that the team's first monocoque would be built with a foam core to simplify the process. With its smaller surface area for bonding, it is critical to make sure a honeycomb is well fitted and pressed on the surfaces, which was a concern as the additional pressure of an autoclave was not available.

Multiple foam types were available, most of them being suitable for use with the chosen reinforcements and their curing cycles. The internal combustion powertrain creates a notable amount of heat when operated at high performance levels, which was one of the additional constraints for material choices. Commonly available PVC foams (such as Diab Divinycell H80 that the team uses in other composite structures) don't have very high operating temperatures, which pivoted the aim at PMI foams, especially Evonik Rohacell.

Compared to other foam types, Rohacell PMI foams have slightly better specific strength properties, which mostly ruled out PET foams. While Evonik has a product line of suitable PMI foams, their industrial grade fine cell IG-F 71 was chosen for its decent structural properties and good availability. A denser variant is also available from some distributors and should be tested in the future when the schedule allows.

6.2 Mould design

It was known at an early stage that the moulds could be machined from some form of tooling block at CSI Composite solutions and innovations, which is one of the team’s most important manufacturing partners, as many components need moulds and composite manufacturing equipment.

The mould design stage was very straightforward, as lessons had been learned during the first iteration of the composite chassis and proper measures were taken to create a chassis shape suitable for simple moulds. The top and bottom portions of the chassis include a three-degree draft angle to ease mould release, and all chassis openings were designed to be finished by machining, so no accurate edges were needed to be made during lay-up. The frontmost area of the chassis needs to be flat to accommodate the impact attenuator mounting plate, so a third mould component was added. This additional feature helps in creating a slightly forwards opening mould. No additional moulds were needed for the third component as it is merely a flat panel attached by flanges to the mould halves. The flanges seen in figure 6.1 were made 70 mm wide to ensure rigidity and proper area for mounting hardware on the split line.

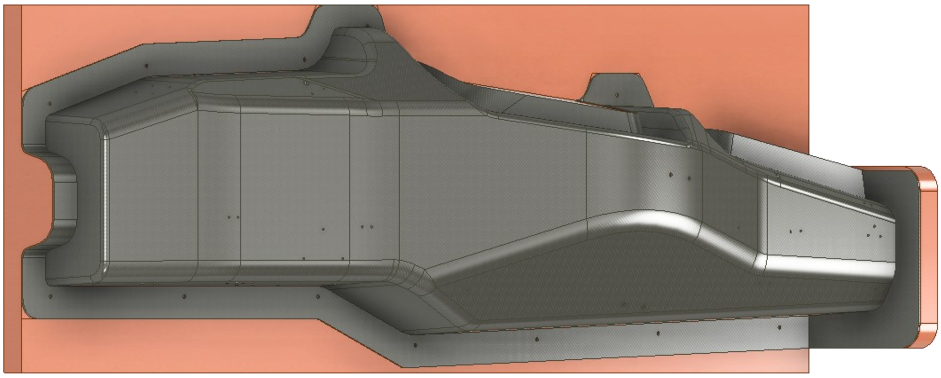


Figure 6.1. CAD Designed left side negative mould including its positive mould.

6.3 Mould materials

In the past the team has used mostly metal or tooling block moulds to create ready to use components. Since dimensional accuracy plays a very large role in the design and manufacturing of a race vehicle chassis, tooling block negative moulds would not be feasible due to their large coefficient of thermal expansion. The structure is also quite large, so using even medium density tooling block would result in a mould that weighs several hundreds of kilograms. Large amounts of tooling block would also be very expensive, especially as it would need to be epoxy based instead of polyurethane, as PU is known to cause cure inhibition with epoxy resin systems in high temperatures.

6.3.1 Tooling block

For cost and handling purposes it was decided that a low-density polyurethane tooling block would be used for the machined positive moulds, also known as plugs. A 300kg/m^3 version of Obo-Werke’s Obomodulan product line was chosen and ordered as 100mm thick blocks which were bonded together using PU adhesive. The bonded blocks were then machined with a large 5-Axis gantry mill that is located at CSI’s production facility in Mänttä-Vilppula, as seen in figure 6.2.

Figure 6.2. Positive mould machining (CSI 2023).

6.3.2 Negative mould material

The material of choice for the laminated negative moulds was out-of-autoclave tooling prepreg carbon fibre. Carbon fibre was chosen over fibreglass to achieve a higher level of thermal stability. It was not absolutely necessary to use prepreg over wet lay-up or resin infusion, but prepreg material has a lower chance of creating surface imperfections on the mould surface and should not need polishing or sanding before adding sealer and release agent given a properly finished plug.

Two types of CFRP prepreg twill fabric were used for the moulds. The first layer on the plug is a surface ply from a 250g fabric, and the rest of the layers use a heavier fabric that also has a higher resin to fibre ratio for improved surface finish and void removal.

6.4 Moulds

The moulds play a key part in creating a proper composite chassis. In an ideal situation they can be used for several years, given that the shape of the chassis is not altered. This means that special care should be taken when designing and building moulds, so finishing work on the actual part does not take a lot of effort.

6.4.1 Positive mould

Work on the moulds began with the delivery of 2,7 cubic meters of PU tooling block. The blocks were then cut into shapes determined by CSI and bonded together. The cutting and bonding took two working days with several people, so thicker material would be ideal for the job.

With the blocks bonded into suitable machining stock, they were then machined to create positive moulds for the split CFRP negative mould. By using a lighter product, the team saved on machining and material costs, but resulting in several days of postprocessing for the plugs to create a proper mould surface. The machined shape was lightly sanded smooth and then painted with a primer and mould surfacing paint. Being a less dense material, the block had quite a lot of porosity and surface pinholes which led to several stages of sanding, filling and repainting to achieve a proper smooth surface finish.

The positive moulds were then polished before adding mould sealer and release agent. The plugs incorporate locating pin holes that determine mounting locations for most key components and their respective inserts. The pins were also sealed and coated with release agent for easy removal, as they needed to be removed quickly when the plugs were still warm, or the moulds would get stuck due to thermal expansion.

6.4.2 Negative moulds

The moulds have a finer surface layer on the part side to create a smooth and pinhole free mould surface. Rest of the layers were backing plies, which were laid four layers thick with a debulk after every second layer. Breather cloth on the pins caused some issues regarding laminate compaction in certain locations, but in the end, it caused no issues on the mould surface. Cure cycles for the tooling prepreg were quite long to ensure adequate resin flow and steady temperature control for the lay-up. While the tooling block was not the densest option, it still needed some time to reach the soak temperature of 65 degrees Celsius.

