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Structural analysis of a chassis for a Formula SAE using finite element software

Análisis estructural de un chasis para un Fórmula SAE mediante software de elementos finitos

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Abstract

The proposal of this research was the structural analysis of a chassis for a Formula SAE by means of finite element software with the objective of analyzing the structural behavior with different materials according to the standards stipulated by the technical regulations. For this, a quantitative approach was used in which the difference between the data of design one and the other designs was evaluated, and the mechanical characteristics of the materials were determined by means of the research method. Finally, the best performing design was defined using the statistical method in which the results of the structural analysis obtained in the finite element software were presented. The results of the analysis showed that the optimum material for the structure was A500 Steel with a weight of 51.2 kg, a deformation of 0.16 mm was achieved in the belt test and a tension of 38.59 MPa. The values obtained in the simulations are compared with design 1 in its legal basis. From the simulations performed, it is determined that design 3 complies with the requirements stipulated

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by the Formula SAE regulations using materials at world, regional and national level; determining that the A500 steel considered as national material presents better performance for this type of competition.
Keywords: Finite Elements, SAE Formula Chassis, Structural Analysis, SAE Formula Standards, A500 Steel.

Resumen

La propuesta de la presente investigación fue el análisis estructural de un chasis para un Fórmula SAE mediante software de elementos finitos con el objetivo de analizar el comportamiento estructural con distintos materiales de acuerdo con las normativas que estipula el reglamento técnico. Para esto, se usó un enfoque cuantitativo en el cual se valoró la diferencia entre los datos del diseño uno y de los demás diseños, mediante el método investigativo se determinó las características mecánicas de los materiales. Finalmente se definió el diseño de mejores prestaciones mediante el método estadístico en el cual se presentó los resultados del análisis estructural obtenidos en el software de elementos finitos. Los resultados del análisis mostraron que el material óptimo para la estructura fue el Acero A500 con un peso de 51.2 kg, se logró una deformación de 0.16 mm en el ensayo de cinturones y una tensión de 38.59 MPa. Los valores obtenidos en las simulaciones son comparados con el diseño 1 en su base legal. A partir de las simulaciones realizadas se determina que el diseño 3 cumple con los requerimientos estipulados por el reglamento de Fórmula SAE usando materiales a nivel mundial, regional y nacional; determinando que el acero A500 considerado como material nacional presenta mejores prestaciones para este tipo de competición.
Palabras clave: Elementos finitos, Chasis Fórmula SAE, Análisis estructural, Normativa Fórmula SAE, Acero A500.

Introduction

Formula SAE is a worldwide competition in which universities from all over the world compete in the design and construction of a Formula SAE racing prototype. (Formula SAE - Nebrija Automobile Club, 2012).. The construction of Formula SAE single-seaters has been implemented in the area of engineering studies in educational institutions. In the country, several universities have a Formula SAE vehicle based on the design of a general chassis, however, when investigating their research work, it is concluded that there is no previous study of the structural analysis with different types of chassis based on different materials and lack of background of a design and construction. The present research was based on the Formula SAE regulations, which establishes design and construction parameters prioritizing the pilot's safety, contemplating guidelines that delimited the scope of the project, considering variables in static and dynamic conditions. Therefore, the aim is to understand from an engineering point of view the data collected from the structural analysis, being able to interpret data for the design and construction, strengthening the engineering students in undertaking the development of these projects for the automotive engineering career.

Based on the following articles, it was determined that the analysis and choice of the design, among other factors, should be optimal for this research article, considering the problems at the time of building a Formula SAE chassis.

The article "Design and static structural analysis of a race car chassis for Formula SAE event" focuses on the chassis structure, being considered as the backbone of all automotive systems dealing with static and dynamic loads therefore poor design and resistances can lead to mechanical failures. (Mohamad et al., 2017)

Research conducted by Universiti Teknologi Malaycia mentions the minimum manufacturing costs of an SAE Formula, without compromising safety and performance in manufacturing, acceleration, braking and handling. (Pal Singh, 2010)

In the article "Design and optimization of a SAE formula" it mentions the design of the frame as a complex component of the system, complying with competition standards by being light and rigid, therefore the design is a procedure that includes research, modeling, optimization and testing. (Auer et al., 2006)

The article "design and analysis of a tubular space frame chassis of a high performance race car" mentions that material selection is of great importance since chassis support different forces, must remain intact and rigid to absorb vibrations and resist high temperatures. (Kumar et al., 2014)

The research of Universite du quebec a chicoutimi mentions three constraints on the basis of chassis design which are the constraints of the SAE formula regulations, constraints of the racing teams and personal constraints. (Morel & Gilbert, 2009).

The purpose of this research is the structural analysis of a chassis for a Formula SAE by means of finite element software. As a first stage of research, the technical regulations of Formula SAE, the types of chassis and materials allowed for a first chassis design in its legal basis, then a comparison of materials and their design for construction was made, finally the chassis was designed using a simulation program which allowed to analyze safety factors, loads, deformation and efforts, thus defining the improvements in the design.

