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Modeling of a chassis for an SAE formula car

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Abstract

The study and design of a tubular chassis for Formula SAE cars used in university competitions is presented. The modeling of the carbon fiber chassis is done in the CAD SolidWorks tool. The chassis has circular section tubes with a specific thickness, which are represented by a different color. The finite element method is used for modeling and verification, the 2019 SAE regulations are used. The ergonomics of the pilot, the restrictions of the suspension system and other mechanical components are the fundamental factors that allow to properly dimension and triangulate the different sections of the chassis.

Keywords: Chassis modeling, SAE prototype, Formula Student, Automotive chassis design.

1. INTRODUCTION

The Formula SAE, or also called Formula Student, is an automobile competition organized in the early 80's by the SAE (Society of Automotive Engineers), where university students from around the world meet to demonstrate all the knowledge acquired during their university career, which allow them to design, manufacture and test a Formula 1 type single-seater. Participating teams must fully comply with a regulation created by the organization, which stipulates the necessary parameters and standardized vehicle design, this ensures that all teams are on equal footing at the time of the competition, which consists of a series of static tests, these are a comprehensive evaluation in front of a jury in terms of design, cost and safety of the vehicle [1], [2]. Afterwards, the dynamic tests are carried out, where the performance of the single-seater is evaluated on track in different semi-professional competition environments [3], [4], taking place in the most important circuits such as Silverstone (United Kingdom), Hockenheim (Germany) and Michigan SpeedWay (United States). Thanks to Formula S.A.E., each student gains the necessary professional experience that allows them an easier transition to the job market [5].

The SAE in each of its Formula Student [6] events worldwide does not allow participating teams to compete with the same vehicle two years in a row. For this reason, the challenge that each team faces every year is to design and manufacture a new chassis, where it exceeds the performance of the previous model. This structure, usually made of steel tubes welded together, must be able to absorb all the stresses produced by both the mechanical components and the forces produced during the dynamic tests that are transmitted from the suspension to the chassis.

The purpose of the chassis, both in commercial and competition vehicles, is to be that internal structure, usually made of cast iron, steel or some other metal which offers good features in terms of strength and performance, capable of integrating and supporting each and every one of the mechanical components that are part of the car, such as the steering system, suspension, engine and bodywork. Its main function, in addition to being traditionally designed to support each of the mechanical components, is to optimally absorb the loads that they transfer to the structure, in order to avoid deformation, so the more rigid and resistant it is, the safer the vehicle will be, since there will be less likely that the driver's cabin will suffer any risk in case of an accident [7].

The evolution of the racing chassis dates back to the early twentieth century, where the mechanical components of the vehicle were increasingly heavier, making the wooden structure that was often used did not support the loads that were exerted on it, endangering the safety of the driver at high speeds. To solve this problem, chassis made of longitudinal beams were implemented, made of steel or cast iron with C-shaped cross section, but their use in both sports and competition cars was a minority, since the total weight increased significantly, so the vehicle performance was affected [8].

Taking into account the above, in 1937, the Auto Union Company initiated a change in the double-beam chassis for sports cars, carrying out the use of a round section twin-tubular structure. The twin-tubular chassis had the same or even greater resistance to stress than its predecessor, being lighter and greatly benefiting the performance of the vehicle. In the same year Mercedes Benz used a similar design with square section profiles, but later changed to closed section oval tubes and replaced the independent rear suspension (standard for sports cars), by a Dion design, used for the first time in the late nineteenth century [9].

Mercedes achieved excellent results with its closed section profile twin-tubular design, offering a superior chassis in terms of torsional stiffness compared to its competitors' structures. The success of this chassis was so resounding, that most European racing cars implemented this structure until the late 1950s [9].

Although the twin-tube structure presented optimum performance, it tended to fail at the suspension anchor points due to the high torsional stresses generated in this area. To solve this problem, a multi-tubular structure was incorporated in the previous design, but the first prototypes lacked an adequate triangulation, which generated a much heavier structure that significantly reduced the torsional stiffness of the vehicle [7]. In 1952 two chassis were built according to the principles of the multi-tubular structure, the Lotus M6 and the Mercedes Benz 300SL, Figure 2, which offered good performance in terms of stress resistance, weight and ease of manufacture.

However, the multi-tubular chassis had several drawbacks. The diameter of the tubes was a key factor in the design, the main structure had to be properly triangulated in order to increase its rigidity and its weight was clearly higher compared to its predecessor.

The construction chassis is a structure in which both the body and the chassis form a single element. The first functional sports appeared in 1937 with the inclusion of Citroën vehicles. This contained steel panels, which were bent and welded together to shape the body of the vehicle, then joined with a series of beams at its base and roof that provided the necessary rigidity to the structure. The front axle and drive train were assembled at the front of the vehicle [8].

Unitary construction was also used in single seater racing cars from the 1962 introduction of the Lotus 25 for Formula 1. It featured an innovative aluminum structure, being much lighter than any car in racing at the time, greatly improving performance and safety.