Figure 6.3. Tooling prepreg laid up on the positive mould

After the initial 18-hour cure cycle the negative moulds were demoulded from the positive moulds and prepared for the post cure cycle. The final soak temperature was 135 degrees Celsius for 3 hours with a very mild ramp of 0.1 degrees Celsius per minute. Full cure cycle is illustrated in appendix 4. The mould surface came out as expected with a very smooth surface finish. Only defects on the surface were caused by the block seams printing though the plug paint, but it was so minor that no action was taken to correct them at that stage.

After curing the mould edges were trimmed to size and a light polish was applied before applying mould sealer and release agent. The mould flanges were also drilled for additional mounting holes to mitigate any possible flex in the mould during lay-up or cure cycles. The final negative moulds can be seen below in figure 6.4.

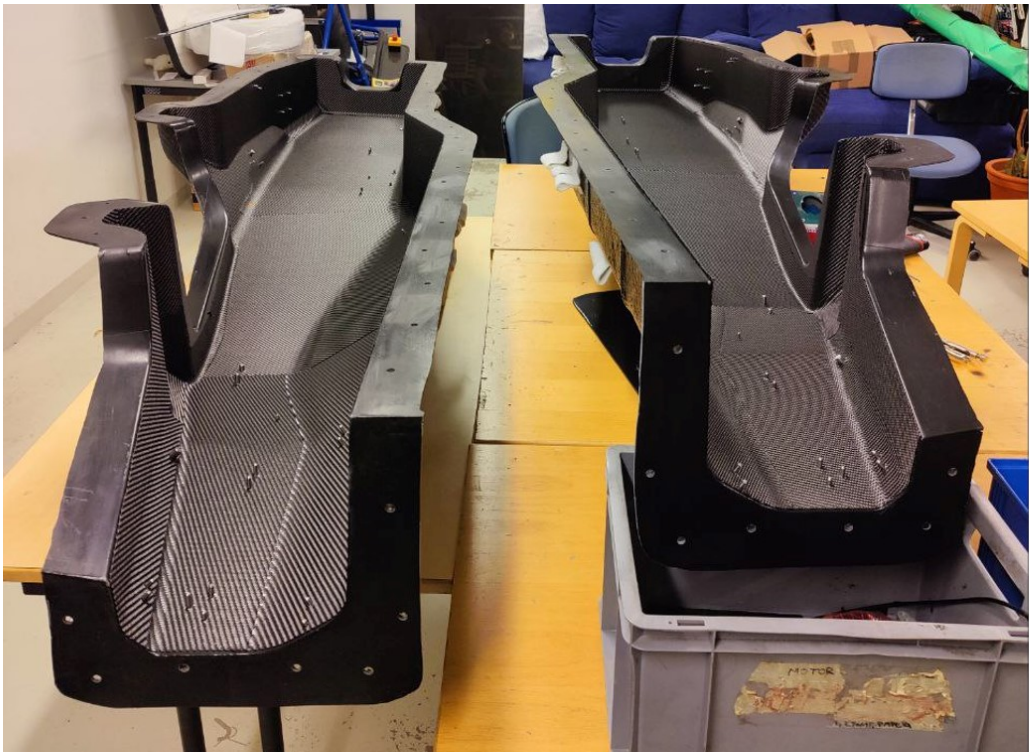


Figure 6.4. Mould halves with the outside chassis ply laid up

6.5 Chassis

Manufacturing a composite sandwich panel chassis is very labour intensive and takes several weeks to complete. Illustrated in figure 6.3, composite manufacturing was split into four stages that are separated with oven cures: lay-up of the outer skin (stage 1), installation of the front hoop and lay-up of the front hoop skin (stage 2), cutting and installation of the core material (stage 3) and finally lay-up of the inner skin and installation of the inserts (stage 4). After those stages, the chassis needed finishing work, such as machining the openings and sanding/polishing the outer surface.

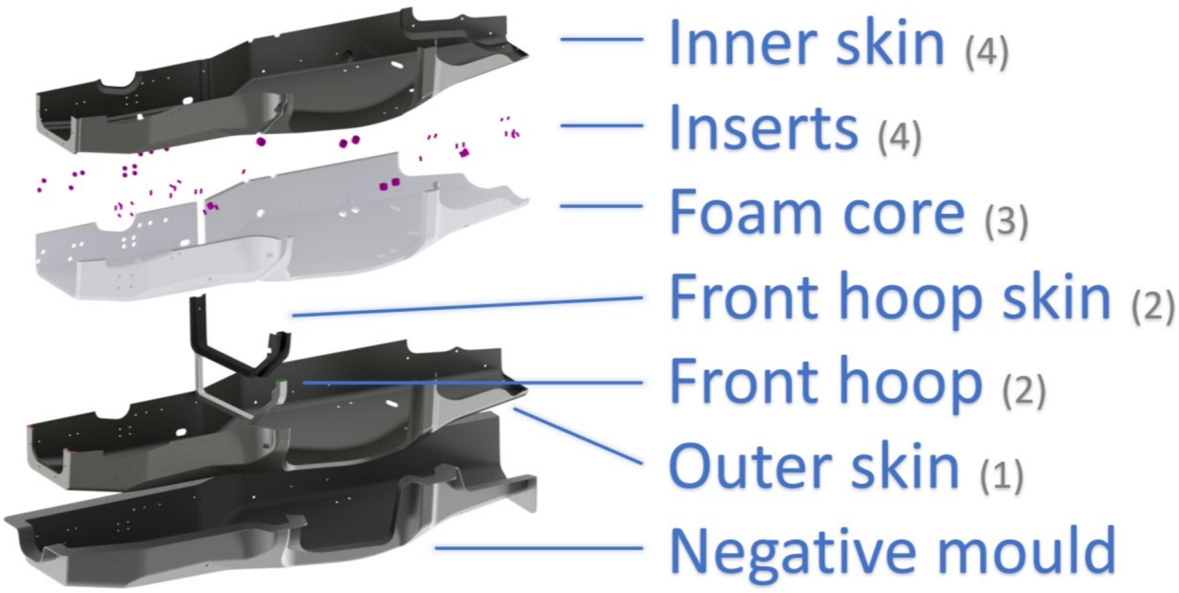


Figure 6.5. Chassis components and cure stages.

6.5.1 Outer skin lay-up

First layer of the outer skin consists entirely of twill fabrics and was laid up with the mould sides still separated for easy access, as seen in figure 6.6. Extra care was taken to ensure every piece of fabric fit well to the shape and other pieces to ensure a high-quality outer surface. With the first layer done the moulds were assembled and bolted together. At this stage the mould was vacuum bagged, and the first layer was debulked to compact it to the mould surface.