Formula SAE regulations are modified every year based on different vehicle systems, including engine, weights and loads as the sole purpose of reinforcing theoretical-practical knowledge for building a racing vehicle, as well as improving engineering, teamwork and project management skills. (Kasi V Rao et al., 2022)

There are different categories in the Formula SAE competition, in which the rules vary depending on the location and edition of the event, this will depend on the authorities of the Society of Automotive Engineers (SAE) as they organize the event.

Table 1. *Formula SAE competition categories*

Categories	Regulations
SAE Combustion Formula	Use of gasoline internal combustion engines
SAE Electric Formula	Use of electric motors and batteries
Formula SAE Autonomous	Vehicles with autonomous operation on specific parts of the runway.
SAE Formula Cost	Evaluation of the total cost of the project and vehicle maintenance.

Note. *Types of categories that exist within the Formula SAE competition, authors.*

Formula SAE Technical Regulations

It is a set of rules established by the SAE organization with the aim of typifying the entire competition ensuring the safety of competitors, some regulations are based on general rules, administrative management, document requirements, vehicle requirements, structural chassis, technical aspects, equipment, etc.. Hence in the present research the chassis design regulations are addressed. (Prasetya et al., 2020)

SAE Formula Chassis

A structural assembly that supports the functional systems of the vehicle, being single, multiple or a combination of composite and welded structures. (SAE Formula, 2023)

They are rigid and stable. There are two types, the monocoques that are integrated to the bodywork and the tubular chassis form a system different from the bodywork, designed by rectangular sections suitable for competition since they resist torsion. (Valenzuela et al., 2013).

Table 2. *Elements that compose a Formula SAE chassis.*

Element	Description of physical elements	Parameters
Tipping arches	SAE Formula Regulations article F.1.3-F.1.13.	Rollover is a factor that the driver avoids receiving.
Main arch	SAE Formula Regulation article F.5.8 appendix F.5.8.1 - (F.3.2.1.g), F.5.8.2, F.5.8.3, F.5.8.4	Piece of closed or continuous section with steel material.
Front Arch	SAE Formula Regulation article F.5.7 appendix F.5.7.1, F.5.7.2, F.5.7.3, F.5.7.4 - (F.5.9.6), F.5.7.5, F.5.7.6, F.5.7.7	It must not exceed 250 mm in front of the steering wheel.
Front impact attenuator	SAE Formula Regulation articles F.8.1, F.8.2	Anti-intrusion plate in front of the front screen area min 200x100 mm.
Node-to-node triangulation	SAE Formula Regulations Appendix F.1.17	Segments forming triangles between upper and lower limbs.

Note: See regulation pages (23, 31, 32), taken from (SAE Formula, 2023)

Loads applied to the chassis SAE Formula

They are forces and moments that act on the structure during its operation, they are classified into two types: static and dynamic. In the present research, it was studied how the structure acts, the loads are defined and the forces are analyzed in a CAD simulation. (Pons, 2016)

Table 3. *Types of loads on a chassis*

Types of Loads	Parameters	Formulas
Dead load	Total weight of chassis and mounted components: 300 kg.	$\boldsymbol{M} = Mt * g$
Live load	Rider weight and components incorporated in the chassis	$\boldsymbol{V} = Vt * g$
Braking Load	Minimum two-wheel braking.	$\boldsymbol{F} = Mt * a$
Acceleration Load	Designed on the basis of the track dimension	$\boldsymbol{Ab} = (Mt) * (-a)$
Aerodynamic drag load	They depend on the aerodynamic devices of the vehicle.	$\boldsymbol{Raf} = \frac{Cx * \rho * Af * V^2}{2}$

Note: Loads applied to the chassis, Authors.

Impact loads

Acting on the chassis during a collision, it is subjected to different tests to evaluate the capacity to withstand impacts, safety level, behavior in rollover conditions and to determine which deformation zones are controlled or not. (Valenzuela et al., 2013)..

Table 4. *Impact loads.*

Front	Lateral	Superior
Formula SAE Regulations article F.8.6 - F.8.7.	Formula SAE Regulations articles F.6.4 to F.6.6.	Formula SAE Regulation article F.6.4 appendix F.6.4.4 to F.6.4.6.

Note: See regulation pages (37, 43, 44), taken from (SAE Formula, 2023)

Design requirements

There are specific guidelines for proper chassis analysis taking into account that it is performed by students.(Saplinova et al., 2020).. The following are the requirements.

Structure

Steel tubes, alternative or composite according to the regulations, will be built by triangulation for better strength, material efficiency and minimize deformation, incorporating all vehicle systems. (SAE Formula, 2023)

Material

Materials have properties such as density, hardness, elasticity, mechanical strength. Therefore they present a key criterion for chassis design. (Mohammed et al., 2018).