This design placed the engine in the rear part, making the construction of the chassis easier, allowing a better protection for the pilot due to its structure. But it was not recommended to use it for the engine compartment, as it presented great problems in the overall rigidity of the vehicle, interfering with the exhaust design and did not allow good accessibility [9].

The tubular chassis, is the most used in the Formula SAE, both by new teams as by the most experienced, as it is an economical structure and responds well to torsional stresses, but being formed by tubes welded together, it increases its weight significantly. The regulations provided by SAE International for this competition contain a series of rules concerning its basic design, which cover: tube profiles, materials, and minimum structure and geometry requirements.

The chassis is made of composite panels, usually carbon fiber reinforced polymer (FRP). This structure has a higher resistance to stress than the tubular structures of steel or aluminum and is much lighter, but its use is a minority, since the costs of raw materials and manufacturing processes are high so not all teams in the competition are allowed to build this type of chassis.

The chassis design for the SAE formula becomes a yearly work, where they try to design the chassis with the best performance, implementing the current regulations for its time, for example a work with the official regulation of 2013, describes that the steel "SAE4130" of 25.4 mm in diameter and 2 mm thick, obtains favorable results compared to those obtained with the steel "SAE 1020", which was the most used [2]. Some designs focus on the structure and manufacturing materials, where they apply it to different competitions according to the country of organization, for example in India the SUPRA SAEINDIA organized by Society of Automobile Engineers India [10], where the study of cost, manufacturing, performance start from a deep study of the design so that the car is finally competitive. Different materials have been studied to enable higher strength and less weight, such as AISI 4130 chrome steel, based on SAE 2019 formula rules, using ANSYS for different tests where it could be determined that the suitable material by comparing with commonly used materials [11]. Recently the works are being directed to the use of alternative energy as it can be an electric single-seater, where the structure must be sized according to the information of the components, such as battery, suspension, etc., and that comply with the limitations in the rules of the competition [12].

Today, in the automotive industry one of the most important aspects is the design of the different systems that make up the vehicle, starting with the main component, the chassis, being a supporting structure whose purpose is to support and fix all the components of the vehicle, such as front and rear suspension systems, which are installed by means of attachment points contained in the chassis structure, as well as the drive system that includes transmission and engine, fuel tank, cooling and electronic systems, all the panels of the aerodynamic structure, in order to achieve an integration and performance between all the systems. That is why this research presents the design of the tubular chassis and its rigidity following the regulations of the Formula SAE, using finite methods and SolidWorks software, based on the location of the pilot, the main arc and front arc, as well as a 3D design of the chassis using carbon fiber.

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2. METHODOLOGY

The most accurate way to determine proper chassis stiffness is through testing and experience. The teams that have participated over the years in this competition have gained the necessary knowledge of how the vehicle must be tuned in order to ensure a proper stiffness value for the chassis. The Formula SAE regulations do not contemplate a specific torsional stiffness value, where the tubular chassis must approach to ensure the integrity of the structure, as this varies according to the weight and geometry of the vehicle. To provide a solution to this, Cornell University has carried out a study of the variation of stiffness in its tubular chassis over the years in competition (Table 1), so this information will be used as a reference value for the design to be developed [13].

Table 1. Cornell University torsional stiffness study.

Year	Weight	Torsional stiffness
1999	25.85 Kg	2169.31 N*m/°
1998	25.85 Kg	2169.31 N*m/°
1997	26.3 Kg	2169.31 N*m/°
1996	27.22 Kg	1898.15 N*m/°
1995	27.22 Kg	1355.82 N*m/°
1993	27.68 Kg	2711.64 N*m/°

Source: [13]

Clearly, the 1993 chassis was very efficient so its stiffness will be taken as the minimum permissible value at the time of making the respective simulations to the proposed design, because it is not possible to make a total study of the single-seater. For the bending stiffness a maximum of 30 mm of lateral and vertical deformation will be taken, since the necessary value for the chassis to touch the ground is 26 mm.

Permanent loads on the chassis

In the different tests to which the chassis will be exposed, the load transmitted by the different mechanical components that are anchored to the structure must be taken into account as shown in figure 1, these are: engine, pilot, battery and fuel tank.

Rider: The chassis of the single-seater is designed in the first instance to ensure the ergonomics and safety of the rider. Taking into account the 95th Percentile standard. The weight of the pilot will be 80 kg and will be located in the center of the vehicle, in order to lower the center of gravity of the structure as much as possible.

Engine: The engine is located at the rear of the chassis, usually 8 anchor points are needed to secure it optimally to the structure. We will use the weight of a HONDA CBR 600 RR engine which is one of the most used by Formula SAE teams, its value will be 60 Kg.

Battery: The battery is located at the rear of the vehicle, near the engine. The weight of the battery is about 15 kg.