The workflow for vacuum bags was to utilize one bag with an inside and outside layer for the debulking stage and then switch to a fresh bag for curing to minimize risk of vacuum leaks during the resin flow stage. A tubular bag with a three-meter circumference was inserted through the mould from the small opening in the front to the larger opening in the rear, and a larger four-meter circumference tube was used on the outer surface of the mould. The bags were sealed together with vacuum tape and a through passage was created in the cockpit opening area as access to the inside of the mould was needed to ensure proper positioning of the vacuum bag on the inner surface.

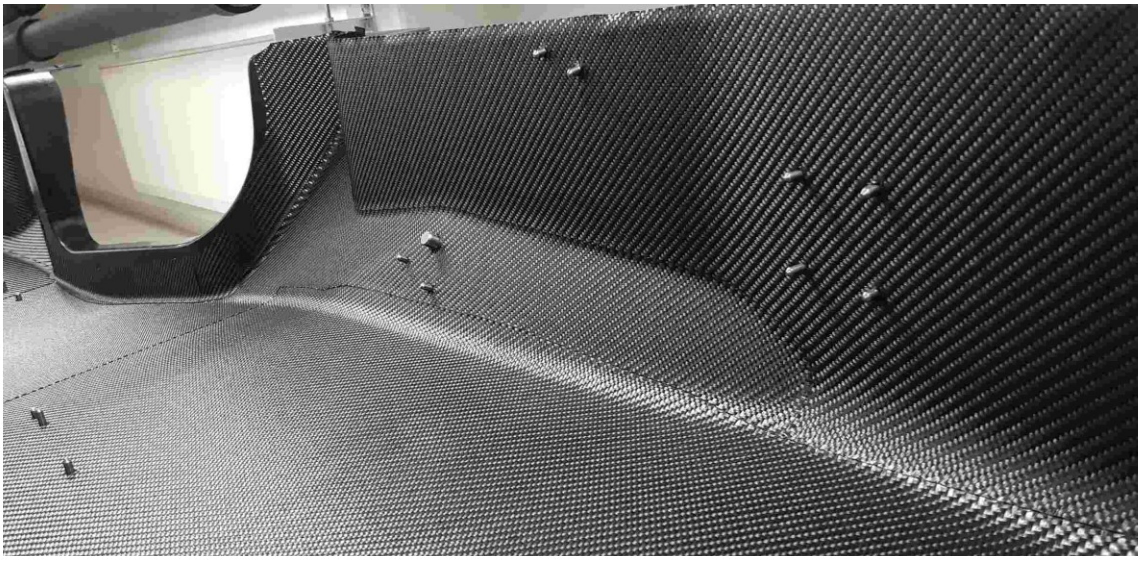


Figure 6.6. First layer of outer skin laid up on the mould halves.

The following layers included both twill and UD pieces dictated by the structural area in question. The first layer was laid up for every panel with a 0/90 fibre orientation, so the next layer had only -45/45-degree twill plies or 15-degree UD plies. After every second layer a debulk was performed to ensure adequate compaction and draping in all areas. With every layer after the initial one, two plies of front bulkhead and rear bulkhead mounting were laminated, as those areas needed a large number of layers. The outer skin of the chassis includes 15 layers of rear bulkhead mounting area plies and 27 layer of front bulkhead plies. Pictured in figure 6.7, the working space inside the mould was limited, and the air inside heated up quickly without proper ventilation. A normal household fan was used under the chassis to circulate air through the mould.

Figure 6.7. UD and twill plies laid up inside the closed mould.

6.5.2 Front hoop mounting

After the outer skin was cured using the cure cycle illustrated in appendix 5, the peel ply was taken off the surface and the front hoop was set in place. The front hoop mounting skin, seen in figure 6.8, is similar to the outer skin with UD but mirrored from the inner surface of the outer skin. The plies were carefully laid in small pieces with debulk stages in between. Debulking was tested with a small section of a vacuum bag sealed to the outer skin, but failure to make it seal properly led to using a full inner and outer bag. The hoop was positioned in place using existing mounting holes as a reference and bonded to the outer skin using epoxy adhesive. In the future proper fixtures should be made speed up positioning the hoop in the chassis. Core trimming was started simultaneously with this stage as there is a lot of room to test core in other areas of the chassis.

Figure 6.8. Front hoop skin lay-up inside the chassis.

6.5.3 Core assembly

Core trimming is an intricate process as the surfaces should fit well together all around and have a uniform thickness. Rohacell can be bent when hot but the oven needs to be suitable for the job, which the team doesn't currently possess. The core was trimmed in the team's facilities at TAMK so simple methods were utilized. During the 2022 season it was noticed that even hot forming is not easy for smaller radii, so not having access to an oven was not considered an issue.

Suitable cutting templates were drawn in CAD and plotted. The templates were used to cut the outer edges of the core pieces which were then carved to fit the inside surface of the skin. To properly test the pieces on the skin, bolts were placed through the moulds to hold the core in place. Fitting the core was the most time-consuming stage of construction, and all departments took part in making the pieces fit.

An adhesive epoxy resin film was used to attach the foam core on the skin inner surface. The moulds were vacuum bagged for oven curing to make the pieces conform to the chassis shape and to ensure proper resin flow on the core surface. After curing the core was carved for inserts in their respective locations with special tools and the locating pins were re-inserted for the final stage.

6.5.4 Inserts and inner skin lay-up

Inner skin lay-up is essentially the same as the outer skin except that it’s mirrored on the core centreline. The inserts were placed in their locations with an epoxy adhesive to keep them in place as the ley-up took place. At this point it was critical to ensure that all inserts were positioned as needed and every pin was firmly seated in its hole, as those set the mounting locations for most components attached to the chassis. Some areas of the mould did not have adequately rigid locations for the pins, so machined plates were used to ensure bolt hole alignment in key areas.

The debulk stages were similar to the outer skin without the additional bulkhead plies. At this point the crew had enough practise to improve the process efficiency significantly and the inner skin lay-up was finished in two days. Due to scheduling constraints the core adhesive film cure and the inner skin cure were done during a single weekend at CSI. Having access to a properly air-conditioned facility turned out to make a notable difference in lay-up time, as working inside the moulds was significantly more comfortable. The chassis was then cured with the same process as before.