Table 5. *Characteristics of the materials*

Material	Technical data	Features
Steel	SAE Formula Regulations F.3.4 Appendix F.3.4.1	Young's modulus (E): 200 GPa or 29,000 ksi Yield strength (Sy) = 305 Mpa or 44.2 ksi Ultimate Strength (Su) = 365 Mpa or 52.9 ksi Welded structures discontinuous materials are: Yield strength (Sy):180 Mpa or 26 ksi Maximum resistance (Su): 300 Mpa or 43,5 ksi
Aluminum	SAE Formula Regulations article F.3.5 appendix F.3.5.3	Aluminum calculations with non-welded properties: Young's modulus (E): 69 GPa or 10,000 ksi Yield strength (Sy) = 240 Mpa or 34.8 ksi Ultimate Strength (Su) = 290 Mpa or 42,1 ksi Aluminum calculations with welded properties: Yield strength (Sy):115 Mpa or 16.7 ksi Maximum resistance (Su): 175 Mpa or 25,4 ksi

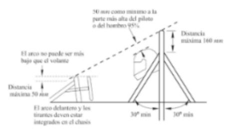
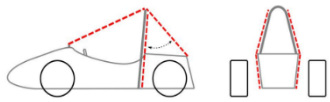
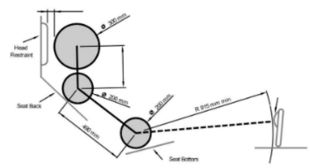
Note: Taken from (SAE Formula, 2023)

Design arches

This structure protects the pilot in case of an accident, known as roll cages, its design is important since it is integrated into the chassis structure closing the area where the pilot is, guaranteeing his safety while driving. (Valenzuela et al., 2013).

Table 6 shows the types of bows on the chassis: safety, main and front bows. The function of the roll bar is to provide protection to the rider in case of rollover or side impact. The main arch contributes to the rigidity of the chassis because it is connected to the other arches and is designed to resist deformation and protect the rider. The front arch provides protection to the rider in case of a frontal impact, it distributes the impact energy along the structure. (Valenzuela et al., 2013).

Table 6. *Chassis bows*

The wheelbase of a Formula SAE vehicle is 1525 mm.		
Safety arches	There should be 50 mm of space between the top of the hull and the tangent generated from the main arch to the front arch.	
Main arch	It should form a triangulation against the front arch and the back of the main with an inclination of 30° in side view. Having a distance of 50 mm will be a space with the pilot's head.	
Front arch	**Upper circle:** 300 mm will have a distance up to 25 mm from the headrest. **Central circle:** 200 mm, representing the pilot's shoulders, to be placed on the seat. **Lower circle:** 200 mm, distance between the center of the circle and the rear face of the pedals, 915 mm.	

Note: See regulation pages (32, 33), taken **from** (SAE Formula, 2023)

Virtual design

It is important to analyze the type of material and identify which are the live loads, dead loads, maximum deflection, elastic or plastic point of the material and restrictions during the analysis.

Table 7. *Mathematical models of the design tests*

Design testing	Specifications	Mathematical model
Weight distribution	Within the structure the weight distribution indicates the way the masses are distributed.	$b = \frac{w_f * l}{w}$
Torsional analysis	It determines the behavior of the vehicle on the track, in order to improve the rigidity and structure of the chassis.	$T = F.L$
Longitudinal acceleration	Refers to the change in velocity along the trajectory, in a straight line.	$a = \frac{\Delta v}{\Delta t}$
Lateral acceleration	Change of vehicle speed in perpendicular direction, generally in curves.	$a_y = \frac{v^2}{R}$
Bending stress	It allows understanding the behavior of structures subjected to bending loads.	$\sigma_f = \frac{3FL}{2bd^2}$

Note. SAE Formula design test specifications, authors.

Welding

Fusion of grains produced by heating materials, welding is the joining of materials at high temperatures that produces a softening of the element, there are different types of welding. (Larry, 2009). Among them are:

Table 8. *Types of Welding*

Welding	Feature	Operating data	Material
Smaw	Generated by direct or alternating electric arc. (Flores, n.d.)	20-40 V 110-220 A	Steel, cast iron, aluminum.
Mig- Mag	Semiautomatic, by means of a manual gun, continuously fed (Uribe, n.d.)	26-30 V 150-350 A	Stainless steel, aluminum.
Tig	Use the electric arc, skip the tungsten electrode. (Larry, 2010)	15-25 V 60 -120 A	Steel, aluminum, other alloys.

Note: Operating characteristics of the welding types, Authors

Methodology

The type of method that was used in the present research has a quantitative approach, which means that the difference that exists between the structural data of the designs was numerically assessed, the type of study that was used is deductive this means that through the interpretation of results the appropriate material was identified and it was determined if the results are favorable in the other designs and compared with what is stipulated in the SAE Formula regulation. (Aneta & Jerzy, 2013)

In the first stage, using the bibliographic method, the technical regulations of Formula SAE were approached, covering the basic design of the chassis and the types of materials established by the regulations, defining the basis for the present study. (Guimaraes et al., 2016)

In a second stage, through a research study, the mechanical properties of the materials that are determinant to analyze the structure and that are admitted within the SAE Formula regulations are detailed.