Fuel tank: According to the regulations, the vehicle must contain a fuel tank of at least 18 liters, this in order to be able to complete the longest competition event, which is a race of about 22 km. The fuel tank is located behind the driver's seat and will have a weight of 18 kg, considering that it is full.

Computer Aided Engineering (CAE) is the standard for every engineering process in the development of a product for any industry. CAE tools not only allow to design the final product, but also to support the engineering process as it allows to analyze and simulate in real environments, the mechanical properties of the model without the need for a physical prototype. On the other hand, CAE systems allow to reduce the time needed for the development of new products, increasing productivity, optimizing the manufacturing process flow.

Fig. 1. Elements affecting the deformation of the chassis

2.1 The finite element method

The finite element method (FEM) has become the most useful tool for the numerical solution of a wide range of engineering problems. These range from static and dynamic analysis in mechanical elements, heat transfer, fluid mechanics, electromagnetic problems and structural analysis [14]. Thanks to this method and advances in computer technology and CAD systems, complex engineering problems can be easily modeled and verified, which allows testing various configurations of the model before building the first prototype, saving costs and manufacturing time. The analysis in a complex model, which defines a continuous system, is discretized into simple geometric shapes called elements which are linked together by nodes.

FEM-based programs formulate mathematical equations that govern the behavior of the system in each of its elements through the nodes. These equations; usually differential equations, define the displacements of each node in the X, Y, and Z directions as a function of the mechanical properties of the material, the applied forces and motion constraints, among other aspects. The displacement that is produced at the nodes allows the software to calculate the solution of these equations depending on the study performed [15]. The post-processing represents the three-dimensional model with a range of colors that indicate the results of the study under the defined boundary conditions.

Main elements

Node: It is the junction point between the elements of the parts of the model. Thus, each node will occupy a coordinate position in the space where the degrees of freedom are defined.

Element: It is the basic building block of finite element analysis. There are different basic types of elements. Thus, the choice of the type of element to be used for FEM analysis will depend on the type of model to be studied. The main types of elements are:

- **One-dimensional element:** These are straight or curved elements with physical properties such as axial and torsional stiffness. 1D elements are widely used to model cables, beams or point masses.
- **Two-dimensional element:** This element is used in the analysis of plates or sheets with a constant thickness, which are called *Shell*.
- **Three-dimensional element:** Three-dimensional elements are used for modeling and analysis of solids, such as machine components. Common element shapes are tetrahedral and hexahedra, where the nodes are located at the vertices and possibly on the inner faces of the element.

2.2 Software Description

The main tool used for the design, analysis and simulation of the proposed Formula SAE chassis has been the SolidWorks software, made and marketed by the French company Dassault Systems. SolidWorks is the most widely used 3D CAD software currently used in education and industry, which covers all aspects of the product development process with a seamlessly integrated workflow, including the stages of design, validation (CAE), sustainable design, manufacturing (CAM), documentation, communication and data management, saving money in production and improving the quality of the final product.

SolidWorks Simulation is an integrated software tool that allows design teams to create and validate each of their projects in a real-world environment. Over the years the software has evolved from analyses that validate the strength, durability and stiffness of parts and assemblies, to fluid analysis, thermal analysis, and vibration, topological and structural optimization. Validation of molds and plastic parts, allowing to give an added value to all products that are designed in the software.

2.3 Meshing

One of the crucial factors when performing an analysis by the finite element method is undoubtedly the meshing process of the geometry under study. First of all, the software divides the body into a system of elements, with their associated nodes and chooses the most appropriate type of element so that the model to be studied has a physical behavior as close to the real one as possible. It is important to consider the time needed to create the mesh, the computational costs, the effect of numerical diffusion, etc., before choosing the most appropriate type of mesh for the study to be carried out.

The software estimates a global element size for the studied model taking into account its volume, area, dimensions and other geometrical details. The generated mesh size (number of nodes and elements) depends on the geometry and dimensions of the model, mesh tolerances, mesh control and contact specifications given by the Engineer.

Types of Mesh

Solid mesh

The solid type mesh generates one of the following types of elements in large parts or assemblies with solid elements.

- Standard and draft quality mesh: The mesher generates linear tetrahedral solid elements (Figure 2a),
- High quality mesh: The mesher generates solid tetrahedral parabolic elements (Figure 2b).

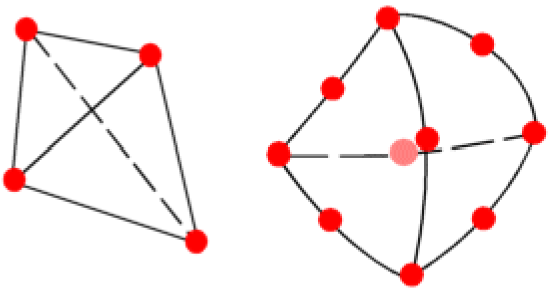

Fig. 21 . a) Linear tetrahedral element, b) Parabolic tetrahedral element. Source: [16]

For the same mesh density (number of nodes and elements), parabolic elements offer better results than linear elements because they represent curved contours which generate higher accuracy, producing better mathematical approximations. Figure 3 shows an example of a solid mesh.