6.5.5 Demoulding and finishing

After the final oven cure the chassis was ready to be demoulded. The moulds were separated at the flanges and split to reveal the final product. The locating dowel pins were shortened before the final cure to minimize the risk of vacuum leaks. This turned out to be an issue, since the pins only had a quick apply of release agent after shortening leading to several of them being seized in the chassis. Some pins were removed by striking them out with a hammer and others needed to be drilled out, which took several days. In the future the pins should be properly polished and prepared to ensure easy removal and disassembly of the moulds.

Openings were machined using the same 5 axis gantry mill that made the plugs. Using the fixture seen in figure 6.9, the chassis was mounted once on each side to reach all areas and holes. After machining the chassis had a light machine polish before assembly. The finished chassis including roll hoops was weighed at 33,6 kg, which is 1,4 kg lighter than the preceding space frame and therefore fulfils the conservative goal of keeping the weight same or lower for the first composite chassis. While the weight difference is fairly small in relation to the amount of additional hours spent on the chassis, future development should yield notably lighter results.

Figure 6.9. The chassis mounted in the mill using a machined fixture.

7 CONCLUSIONS & DISCUSSION

This multi-stage design project was performed emphasizing the goal of creating a solid foundation for future chassis and vehicle development. Short term goal for the 2023 season was creating small improvements in comparison to the previous tubular frames, these focusing on chassis weight and component positioning. The previous vehicles utilized a space frame originally designed from scratch in 2017 and upgraded yearly to accommodate rule changes and suspension updates, which in places led to sub-optimal design choices. The new concept was developed in harmony with suspension and powertrain departments to achieve the best possible solution in terms of packaging and maintainability.

Different options were evaluated for chassis type and construction. In many cases the driving design factors were based on either the FSG ruleset or other departments' needs and wishes. Materials and manufacturing methods were chosen based on available data and resources. Several material tests were performed to find physical properties of composite structures with different lay-ups and constructions. An out-of-autoclave CFRP solution was chosen for structural reinforcements with the absence of suitable autoclaves in Finland. The result is a carbon fibre full length monocoque with a foam core sandwich structure.

The manufacturing phase and methods were properly documented through the process to give the team a proper knowledge base that can be used in later developments as well as an introduction to some of the methods and their use cases. More time went into manufacturing related preparations and iterations than rest of the design work for the chassis. A complete chassis redesign was executed after the first iteration, which was mostly due to several manufacturing problems. CNC-machined positive moulds were created out of polyurethane tooling block to create plugs for negative moulds. The carbon fibre prepreg negative mould is a three-part structure consisting of left and right chassis halves with a flat panel closing the rear of the mould.

Future development

In the beginning of the work, it was known that some improvements and innovations would need to be moved to upcoming development seasons due to time and workload constraints. A solid base was laid for a high-quality composite chassis and several areas were knowingly created with options for future improvement.

While outside the scope of this thesis, structural simulation of composites will play a key role in the future development of lighter and stiffer composites for the team. Many of the composite structures currently developed by the team don’t have much consideration in terms of structural calculations and optimization, mainly due to an absence of proper workflows and material data for composites. Creating proper libraries from new and existing material tests will help in choosing and simulating composites in the future.

Time and manufacturing constraints necessitated simplification of certain areas in the chassis. With further material tests more optimal materials can be chosen to save weight and debulking steps by eliminating the solid CFRP front bulkhead. Finding a reliable partner for aluminium welding can help make the front hoop lighter by switching to a welded construction. As discussed in chapter 5.2.3, the mounting area for the driver’s shoulder harness could be integrated into the composite chassis instead of the tubular hoop assembly, but a separate mould and testing fixture would be needed to create and test the mounting area.

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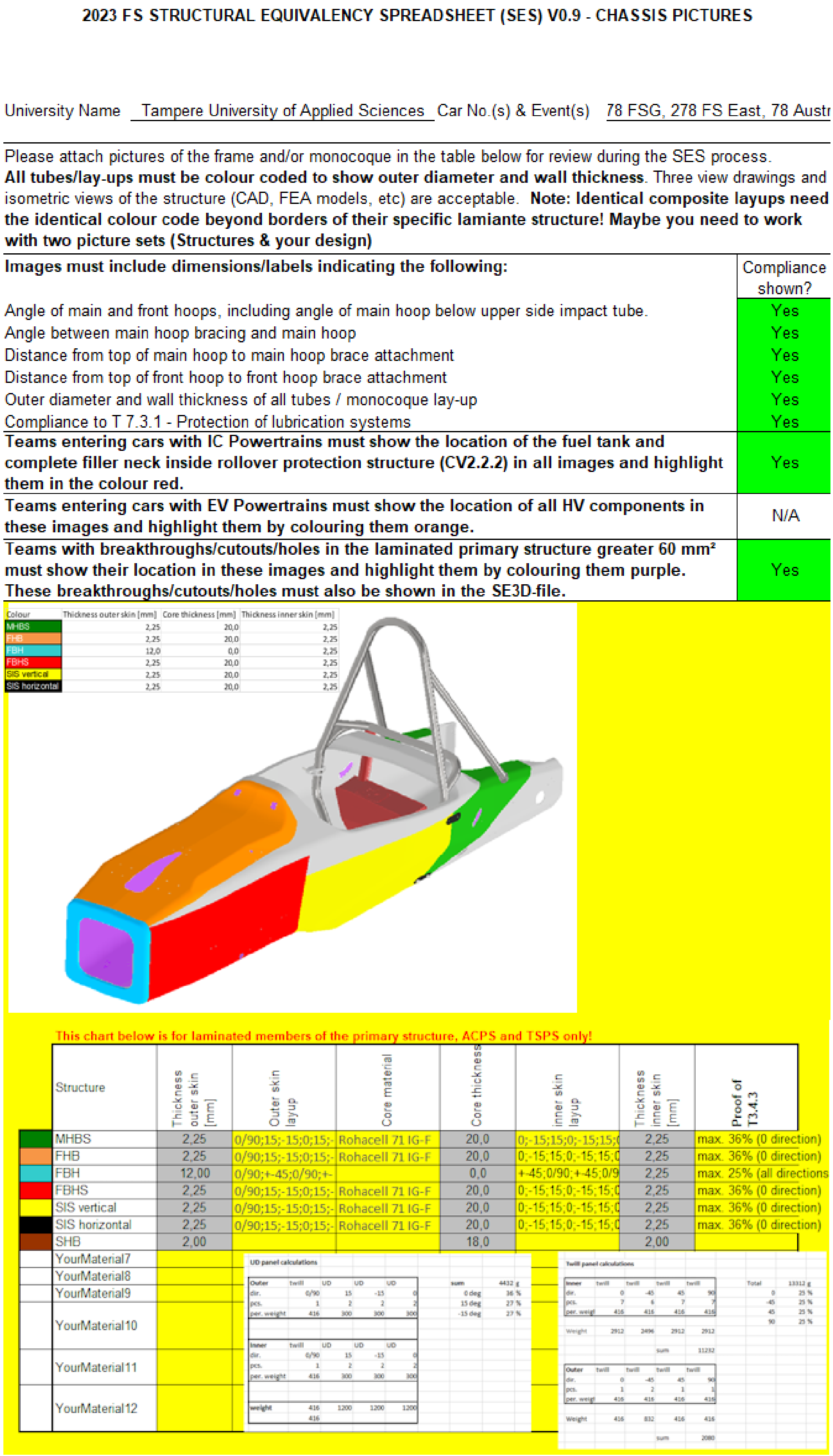
APPENDICES

Appendix 1. Chassis pics sheet of SES (FS23 SES v1.0 2023).