Finally, the design of the chassis was determined by means of software, using the statistical method to determine the design that presented the best performance for the competition and that complied with the structural regulations and thus validate the design.

As a guide for the design of the structure, the regulations are fundamental to establish the parameters and standards of the chassis to be proposed, the weights, distances and types of materials required as shown in the following table.

Table 9. *Design parameters of the structure of a SAE Formula.*

Chassis	Request
Wheelbase	1704 mm
Front wheelbase	1159 mm
Rear wheelbase	1057 mm
Main structure	Tubular steel, mild or alloy min. 0.1% C.
Marco	Must include "Main Hoop" and "Front Hoop".
Length	2050 mm
Pilot weight	75 kg
Chassis weight	42 kg
Engine weight	58 kg
Other elements	97 kg
Total vehicle weight	300 kg

Note: Specifications for chassis design, taken from (SAE Formula, 2023)

Design

The Formula SAE chassis is a safe and robust structure designed to provide and ensure chassis rigidity and rider safety in rollover conditions. The central part of the structure features a Main Hoop, located next to or behind the rider's torso, a Front Hoop located above the rider's legs. These elements form the Roll Hoops and the reinforcements and supports that are added to the chassis form the primary structure. The chassis features a side impact structure, a front bulkhead called Front Bulkhead, and a support system. All the members that make up the chassis are designed in a continuous, non-cutting manner while maintaining structural cohesion to meet Formula SAE safety standards and regulations. This ensures that the chassis provides efficiency and safety for all vehicle systems.

Table 10. Design parameters

Application part	Outside diameter and thickness
Main arch, front, shoulder harness mounting bar.	25.4mm x 2.4mm or 25.0mm x 2.50mm
Side impact structure, accumulator protection	25.4mm x 1.65mm or 25.0mm x 25.0mm x 1.20mm
Front plane support, main arch reinforcements.	25.4mm x 1.20mm 25.0mm x 1.5mm
Bent upper side impact limb.	35.0mm x 1.2mm

Note: Specific parameters for the chassis parts, taken from (SAE Formula, 2023)

It is verified where it is possible to change the material in the structural parts that are within the regulation and see how it influences the analysis.

The material allowed by the regulations is carbon steel, however, other materials will be taken into account, aspects for their selection were verified one of them is the union of the chosen materials, as a first stage this article proposes a base structure, as a second stage in the design and with the use of other materials different analyses will be performed on the chassis. (Sanborn et al., 2017)

The following materials were selected due to their availability and the physical properties required according to the technical regulations. The regulation specifies that the materials will have a minimum of 0.1% carbon, this steel meets the requirement considering it for the design. AISI 1010 steel is used in the construction of SAE Formula vehicles as it meets all the requirements specified in the regulation. (SAE Formula, 2023)

Table 11. *Properties of the types of materials*

Physical properties	ASTM A36 steel	Aluminum 6061	ASTM A572 steel	ASTM A500 steel	AISI 1010 steel
Young's modulus [GPa].	200	68-70	200	200	200
Poisson's ratio	0.26-0.28	0.33-0.35	0.28-0.30		
Density [g/cm3].	7.85	2.70	7.85		
Shear modulus [GPa].	50	25-30	77		
Elastic limit [MPa].	250	40-280	290-450	290	305
Maximum tensile strength [MPa].	400-550		450-650	400	365
Thermal conductivity [W/m-K].	25-45	237	25-45		
Specific heat [J/g-°C].	0.473	0.897	0.465		
Coefficient of thermal expansion [µm/m-°C].	11*10-6	23*10-6	10.8		

Note: Selection of materials at national, regional and global levels, Taken from. (Romero, 2019)

Table 12. *Composition of materials*

Material composition	ASTM A36 steel	Aluminum 6061	ASTM A572 steel	ASTM A500 steel	AISI 1010 steel
Carbon (C)	0.26%	-	0.23%	0.26%	0.13%
Manganese (Mn)	0.90%	0.15%	0.6%	1.35%	0.60%
Phosphorus (P)	0.04%	0.05%	0.04%	0.04%	0.040%
Sulfur(S)	0.05%	0.05%	0.045%	0.05%	0.050%

Note: Authors.

There are two types of joints within the category, the first type is welding and must be subject to a standard such as American Welding Society (AWS). The second type is bolted joints which must be subject to standards such as SAE grade 5 or AN/MS specifications as stated in T.8.1 to T.8.4.

