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Article

Experimental proposal of a 'HALO'-type security device in a FORMULA SAE 2024 type vehicle

Propuesta experimental de dispositivo de seguridad tipo 'HALO' en un vehículo de tipo FORMULA SAE 2024

Noguez-Jimenez, Víctor Manuel[a], Cordero-Guridi, José de Jesús[b], Peréz-Carrillo, Daniel[c] and García-Tépox, José Domingo[d]

[a] Universidad Popular Autónoma del Estado de Puebla • 0009-0009-6354-4789
[b] Universidad Popular Autónoma del Estado de Puebla • 0000-0001-5201-1906
[c] Universidad Popular Autónoma del Estado de Puebla • 0009-0000-3902-9546
[d] Universidad Popular Autónoma del Estado de Puebla • 0000-0001-7030-7735

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* ✉ [josejesus.cordero@upaep.mx]

Abstract

This study conducts a numerical and experimental analysis of the use of a "Halo" device, inspired by Formula 1, within the Formula SAE competition. Several alternatives were developed to meet the regulatory requirements of Formula SAE, and the selected proposal was modeled in CATIA V5 using both surface and solid modeling techniques. The model underwent a structural analysis similar to the "Quasi-static Test 1" used for the Formula 1 "Halo," utilizing ANSYS Workbench 2023 R2 for finite element analysis (FEA). Additionally, physical tests were carried out to validate and compare the virtual results, with the aim of assessing the relevance and benefits of this safety device.

Objectives

Develop and validate a 'HALO' safety device for a Formula SAE 2023 vehicle through structural analysis and physical testing.

Methodology

The 'HALO' device will be designed, its resistance will be validated through FEA analysis, and physical tests will be conducted to verify its performance.

Contribution

Procedure for Development, Analysis, and Physical Evaluation for FSA-Type Cars

Formula SAE, ANSYS, CATIA, FEA, SAFETY DEVICE, HALO

Resumen

Este estudio analiza numérica y experimentalmente el uso de un dispositivo tipo "Halo", inspirado en Fórmula 1, dentro del contexto de la competencia Fórmula SAE. Se desarrollaron diversas alternativas para cumplir con los requisitos regulatorios de la Fórmula SAE, y la propuesta seleccionada fue modelada en CATIA V5 utilizando técnicas de modelado de superficies y sólidos. El modelo fue sometido a un análisis estructural similar al "Quasi-static Test 1" del "Halo" de Fórmula 1, empleando el software de análisis por elementos finitos (FEA) ANSYS Workbench 2023 R2. Además, se realizaron pruebas físicas para validar y comparar los resultados virtuales, con el objetivo de evaluar la relevancia y beneficios de este dispositivo de seguridad..

Objetivos

Desarrollar y validar un dispositivo de seguridad tipo 'HALO' para un vehículo Fórmula SAE 2023 mediante análisis estructural y pruebas físicas.

Metodología

Se diseñará el dispositivo 'HALO', se validará su resistencia con análisis FEA y se realizarán pruebas físicas para verificar su desempeño.

Contribución

Procedimiento de desarrollo, análisis y evaluación física para automóviles tipo FSA.

Formula SAE, ANSYS, CATIA, FEA, SEGURIDAD, HALO

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Introduction

The Formula SAE competition, organised by the Society of Automotive Engineers (SAE), represents a unique challenge for engineering students to design, build and race vehicles that demonstrate and apply knowledge in a practical and safe environment. This event encompasses tests such as acceleration, skidpad, autocross, endurance and efficiency, and not only encourages innovation and creativity, but also emphasises safety as a fundamental aspect of automotive design. Within the framework of the competition, a rigorous set of rules and regulations governs the requirements for team participation. These regulations, designed to ensure both the functionality and safety of the vehicles during the various tests, emphasise the importance of the vehicle structure as a key element for the integrity of the car and the protection of the driver. [5] In this context, a proposal arose to use a Halo-type device, similar to that used on Formula 1 cars, as an additional safety measure for Formula SAE vehicles. To validate this proposal, a Quasi-static 1 test was carried out on an A36 steel structure. Complemented with the finite element analysis (FEA) performed in ANSYS Workbench 2023 software and a visualisation analysis with dummy in CATIA V5 software to validate the visual section requested by the student competition regulations. [1, 5]