2023 FS STRUCTURAL EQUIVALENCY SPREADSHEET (SES) V0.9 - CHASSIS PICTURES

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Please attach pictures of the frame and/or monocoque in the table below for review during the SES process. **All tubes/lay-ups must be colour coded to show outer diameter and wall thickness.** Three view drawings and isometric views of the structure (CAD, FEA models, etc) are acceptable. **Note: Identical composite layups need the identical colour code beyond borders of their specific lamiante structure! Maybe you need to work with two picture sets (Structures & your design)**

Images must include dimensions/labels indicating the following:	Compliance shown?
Angle of main and front hoops, including angle of main hoop below upper side impact tube.	Yes
Angle between main hoop bracing and main hoop	Yes
Distance from top of main hoop to main hoop brace attachment	Yes
Distance from top of front hoop to front hoop brace attachment	Yes
Outer diameter and wall thickness of all tubes / monocoque lay-up	Yes
Compliance to T 7.3.1 - Protection of lubrication systems	Yes
Teams entering cars with IC Powertrains must show the location of the fuel tank and complete filler neck inside rollover protection structure (CV2.2.2) in all images and highlight them in the colour red.	Yes
Teams entering cars with EV Powertrains must show the location of all HV components in these images and highlight them by colouring them orange.	N/A
Teams with breakthroughs/cutouts/holes in the laminated primary structure greater 60 mm² must show their location in these images and highlight them by colouring them purple. These breakthroughs/cutouts/holes must also be shown in the SE3D-file.	Yes

Colour	Thickness outer skin [mm]	Core thickness [mm]	Thickness inner skin [mm]
MHBS	2,25	20,0	2,25
FHB	2,25	20,0	2,25
FBH	12,0	0,0	2,25
FBHS	2,25	20,0	2,25
SIS vertical	2,25	20,0	2,25
SIS horizontal	2,25	20,0	2,25

This chart below is for laminated members of the primary structure, ACPS and TSPS only!

	Structure	Thickness outer skin [mm]	Outer skin layup	Core material	Core thickness	inner skin layup	Thickness inner skin [mm]	Proof of T3.4.3
🟩	MHBS	2,25	0/90;15;-15;0;15;-	Rohacell 71 IG-F	20,0	0;-15;15;0;-15;15;(	2,25	max. 36% (0 direction)
🟧	FHB	2,25	0/90;15;-15;0;15;-	Rohacell 71 IG-F	20,0	0;-15;15;0;-15;15;(	2,25	max. 36% (0 direction)
🟦	FBH	12,00	0/90;+-45;0/90;+-		0,0	+-45;0/90;+-45;0/9	2,25	max. 25% (all directions
🟥	FBHS	2,25	0/90;15;-15;0;15;-	Rohacell 71 IG-F	20,0	0;-15;15;0;-15;15;(	2,25	max. 36% (0 direction)
🟨	SIS vertical	2,25	0/90;15;-15;0;15;-	Rohacell 71 IG-F	20,0	0;-15;15;0;-15;15;(	2,25	max. 36% (0 direction)
⬛	SIS horizontal	2,25	0/90;15;-15;0;15;-	Rohacell 71 IG-F	20,0	0;-15;15;0;-15;15;(	2,25	max. 36% (0 direction)
🟫	SHB	2,00			18,0		2,00	
	YourMaterial7							
	YourMaterial8							
	YourMaterial9							
	YourMaterial10							
	YourMaterial11							
	YourMaterial12							

UD panel calculations

Outer	twill	UD	UD	UD
dir.	0/90	15	-15	0
pcs.	1	2	2	2
per. weight	416	300	300	300

sum	4432	g
0 deg	36	%
15 deg	27	%
-15 deg	27	%

Inner	twill	UD	UD	UD
dir.	0/90	15	-15	0
pcs.	1	2	2	2
per. weight	416	300	300	300
weight	416	1200	1200	1200
	416			