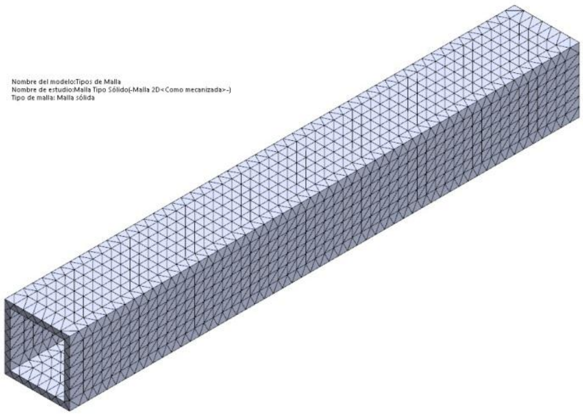

Fig. 3. Solid Mesh generated in a rectangular tube

Pouring Mesh

The shell mesh generates one of the following types of elements in parts or assemblies modeled with the sheet metal and surface tools:

- Linear Triangular: When using the standard or draft quality mesh option, the software generates linear triangular shell elements as shown in figure 4a.
- Parabolic Triangles: When using the mesh quality option of being or draft quality, the software generates parabolic triangular shell elements as shown in figure 4b.

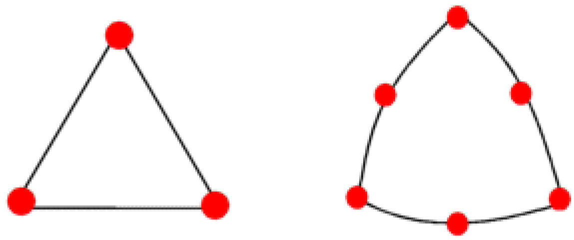

Fig. 42 . a) Linear triangular element, b) Parabolic triangular element. Source: [16]

An example of the cast mesh is shown below (Figure 5).

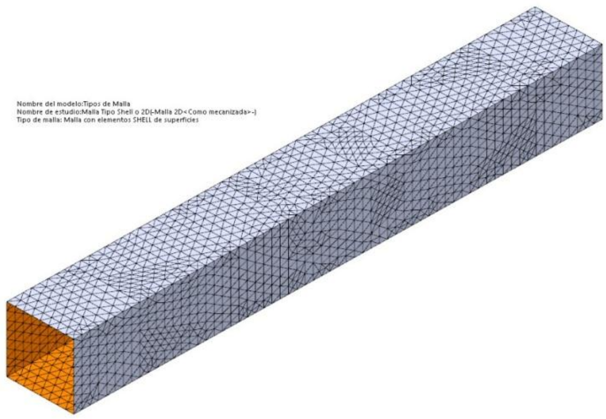

Fig. 3Example SolidWorks generated shell mesh in a rectangular tube

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Beam Mesh

A structural member is automatically identified as a beam and meshed with beam-like elements. Once the mesh has been created, it is possible to apply mesh controls on the structure, allowing to increase the number of elements for each of the selected beams. Structural members can be displayed with their actual geometry or as hollow cylinder elements, regardless of their cross-section as shown in Figure 6.

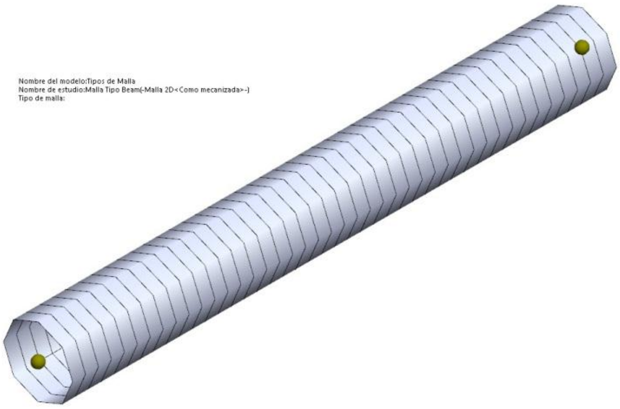

Fig. 6. Example of generated beam mesh. Source: [16]

At the free ends and at the intersections of two or more structural members a joint is generated, which is represented by a purple or yellow sphere. SolidWorks provides a tool that allows you to define each of the intersection points in a complex structure correctly.

3. RESULT

In order to obtain an optimal and competitive chassis for the demanding tests of the Formula SAE, the tubular structure must be designed and simulated in its entirety by the current regulations. The results of each simulation will give us to know the critical points of the structure, which will be the references in the process of structural optimization. In this section is the development of the base prototype of the proposed chassis, with its respective simulation studies to which it will be exposed. Next, the 2D designs of the main structure of the tubular chassis are presented.

3.1 Location of the pilot

Taking into account the Formula SAE regulations and the ergonomic study of the pilot, the design of the geometry of the tubular structure began with the 2D modeling of the Percy template as shown in Figure 4, which allowed to know the total location of the pilot in the single-seater, the positioning of the side impact zone, the main arch and the front arch (Figure 7).