Statistics from organisations such as the World Health Organization (WHO) and the Insurance Institute for Highway Safety (IIHS) highlight the importance of improving vehicle safety, reporting in their 2021 fatality statistics that there were 10,229 fatalities due to frontal crashes or rollovers. At racing events, where the risk of accidents is inherent, it is vital to prioritise the safety of participants. [3]

To assess the safety of the Halo device in terms of head injury protection, the Head Injury Criterion (HIC) is used. The HIC is a measure used in biomechanics to determine the probability of an impact causing a serious head injury. This metric is calculated using the acceleration recorded during an impact and provides an estimate of the risk of injury as a function of the duration and magnitude of the acceleration. In this project, simulations were performed to calculate the HIC and evaluate how the "Halo" device influences the reduction of injury risk in the event of a crash [6].

Finite Element Analysis (FEA) focuses on understanding how the Halo device affects the vehicle structure and ultimately the protection of the driver. This study uses numerical methods to break a complex object into small elements in order to model its behaviour, evaluating each element individually to gain a detailed view of the system's response under various conditions.

Project approach

The main objective of the project is to improve driver safety in Formula SAE competition through the implementation of a safety device known as the "Halo", endorsed by the Fédération Internationale de l'Automobile (FIA). The "Halo" is a titanium arch designed to surround the cockpit of the car, providing an additional physical barrier to protect the driver's head. [9, 7].

Box 1

Figure 1
Demonstration image of the Halo device used in F1

Source: FIA STANDARD 8869-2018

The implementation of this device is based on fundamental reasons centred on rider safety, addressing two critical aspects:

1. rider head protection: the Halo was specifically designed to protect the rider's head, acting as a physical barrier that reduces the risk of injury caused by large objects, such as parts of other vehicles. [9]

2. Rollover Risk: The Halo is also designed to prevent injury to the rider's head by providing a solid structure that prevents direct contact of the vehicle with the rider's helmet in the event of a rollover. [9]

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Planning

Develop a driver protection system (Halo) for the Formula SAE vehicle, complying with competition safety standards.

Box 2

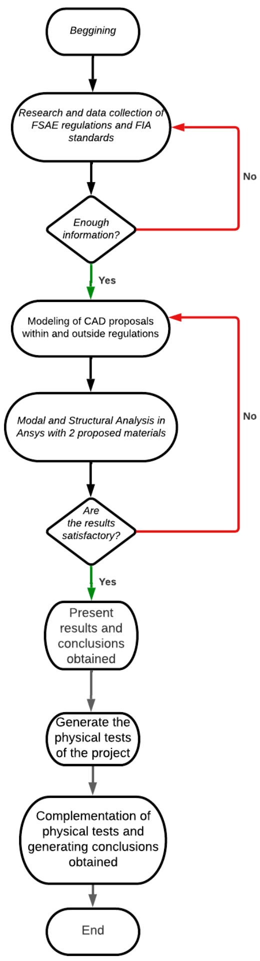

Figure 2
Method used in the development of the project.

Source: Own elaboration

Part I: Planning and Design

- Investigation of security requirements.
- Defining objectives and design criteria.
- Creating the design plan and assigning roles.

Part II: Development and Prototyping

- Creation of CAD models of the prototype.
- Strength testing and preliminary adjustments.

Part III: Implementation and Validation

- Procurement of materials.
- Integration of the Halo into the vehicle.
- Final functional, safety and endurance testing.
- Validation of compliance with standards.

Constraints, Risks and Assumptions

With the above approach it is expected that our research will be limited by various situations, such as: the material on which it is planned to print in the final stage of the project, failures in the study machines, poor execution of the tests made to the prototype. It is also taken into account that we have an important restriction where we are restricted to use only the materials that the school has, which in this case is Onyx or Resin V5 [B].