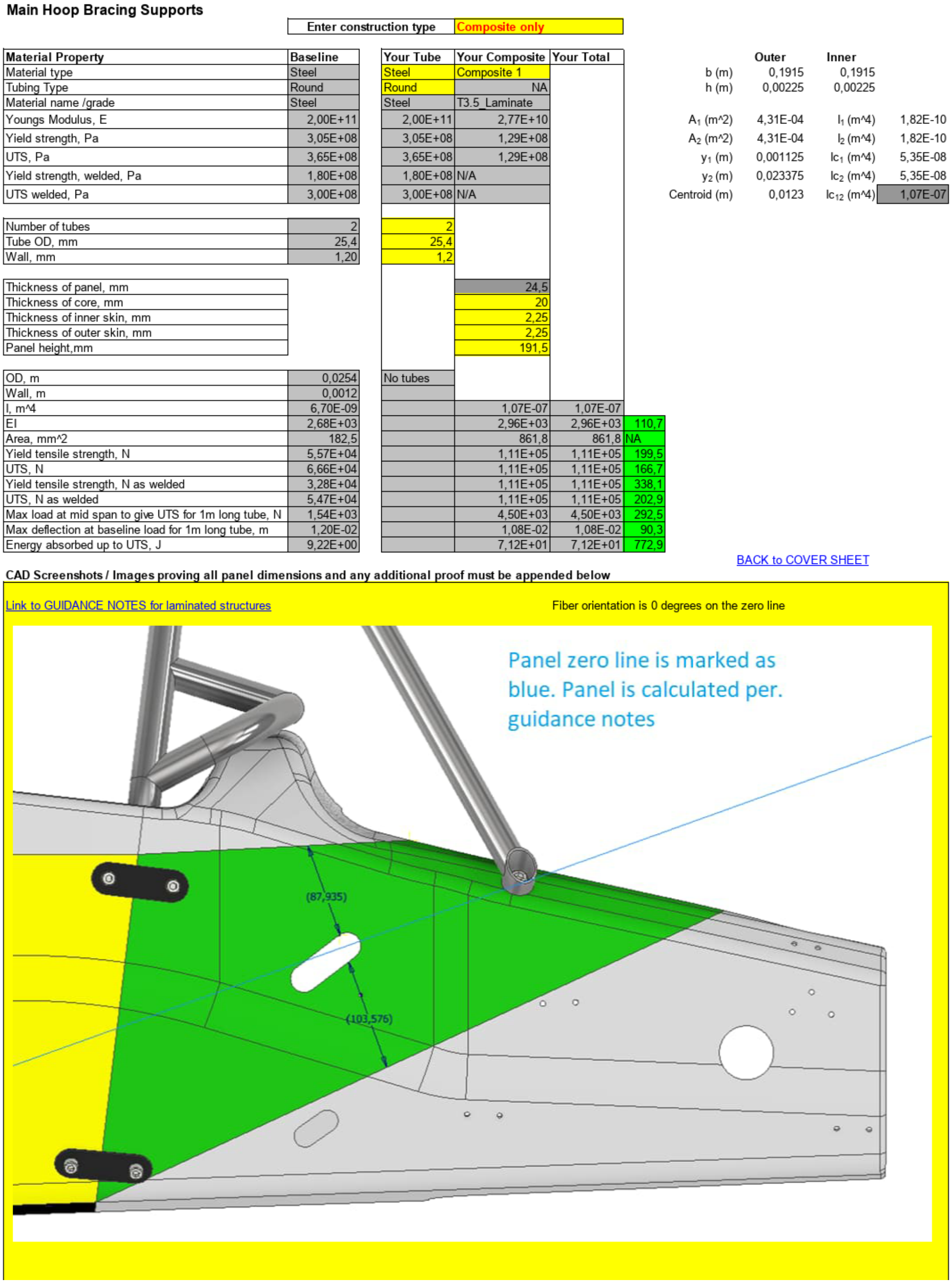
Twill panel calculations

Inner	twill	twill	twill	twill
dir.	0	-45	45	90
pcs.	7	6	7	7
per. weigl	416	416	416	416
Weight	2912	2496	2912	2912
			sum	11232

Total	13312	g
0	25	%
-45	25	%
45	25	%
90	25	%

Outer	twill	twill	twill	twill
dir.	0	-45	45	90
pcs.	1	2	1	1
per. weigl	416	416	416	416
Weight	416	832	416	416
			sum	2080

Appendix 2. Main hoop bracing support sheet of the SES (FS23 SES v1.0 2023).



Main Hoop Bracing Supports

Enter construction type	Composite only

Material Property	Baseline	Your Tube	Your Composite	Your Total	
Material type	Steel	Steel	Composite 1		
Tubing Type	Round	Round	NA		
Material name /grade	Steel	Steel	T3.5_Laminate		
Youngs Modulus, E	2,00E+11	2,00E+11	2,77E+10		
Yield strength, Pa	3,05E+08	3,05E+08	1,29E+08		
UTS, Pa	3,65E+08	3,65E+08	1,29E+08		
Yield strength, welded, Pa	1,80E+08	1,80E+08	N/A		
UTS welded, Pa	3,00E+08	3,00E+08	N/A		
Number of tubes	2	2			
Tube OD, mm	25,4	25,4			
Wall, mm	1,20	1,2			
Thickness of panel, mm			24,5		
Thickness of core, mm			20		
Thickness of inner skin, mm			2,25		
Thickness of outer skin, mm			2,25		
Panel height,mm			191,5		
OD, m	0,0254	No tubes			
Wall, m	0,0012				
I, m^4	6,70E-09		1,07E-07	1,07E-07	
EI	2,68E+03		2,96E+03	2,96E+03	110,7
Area, mm^2	182,5		861,8	861,8	NA
Yield tensile strength, N	5,57E+04		1,11E+05	1,11E+05	199,5
UTS, N	6,66E+04		1,11E+05	1,11E+05	166,7
Yield tensile strength, N as welded	3,28E+04		1,11E+05	1,11E+05	338,1
UTS, N as welded	5,47E+04		1,11E+05	1,11E+05	202,9
Max load at mid span to give UTS for 1m long tube, N	1,54E+03		4,50E+03	4,50E+03	292,5
Max deflection at baseline load for 1m long tube, m	1,20E-02		1,08E-02	1,08E-02	90,3
Energy absorbed up to UTS, J	9,22E+00		7,12E+01	7,12E+01	772,9

	Outer	Inner	
b (m)	0,1915	0,1915	
h (m)	0,00225	0,00225	
A_1 (m^2)	4,31E-04	I_1 (m^4)	1,82E-10
A_2 (m^2)	4,31E-04	I_2 (m^4)	1,82E-10
y_1 (m)	0,001125	Ic_1 (m^4)	5,35E-08
y_2 (m)	0,023375	Ic_2 (m^4)	5,35E-08
Centroid (m)	0,0123	Ic_{12} (m^4)	1,07E-07

BACK to COVER SHEET

CAD Screenshots / Images proving all panel dimensions and any additional proof must be appended below

Link to GUIDANCE NOTES for laminated structures

Fiber orientation is 0 degrees on the zero line

Panel zero line is marked as blue. Panel is calculated per. guidance notes

Appendix 3. Main structural panel test data in SES (FS23 SES v1.0 2023).

1(2)

SES - LAMINATE TEST RESULTS

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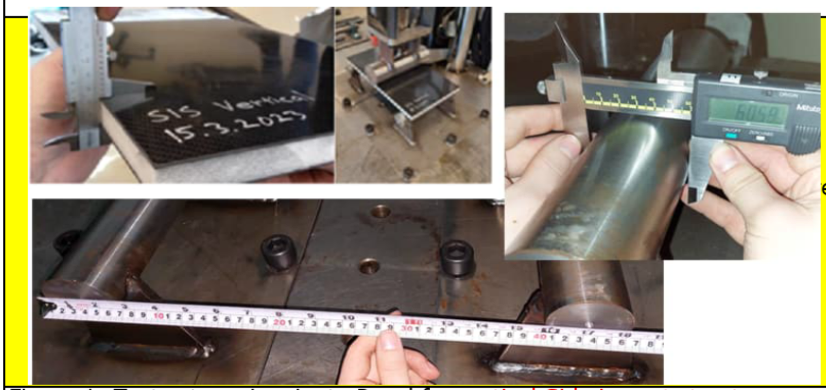


es!