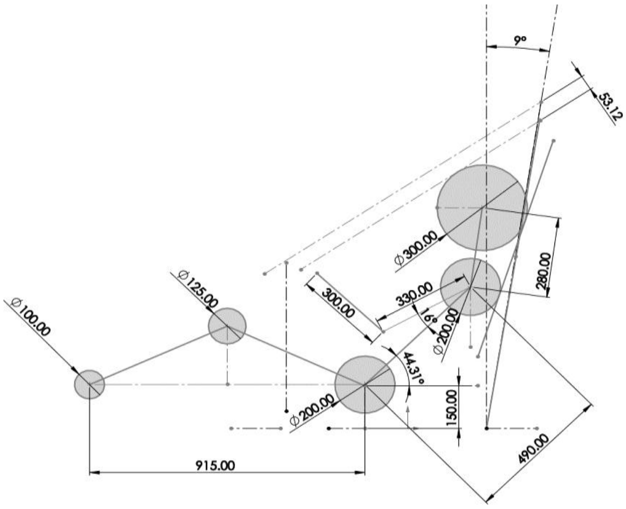

Fig. 7. 2D modeling of the Percy template.

3.2 Chassis Base

The base of the chassis is the structure in charge of supporting the other structural members and some mechanical components of the vehicle. For this, the following measurements were taken: 1605 mm wheelbase, the 95th percentile standard where the dimensions of the driver are specified, the dimensions of the engine, the rear suspension, the templates corresponding to the opening of the cockpit and the minimum front section of the single-seater. Figure 8 shows the 2D sketch of the base from a top view.

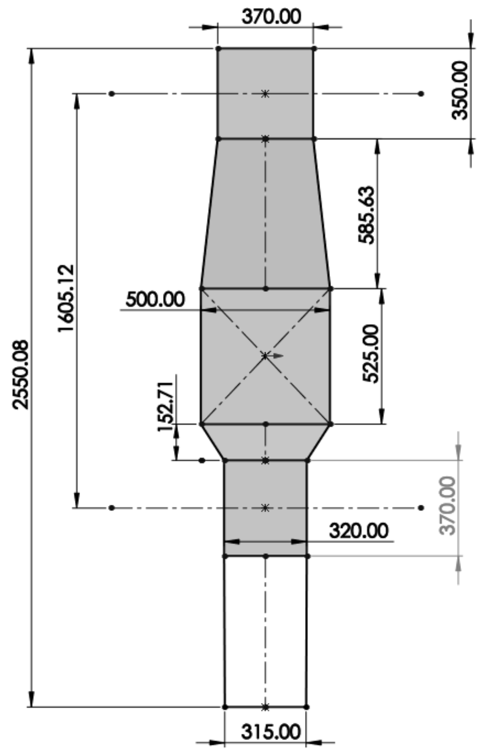

Fig. 8. 2D modeling of the chassis base from top view

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3.3 Main Arch and Front Arch

The design of the main arch started from its lower structure, for which the width of the chassis was taken as a base member. On both sides of this and up to the corresponding height, the waist of the pilot was given an inclination of 116° with the horizontal, this in order to ensure an adequate opening of the cockpit and avoid forming a rectangular structure that later can be a concentrator of efforts, compromising the integrity of the chassis and the safety of the pilot. Subsequently, from a lateral view, an angle of 9° with respect to the vertical was assigned to the whole structure, this with the objective of improving the ergonomics of the pilot, knowing that his torso is slightly inclined backwards in a normal driving position.

Bearing in mind what the Formula SAE regulations indicate for the maximum height of the main arch, a tangent line to the circle representing the pilot's helmet was placed in the 2D modeling of the Percy template, located at a distance of 53 mm as shown in Figure 9. The point of intersection of this with the construction line at 9° from the base of the main arch indicates the optimum height for the structure. The final 2D model of the main arch is shown below.