Benchmarking

In the study of Head Injury Analysis of Vehicle Occupant in Frontal Crash Simulation: Case Study of ITB's Formula SAE Race Car, a study was carried out to analyse the effect of speed on the impact of a Formula SAE type vehicle, where it was found that for speeds of less than 40 km/h the attenuator requested by the regulations may be sufficient to avoid generating a major trauma, based on the HIC scale, as values of less than 700 safe values are produced. However, once the speed exceeds 43 km/h these values are higher as the G forces experienced are greater than 140 G 's, at this point the probability of a skull fracture increases to 5% [6].

Box 3

Table 1
Table of accidents by type of accident and type of vehicle

Passenger deaths per vehicle in all accidents by point of impact and type of vehicle in 2021								
Initial point of impact	Car		Pickup		SUV		All	
	Number	%	Number	%	Number	%	Number	%
Frontal	8742	59	2891	60	3892	59	15742	59
Side	3662	25	843	17	1258	19	5824	22
Rear	853	6	181	4	369	6	1423	8
Other (rollover)	1487	10	940	19	1117	17	2596	14
Total	14744	100	4855	100	6636	100	26555	100

Source: NHTSA and the IIHS

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The project proposes the implementation of a "Halo" type safety device for Formula SAE competition vehicles, inspired by the model used in Formula 1, with the aim of improving driver protection in situations of head-on collisions and rollovers, which according to Fatality Facts 2021 - Passenger vehicle occupants statistics, account for almost 10,300 fatalities. It focuses on adapting this professional technology to a school environment, taking into account the specific constraints and requirements of competition. [3]

Box 4

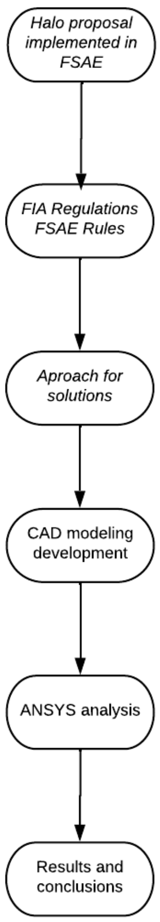

Figure 3
Method used for the development of the project

Source: *Own elaboration*

The method followed for the development of the project is noted. As such, the scope of the project was considered experimental, recognising that the proposed modifications may affect compliance with certain sections of the Formula SAE regulations, particularly sections F.1.13 and F.5.6.3, which refer to vehicle geometry.

Reference is made to FIA STANDARD 8869-2018, which sets out the design requirements for Additional Frontal Protection (AFP) systems on open cockpit vehicles, ensuring that the Halo device is designed and fitted in accordance with the criteria defined in that standard. In addition, the project must comply with the specific Formula SAE regulations, including aspects such as cockpit dimensions (section T1), the position of the main hoop and front hoop of the chassis (F.5.6), and the protection of the steering system (F.5.14). Structural integrity, dictated by the triangulation of elements (F.3.2.1), is essential to meet these stringent standards. [5]

To assess the strength of the Halo device, a Quasi Static Test 1 similar to that used in Formula 1 is performed. It is important to take up the scope of this project as the Halo device used in an F1 car is a professional grade device, in this case being a school project we consider a maximum deformation tolerance higher than that of the tests of a real Halo device, which is 45 mm where we double the value over the aforementioned, given that the value given by FIA justifying that this is subjected to an average speed of a Formula 1 car, which is 264 km/h in the fastest circuits and 167 km/h in the slowest ones, otherwise in a Formula SAE the speeds are much lower, generally limited to 80 km/h, thus resulting in a maximum allowed deformation of 90 mm. [1, 8, 10].

Box 5

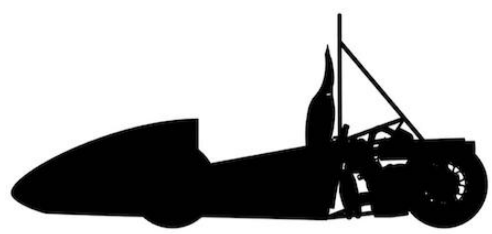

Figure 4
Representative image of a Formula SAE type vehicle.