Table 13. *Bolted joints specifications*

Components	Specifications
Primary structure	Sae formula regulation article F5.4.1-F5.4.3
Butt seals	Sae Formula Regulation article F5.12.7
straps	Sae Formula Regulation Article 5.13.1
Front screens	Sae formula regulations F.8.2.3
Impact attenuator	Sae Formula Regulation F.8.5.5

Note: Gasket specifications for each chassis component, (SAE Formula, 2023)

A finite element software is chosen to analyze the behavior of the chassis, due to its versatility and its wide testing capacity required in this project, allowing to evaluate, optimize designs and understand its behavior under different loading conditions. (Engineering Simulation Software, 2024)

Table 14. *Software features*

Capabilities	Inconveniences
Breadth of analysis capabilities for designs.	It is not open source.
Coupled simulations for different physical phenomena	Learning curve
Best graphical interface	Complex licensing
Broad industry adoption	Significant computational resources.

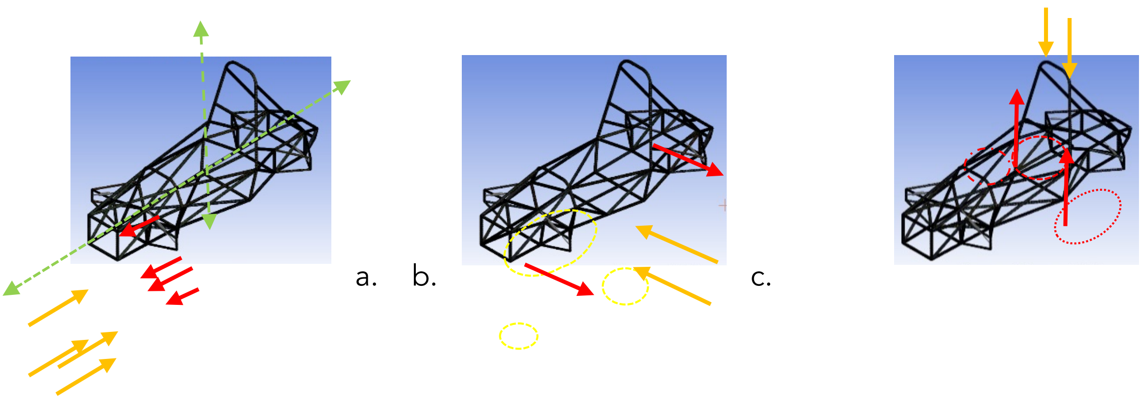
Note: Description of software capabilities and drawbacks, taken from. (Engineering Simulation Software, 2024)

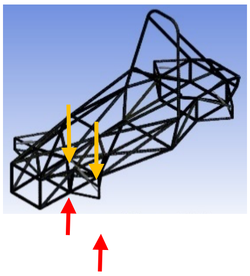
Results

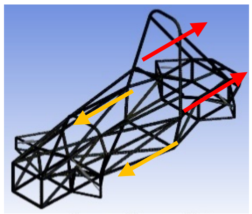
For the proposed design of the chassis structure of this study, the Formula SAE regulations were taken into account under the 5 structural analysis conditions: front, rear, side, main arch, front and seat belt anchorage, establishing the maximum forces and deformations that the chassis will have in the simulations. Each simulation was carried out with the purpose of verifying which material presents the best performance for the competition, taking into account the joints that best adapt to the design. With the input data, the third objective of analyzing the safety factor, deformation and bending of each design is fulfilled.

Three chassis proposals were presented which vary geometries and materials while maintaining the pipe sizes in order to reduce deformations, optimize stiffness and bending strength. The cross sections vary to adapt to the chassis loads, thus each proposal has its differences that significantly influence the performance and behavior on the track.

***Figure 1**. Analysis of forces applied to the chassis.*







Note: a) DCL I. front, b) DCL I. side, c) DCL A. main; d) DCL A. front e) DCL A. belts; The loads applied on the chassis (yellow) and the reactions (red) are observed.

Table 15. *Parameters for design analysis*

Structural analysis	Loads (kN)			Point of application	Max. allowable deflection (mm)	Breakage
	Fx	Fy	Fz			
Frontal impact	120	0	0	Connection points	25	no breakage
Side impact	0	7	0	Front and main arch	25	no breakage
Main arch	6	5	-9	Upper front arch	25	no breakage
Front arch	6	5	-9	Upper front arch	25	no breakage
Seat belt anchorage	7	7	7	Two points simultaneously	25	no breakage

Note: Description of the points of application for the respective analysis and deformation, Authors.

Table 15 describes the loads in the 3 axes used in the analysis of the structure and the points of application. According to the SAE Formula regulation, the deformation should not exceed 25 mm.

Table 16 specifies the selection of the following materials: ASTM A500 steel, aluminum 6061 and AISI 1010 steel, calling them national, regional and global materials, respectively. It specifies the values of importance by compliance for the selection of the material, with a range of high, medium and low for the importance, for the compliance its values are good, regular and bad, according to this a multiplication was made between the needs and the importance as shown in Table 17.