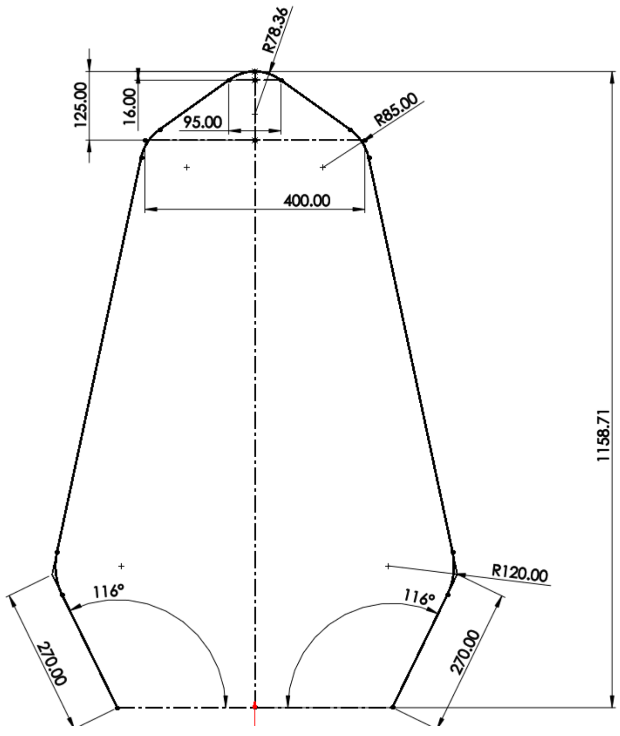

Fig. 9. 2D modeling of the main arch

The front arch is located at a distance of 101.5 mm with respect to the pilot's hands, the position where the steering wheel is located, this distance should not be greater than 250 mm. As for the front arc, the optimal height was calculated by drawing a vertical line from the base of the structure to the point where it intersects the line tangent to the pilot's helmet. Its geometry was modeled with respect to the minimum chassis cross section template where a rectangular structure was avoided. Figure 10 represents the 2D model of the front arch.

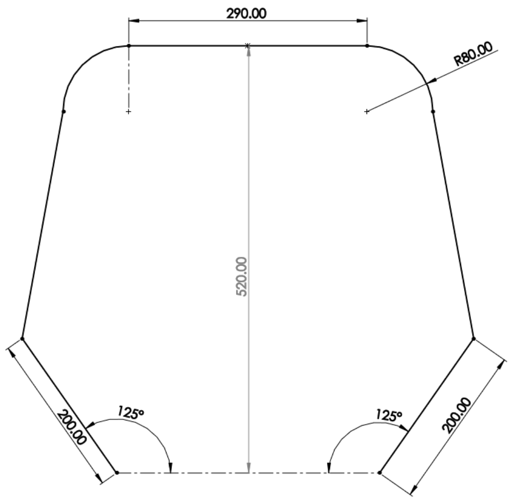

Fig. 10. 2D modeling of the main arch in a front view

3.4 3D design of the base prototype

Once the roll bars were integrated to the base structure and using the 3D sketch tool integrated in the software, we proceeded to make the total modeling of the chassis. In this step, the frontal protection plane, the lateral impact area, the supports of each roll bar, the anchoring points of the engine and the suspension system were designed, all properly triangulated and with the parameters of the regulations. Figure 11 shows the final 3D sketch of the base prototype.

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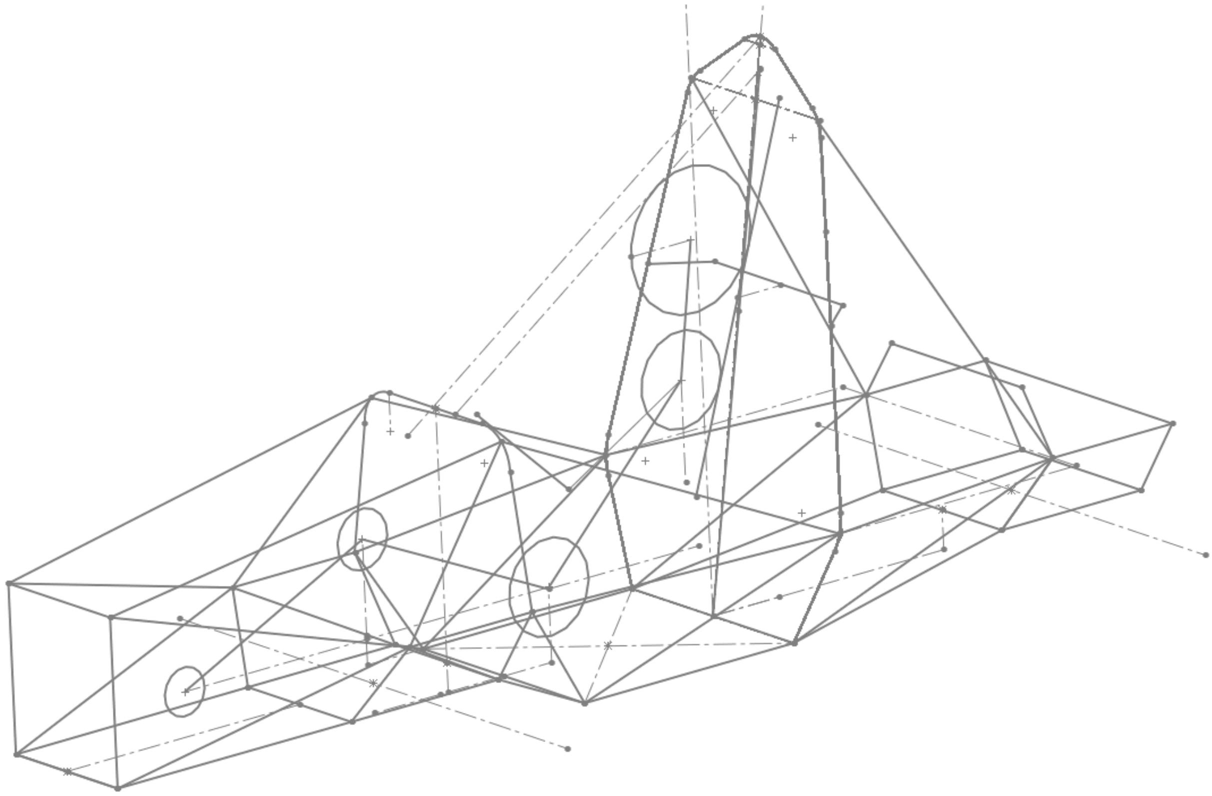