Source: Own elaboration

The use of A36 steel is proposed for the structure of the "Halo", evaluating its performance under the specific conditions of the competition. The design process can be divided into 2 main stages, starting with the research and data collection of the FSAE regulations and the FIA (Halo) standard, where the following design constraints are highlighted. [5]

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Box 6

F.5.6 **Roll Hoops**

F.5.6.1 The Chassis must include both a Main Hoop and a Front Hoop.

F.5.6.2 The Main Hoop and Front Hoop must be Triangulated into the Primary Structure with structural tubing.

The Triangulation must be at a node in side view for:

a. Bends in side view

b. Bends in front view below the Upper Side Impact Structure F.6.4, F.7.5

F.5.6.3 Roll Hoop and Driver Position

When seated normally and restrained by the Driver Restraint System, the helmet of a 95th percentile male (see V.2.1.1) and all of the team's drivers must:

a. Be a minimum of 50 mm from the straight line drawn from the top of the Main Hoop to the top of the Front Hoop.

b. Be a minimum of 50 mm from the straight line drawn from the top of the Main Hoop to the lower end of the Main Hoop Bracing if the bracing extends rearwards.

c. Be no further rearwards than the rear surface of the Main Hoop if the Main Hoop Bracing extends forwards.

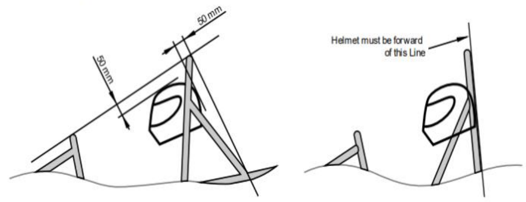


Figure 5
Restriction F.5.6

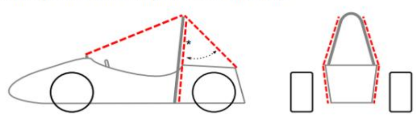
Source: FSAE Regulation 2023

Box 7

F.1.13 **Rollover Protection Envelope**

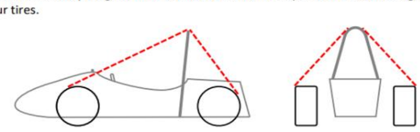
The Primary Structure plus a plane from the top of the Main Hoop to the top of the Front Hoop, plus a plane from the top of the Main Hoop to the rearmost Triangulated structural tube, or monocoque equivalent.

* If there are no Triangulated Structural members aft of the Main Hoop, the Rollover Protection Envelope ends at the rear plane of the Main Hoop



F.1.14 **Tire Surface Envelope**

The volume enclosed by tangent lines between the Main Hoop and the outside edge of each of the four tires.



F.1.15 **Component Envelope**

The area that is inside a plane from the top of the Main Hoop to the top of the Front Bulkhead, plus a plane from the top of the Main Hoop to the rearmost Triangulated structural tube, or monocoque equivalent. * see note in step F.1.13 above

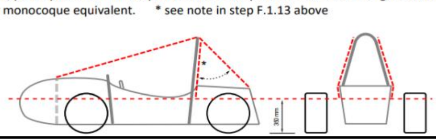


Figure 6
Constraint F.1.13

Source: *FSAE Regulation 2023*

Box 8

F.5.12 **Mechanically Attached Roll Hoop Bracing**

F.5.12.1 When Roll Hoop Bracing is mechanically attached:

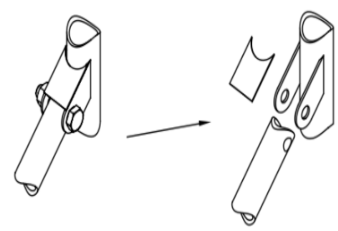
a. The threaded fasteners used to secure non permanent joints are **Critical Fasteners**, see **T.8.2**. Additional requirements apply in **F.5.12.5** and **F.5.12.7**

b. No spherical rod ends are allowed.

c. The attachment holes in the lugs, the attached bracing and the sleeves and tubes must be a close fit with the pin or bolt.