Table 16. *Importance x Compliance*

Importance	Value	Compliance	Value
High	3	Good	3
Media	2	Regular	2
Download	1	Malo	1

Note*:* Table of levels of importance and compliance, authors.

Table 17 shows that AISI 1010 steel is the most suitable for the structure since it presents better results in terms of fabrication, impact resistance and weight; however, certain requirements such as cost are high and accessibility in the locality is complex, unlike ASTM A500 and Aluminum 6061, which present better results in these aspects.

Table 16 specifies the parameters and values of importance x compliance, the same principle was used to select the most suitable weld for the structure, taking into account the needs described below.

Table 17. *Types of welding*

Needs	Importance	Compliance			Results		
		ASTM A500	Aluminum 6061	AISI 1010	ASTM A500	Aluminum 6061	AISI 1010
Manufacturing	3	2	2	3	6	6	9
Cost	2	2	2	1	4	4	2
Impact resistance	3	2	2	3	6	6	9
Accessibility	3	3	2	1	9	6	3
Weight	2	2	3	2	4	6	4
				Total	29	28	27

Note: Requirements for the choice of the type of welding, authors.

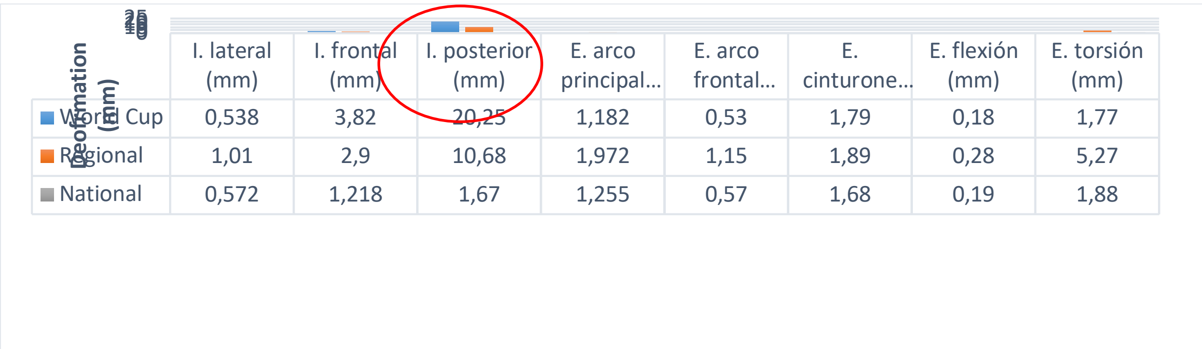
MIG welding was selected because it produces high quality joints with characteristics such as 66% impact resistance and 100% accessibility, while TIG welding has a high cost value. SMAW welding is 33% less efficient due to the excess slag it emits, which makes MIG welding more suitable.

The design takes into account the types of materials such as: national (ASTM A500), regional (ASTM A572, Aluminum 6061) and worldwide (AISI 1010), characteristics of the piping. The results obtained from the analysis of each chassis are presented below.

Design 1

The design is divided into 3 sections specifying the diameter and thickness of the material, the first section being 25.5 x 2.6 mm, the second 25.5 x 1.9 mm and the third 25.5 x 1.5 mm. With the established data, the analyses described below were developed.

Figure 2. Structural analysis

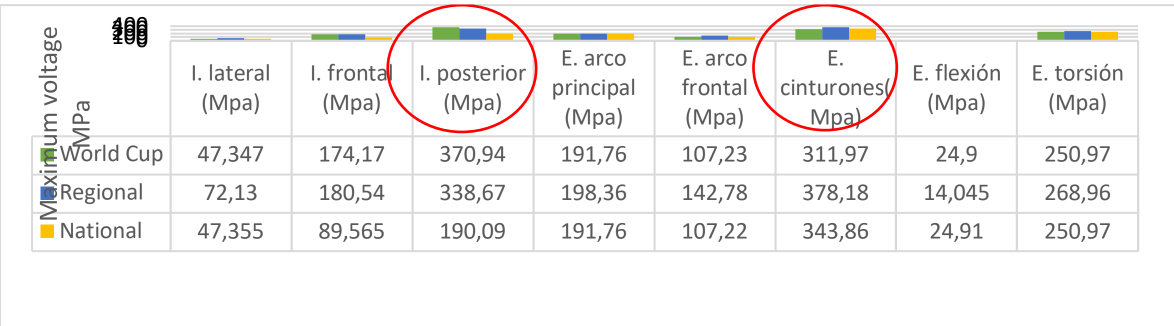


	I. lateral (mm)	I. frontal (mm)	I. posterior (mm)	E. arco principal...	E. arco frontal...	E. cinturone...	E. flexión (mm)	E. torsión (mm)
World Cup	0,538	3,82	20,25	1,182	0,53	1,79	0,18	1,77
Regional	1,01	2,9	10,68	1,972	1,15	1,89	0,28	5,27
National	0,572	1,218	1,67	1,255	0,57	1,68	0,19	1,88

Note: Results of finite element structural analysis, authors.