Fig. 11. 3D sketch of the base tubular prototype

With the 3D sketch obtained, the required structural profiles for each of the chassis tubes were introduced into the software as indicated in the regulations in order to model the structure in its entirety with the welded structures tool *(Weldments)* integrated in the software, as shown in Figure 12.

The chassis has circular section tubes with a specific thickness, which are represented by a different colour in figure 13, Table 2 indicates the dimensions of each profile used in the structure.

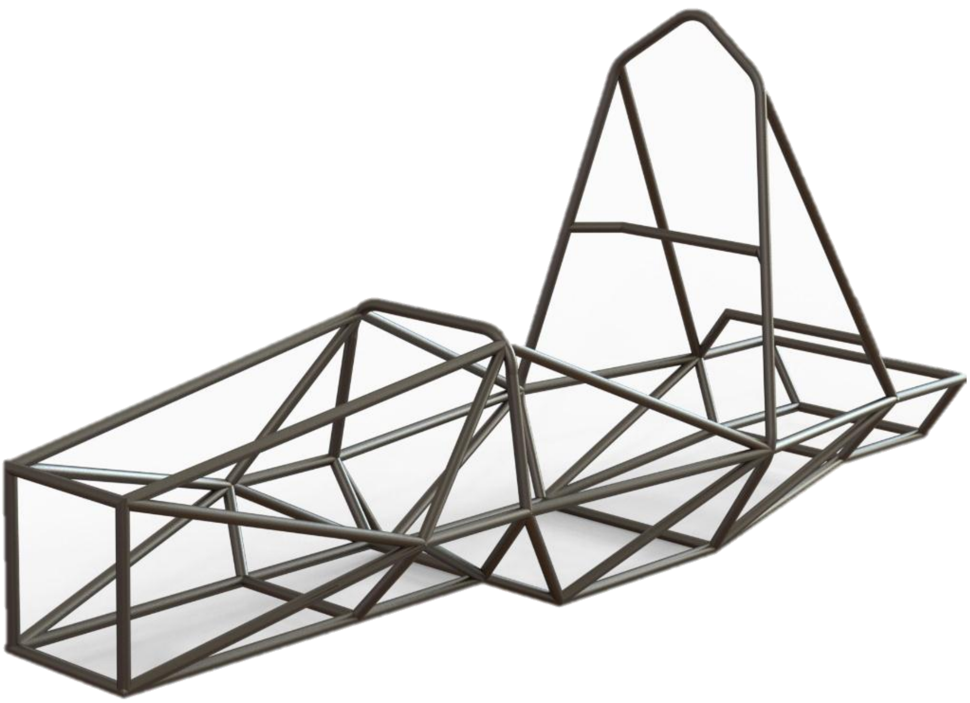

Fig. 12. Base prototype tubular chassis

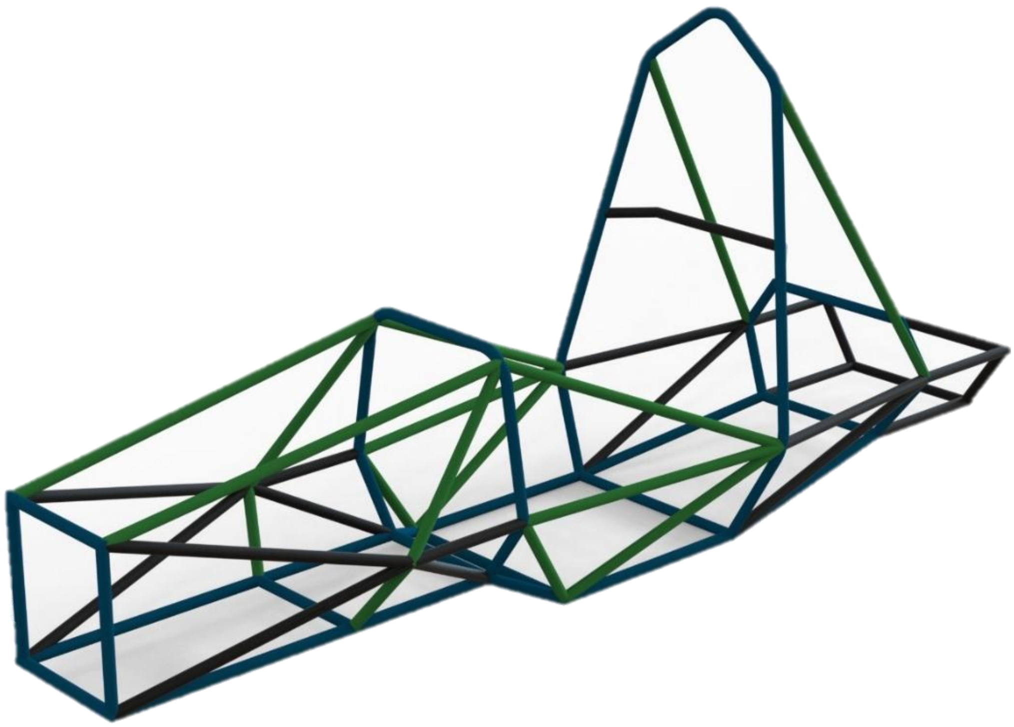

Fig. 13. Distribution of tubing used in the tubular chassis

2D Carbon Fiber Chassis Design

To make the modeling of the carbon fiber chassis in the CAD SolidWorks tool, we started by taking as a reference the 2D sketches of the protection arches of the tubular structure. After this and with the use of the surfaces tool integrated in the software, the corresponding profiles of the vehicle structure were shaped as shown in figure 14.

Finally, the cockpit was designed bearing in mind at all times the current regulations. The final modelling of the carbon fibre base chassis is shown in Figure 15.

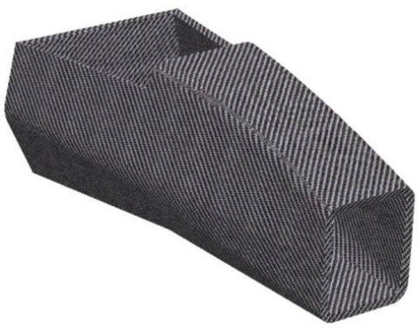