Figure 1: Test setup - Laminate Panel for vertical Side impact structure

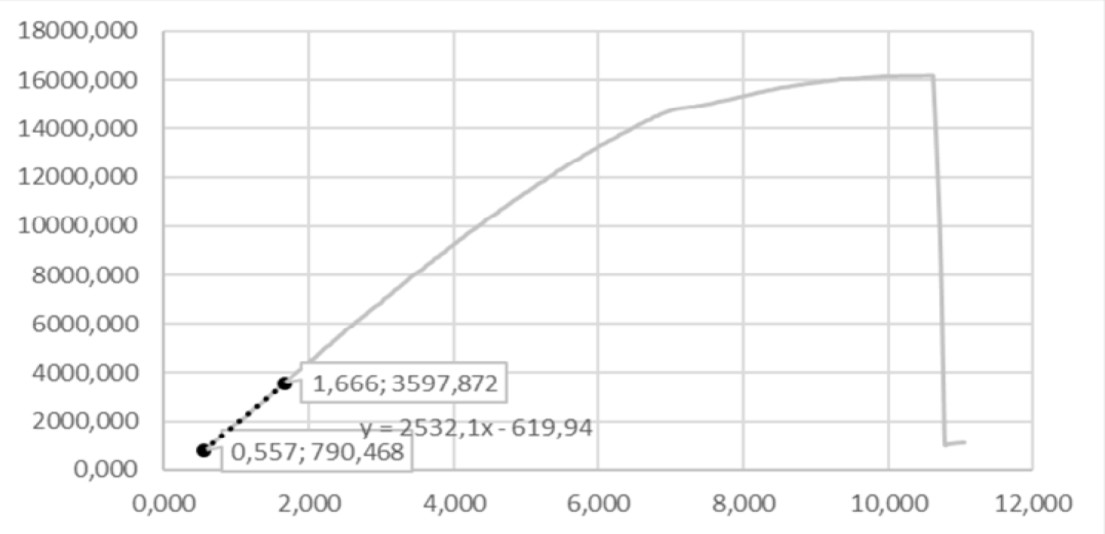


Figure 2: Load Deflection Curve for vertical Side impact structure

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

x_1 (mm)	0,557	y_1 (N)	790,462	Gradient (N/mm)	**3193**
x_2 (mm)	1,666	y_2 (N)	3597,872		

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

y_{max} (N) **16165,3** (>= bending strength of two baseline side impact tubes)

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

Energy (J) **110,2**

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)	2,25	Inner Skin Thickness
t_2 (mm)	2,25	Outer Skin Thickness
I (mm^4)	153682	Second moment of area
E (GPa)	**27,7**	Skin modulus of elasticity
σ_{UTS}(MPa)	**129**	UTS of skins

(continues)

SES - STEEL TUBE TEST RESULTS

University Name Tampere University of Applied Sciences Car No.(s) & Event(s) 78 FSG, 278 FS East, 78 Austri

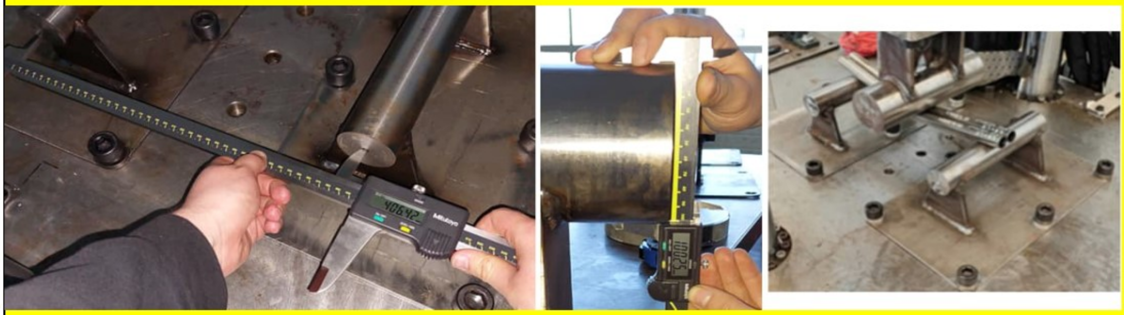


Figure 3: Test setup - Steel tubes as required for baseline design (T3.2)

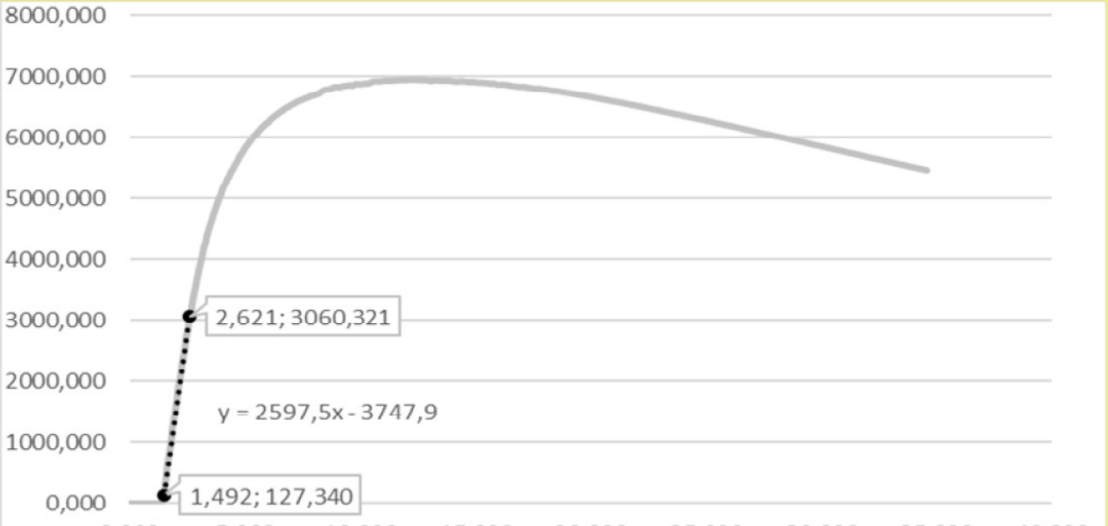


Figure 4: Load Deflection Curve - Steel Tubes as required for baseline design (T3.2)

Enter values for minimum and maximum load/deflection in linear-elastic region

x_1 (mm)	1,49	y_1 (N)	127,34	Gradient (N/mm)	**2598**
x_2 (mm)	2,62	y_2 (N)	3060,321		

Enter value of absorbed energy upto 12.7mm of deflection

Energy (J) **64,0**

Enter details of tube(s) tested

l (mm)	400	Tube Support Span	Theoretical EI (N.mm^2)	4,40E+09		
n	2	Number of Tubes	Tested EI (N.mm^2)	3,46E+09	78,7	%
D_o (mm)	28	Tube Outer Diameter	Rig Compliance (N/mm)	**12222**		
D_i (mm)	25	Tube Inner Diameter				

Appendix 4. XT135 Tooling prepreg cure cycle (EasyComposites, 2017).