With the world material, the structure weighs 51.29 kg. When observing Fig. 1, we obtain results that do not exceed 25 mm of deformation. The posterior impact has a value of 20.25 mm compared to the analysis with the regional and national material which have a reduction of 38.56% and 74.32% respectively, establishing the national material as the one with the best performance.

Figure 3. Peak stress analysis.



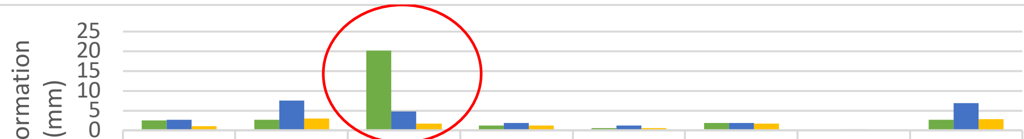
	I. lateral (Mpa)	I. frontal (Mpa)	I. posterior (Mpa)	E. arco principal (Mpa)	E. arco frontal (Mpa)	E. cinturones(Mpa)	E. flexión (Mpa)	E. torsión (Mpa)
World Cup	47,347	174,17	370,94	191,76	107,23	311,97	24,9	250,97
Regional	72,13	180,54	338,67	198,36	142,78	378,18	14,045	268,96
National	47,355	89,565	190,09	191,76	107,22	343,86	24,91	250,97

Note: Results of stress analysis, authors.

Fig.3 shows the obtained values of the stress, based on this the elastic limit of the material was determined, in the subsequent impact analysis it presents values higher than 365 MPa so the world material presents a high stress than the one allowed in the regulations, the belt test with the regional material has a value of 378 MPa exceeding the allowed, which led us to make another design.

We modified parts of the structure focused on improving the rear impact analysis and belts, varying the lateral triangulation, disappearing the upper cross bar and the lower bar generating a support triangle that goes from the mid-section of the front arch to the main arch. And to verify if the change in design philosophy is on the right track.

Figure 4 *Structural analysis design 2*

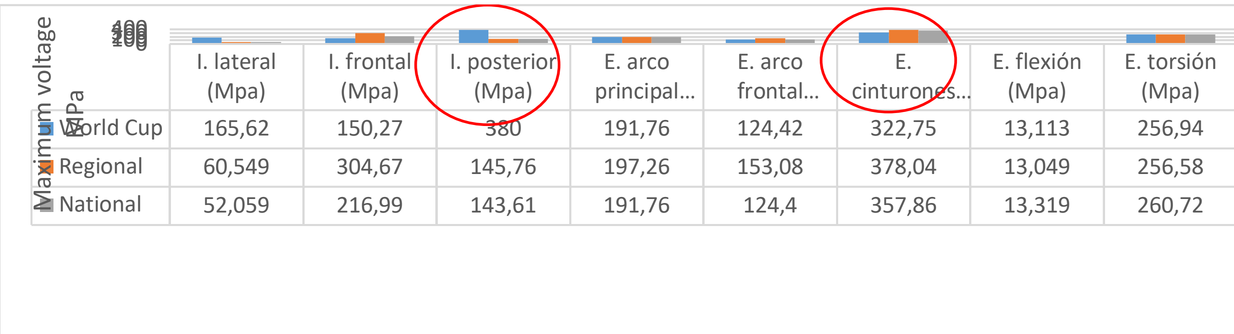


	I. lateral (mm)	I. frontal (mm)	I. posterior (mm)	E. arco principal (mm)	E. arco frontal (mm)	E. cinturon es(mm)	E. flexión (mm)	E. torsión (mm)
World Cup	2,464	2,65	20,11	1,182	0,55	1,79	0,1	2,62
Regional	2,625	7,53	4,85	1,874	1,146	1,88	0,3	6,84
National	1,069	2,92	1,62	1,255	0,594	1,68	0,11	2,78

Note: Results of finite element structural analysis, authors.

With a weight of 46.11 kg, Fig. 3 shows the deformation of the posterior impact with the regional material, which is 4.85 mm, obtaining an improvement in the structure. With the global and national material their variation of values is minimal, so the regional material presents better performance, taking into account the stresses these do not favor the other analyses so another design is required.

Figure 5. *Maximum design stress analysis 2*



	I. lateral (Mpa)	I. frontal (Mpa)	I. posterior (Mpa)	E. arco principal...	E. arco frontal...	E. cinturones...	E. flexión (Mpa)	E. torsión (Mpa)
World Cup	165,62	150,27	380	191,76	124,42	322,75	13,113	256,94
Regional	60,549	304,67	145,76	197,26	153,08	378,04	13,049	256,58
National	52,059	216,99	143,61	191,76	124,4	357,86	13,319	260,72

Note: Results of stress analysis, authors.