Fig. 15. *Carbon fibre chassis prototype.*

Table 2. Profiles used for different chassis sections

PROFILE DIMENSIONS	**COLOR**	**LOCATION**
25 mm x 2.5 mm	Blue	Front plan, roll bars, chassis base
25 mm x 1.65 mm	Green	Side impact zone, roll-over arch supports
25 mm x 1.2 mm	Black	Reinforcements of each roll-over arch supports, engine anchor points and suspensions

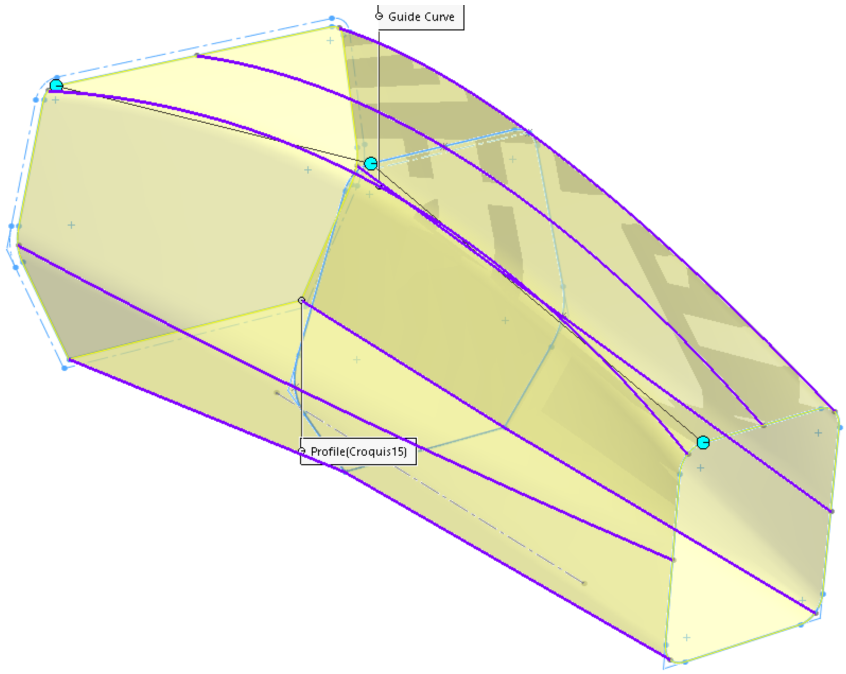

Fig. 4Carbon fibre chassis design process

4. CONCLUSION

The study and analysis of the theoretical basis behind the competition vehicles, allowed to establish and identify the structural considerations, restrictions and regulations relevant to the design and optimization of the proposed chassis.

In the design phase of the Formula SAE single seater, the ergonomics of the driver, the constraints of the suspension system and other mechanical components are the fundamental factors that allow the different sections of the chassis to be properly sized and triangulated.

The use of a mesh with beam-type elements allows obtaining very accurate results in each simulation, since this type of element determines the stresses in tension, compression, bending and torsion in a punctual way on the structural members of the chassis.

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