Cure Cycle

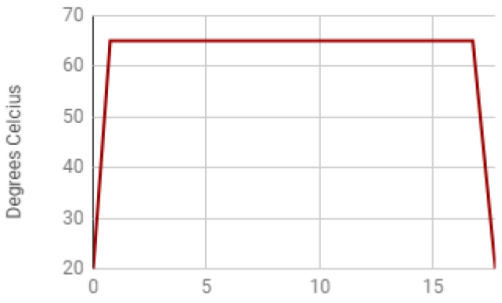
To achieve optimum surface finish and mechanical performance from XPREG® XT135 it is essential that the proper cure cycle is used.

The cure cycles specified are for oven air temperature, these allow for typical lag caused by standard composite tooling. If particularly bulky or heavy mould tools are used the tool surface temperature should be monitored to ensure that the lag does not go beyond acceptable limits. Temperatures should be held +/- 3°C where possible. Ovens should be periodically checked to ensure that they are achieving the required levels of accuracy and stability.

Controlled Ramp-Rate Cycles

Initial Cure Cycle

This initial cure cycle is recommended in all tooling applications this low temperature cure on the pattern ensures optimal dimensional accuracy and exceptionally low void content. This should be conducted for a minimum of 16hrs, increasing the soak time from 16hrs to upto 48hrs can reduce the effects of surface print-through.

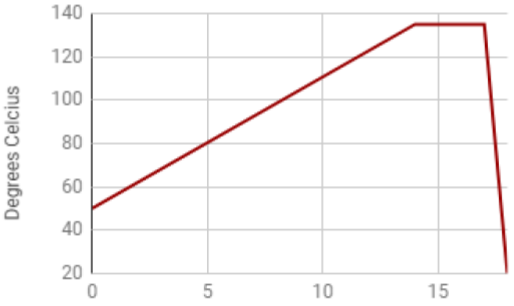


Step #	Start Temp	Ramp Rate	Time	End Temp	Elapsed Time
1	~20°C	1°C /min	00:45	65°C	00:45
2	65°C	Soak	16:00(min)	65°C	16.45
3	65°C	Natural Cool	--	~20°C	17.30

(continues)

Post Cure Cycle

The post cure cycle is required to achieve the full service temperature of the mould. A slow and controlled ramp is essential to ensure best surface finish and dimensional stability. The post cure should be conducted free-standing (off the pattern) for large mould structures it may be advantageous to support the mould during post-cure to minimise the risk of warping.



Step #	Start Temp	Ramp Rate	Time	End Temp	Elapsed Time
1	50°C	0.1°C /min*	14:10	135°C max **	14:10
2	135°C **	Soak	3:00	135°C **	17:10
3	135°C **	Natural Cool	--	~20°C	18:40

**Faster ramp rates up to 0.5°C/min are possible but may lead to increased surface 'print-though' and increased risk of warping.*

*** The final cure temperature should be set to the final operating temperature for the mould (to a maximum of 135°C) for instance if the final service temperature required is 120°C then this should be the upper temperature used, conducting the final cure at lower temperatures has the advantage of reducing the effect of 'print-through' on the mould surface.*

Switched Cycles

Switched cycles should only be used where your oven controller does not have ramp control. This does not provide optimal flow or cure control but will still in many cases offer excellent results. The cycles are essentially the same ramp controlled cure cycles with switched steps to replicate the ramps as closely as possible, This processing method allows simple control by timer switches or manual control.

Initial Cure (Switched) (only for use when oven ramp control is not available)

The initial cure can be conducted by simply loading the laminate into a cold oven and switching on at 65°C and allowing the oven to ramp naturally the soak for a minimum of 16hrs should be held as-per the recommended initial cure.

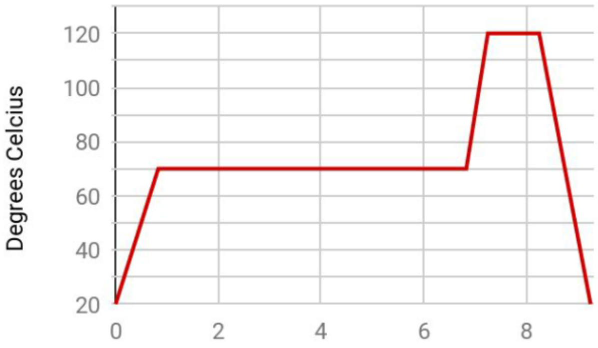
Post Cure (Switched) (only for use when oven ramp control is not available)

The post-cure should be switched in as many steps as is reasonably practical starting at 50°C and switching the temperature up every hour by 5°C to the final cure temperature will provide excellent results, if it is not practical to to this every hour then any/every single step can be run for an extended time without adverse effects.

Appendix 5. XC110 Prepreg cure cycle (EasyComposites 2021).

Extended Soak Cycle

This cure cycle is recommended for use on laminates above 4 plies, or components of high complexity, with the extended initial soak of 6hrs this capitalises on the full flow time available and will yield the lowest void content possible in nearly all applications, the only downside of this cycle against the 'Standard' cure cycle is the processing time as it is 2 Hours longer at 9hr 15min.



Step #	Start Temp	Ramp Rate	Time	End Temp	Elapsed Time
1	~20°C	1°C /min	00:50	70°C	00:50
2	70°C	Soak	06:00	70°C	06:50
3	70°C	2°C /min	00:25	120°C	07:15
4	120°C	Soak	01:00	120°C	08:15
5	120°C	Natural Cool	--	~20°C	09:15

Low Temp Cycle

This cure cycle is recommended when the maximum temperature capability of either the mould or the oven is lower than 120°C used in the 'Standard' cure. This cycle does not reflow the resin to the same degree and may in rare cases lead to an increased void content and reduce surface finish. The reduced final cure temperature increases the process time and reduces the final HDT (max temp) of the laminate unless subsequently post-cured.

Step #	Start Temp	Ramp Rate	Time	End Temp	Elapsed Time
1	~20°C	1°C /min	00:50	70°C	00:50
2	70°C	Soak	04:00	70°C	04:50
3	70°C	2°C /min	00:08	85°C	04:58
4	85°C	Soak	10:00	85°C	14:15
5	85°C	Natural Cool	--	~20°C	15:00

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