In Fig.5 in the post impact analysis with the world material presents a value of 380 MPa, with the regional and national materials the stress decreases. In the belt test with the regional material its value is 378 Mpa similar to design 1, with the other materials the results increase, there is a deficit in the triangulations of the structure so it is required to design the chassis focusing on all areas of the design.

Different characteristics of the previous designs were taken into account, focusing on all areas of the structure. The world material shows a high deformation in the impact analysis, however, with the other materials the value of this analysis is low, thus determining that the new geometry of the chassis is resistant and presents better safety than the previous designs.

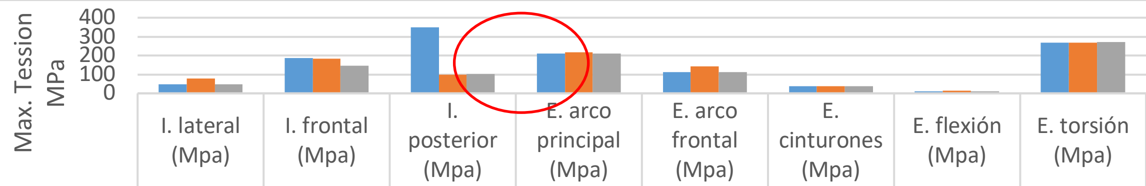
Figure 6. Structural analysis design 3

World Cup	0,8	3,843	21,56	1,307	0,53	0,15	0,09	1,77
Regional	1,11	2,88	2,89	2,07	1,15	0,16	0,28	5,27
National	0,85	0,941	2,81	1,417	0,57	0,16	0,09	1,88

Note: Results of finite element structural analysis, authors.

The weight presented by design 3 is 51.2 kg, in the subsequent impact analysis with the world material, it is 1 mm higher than design 2, which is within the established norms, with the regional material it was possible to reduce 2 mm and for the national material this result was 1 mm higher. In the belt test with the 3 materials, a reduction of approximately 1 mm was obtained, improving in these aspects.

Figure 7. Maximum design stress analysis 3.



	I. lateral (Mpa)	I. frontal (Mpa)	I. posterior (Mpa)	E. arco principal (Mpa)	E. arco frontal (Mpa)	E. cinturones (Mpa)	E. flexión (Mpa)	E. torsión (Mpa)
World Cup	47,86	188,04	348,87	209	113,3	38,585	12,012	266,36
Regional	77,503	184,32	97,97	218,15	142,83	38,59	14,028	268,96
National	47,868	145,99	102,56	209	113,29	38,59	12,005	270,46

Note: Results of stress analysis, authors.

The stress analysis focused on the improvement of the rear impact, obtaining a result of 348.87 MPa with the world material and with the other materials it was significantly reduced. For the belt test, the maximum tension with the 3 materials is around 38 MPa, unlike the previous designs, this result improves significantly. The safety factor must be taken into account for the analysis, taking into account the subsequent impact analysis, the safety factor calculation is performed:

$$FS = \frac{Tensión\ de\ Fluencia}{Tensión\ Máxima\ en\ el\ chasis}$$

$$FS = \frac{290\ MPa}{102{,}56\ MPa}$$

$$FS = 2{,}82$$

Conclusions

Addressing the technical regulations of Formula SAE, the technical regulations regarding design and manufacturing were analyzed, identifying the types of chassis allowed, the appropriate materials, and the specific construction and safety requirements, such as an approximate Young's modulus of 200 GPa with a maximum resistance of 360 Mpa in order to develop a chassis that meets the standards of the competition, optimizing both the performance and safety of the vehicle within the available resources. These resources are not available at the national level; therefore, considering these characteristics, we opted for national materials with physical characteristics similar to those stipulated by the regulations.

Based on the second objective and the calculations of importance for compliance, AISI 1010 steel was defined as the one with the best performance for manufacturing with a disadvantage in the high costs approximately (13.68 € x tube) and low level of accessibility at national level. A500 steel enters as a suitable material due to its similar performance, low cost and national feasibility. Considering this material and based on the AWS standard, MIG welding was selected as the suitable joint since it presented high impact resistance, low cost and more accessible compared to TIG welding which presented similar characteristics, but with the disadvantage that at national level it is less accessible while SMAW welding presented a greater weight for the structure and therefore it was not feasible.

In the design 3 of the chassis, important results were considered based on the analyses carried out with the selected materials, a minimum safety factor of 2.82, which is within the established safety standards for the pilot. The maximum resistance of the A500 steel is 8.75% higher than the characteristics of the AISI 1010 steel. The maximum deformation values are below 25 mm as specified by the regulations, thus guaranteeing functionality, obtaining a maximum deformation of 21.56 mm in the post impact analysis and a minimum deformation of 0.09 mm in the bending test with the world material, with the national material presenting a maximum and minimum deformation of 2.81 and 0.09 respectively. Therefore, design 3 presents favorable results with the A500 steel considering the national material suitable for the Formula SAE competition.

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