F.5.12.2 Any non permanent joint at the end(s) must be a Double Lug Joint or a Sleeved Butt Joint

Figure – Double Lug Joint



F.5.12.3 For Double Lug Joints, each lug must:

a. Be minimum 4.5 mm (0.177 in) thickness steel

Figure 1
Restraint of restraint F.5.12

Source: *FSAE Regulation 2023*

An optimisation to the CAD model of the Halo safety device was considered, with the aim of reducing the amount of material used while maintaining or increasing its performance.

This optimisation was achieved by modifying the design for weight reduction in non-critical areas, resulting in a more efficient design.

A new clamping geometry was proposed that retains the lug design, but reducing the amount of material. In addition, a smaller diameter solid profile is suggested for the tubular instead of hollow.

Despite being solid, its dimensions were reduced while maintaining structural rigidity. This optimisation strategy reflects an innovative and progressive approach to safety in FSAE competition. [5]

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Box 9

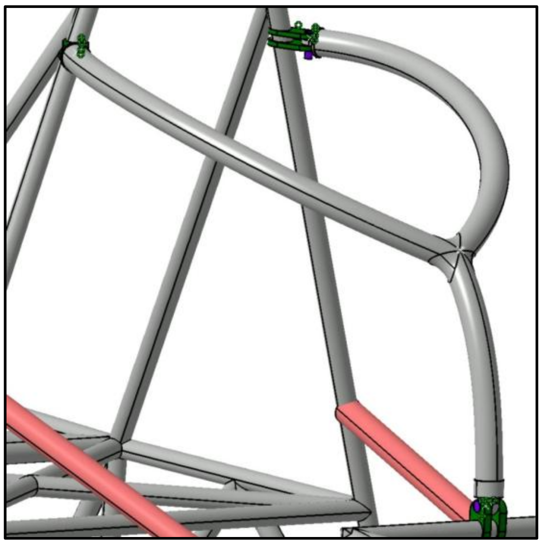

Figure 8
HALO FSAE 2024 proposal

Source: Own elaboration

So the assembly consists of a double-ear fastening system, with a minimum requested thickness of 4.5 mm [5]. But a thickness of 8.0 mm is chosen to ensure greater robustness and structural strength. These fasteners are joined by a 10.0 x 70.0 mm hex bolt and nut, ensuring a secure and stable connection between the Halo device and the vehicle frame, as shown below:

Box 10

Figure 9
Technical characterisation of a Formula 1 joint assembly

Source: FIA STANDARD 8869-2018

Box 11

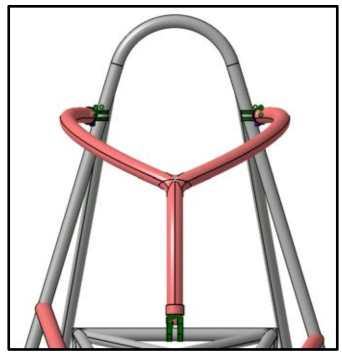

Figure 10
Proposed linkage of the CAD model for FSAE 2024

Source: Own elaboration

Box 12

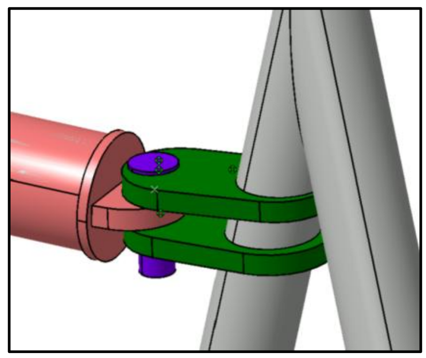

Figure 11
Proposed linking of the CAD model in FSAE 2024

Source: Own elaboration

For the validation of the design of the Halo device for the Formula SAE vehicle, it is essential to apply the principles of Failure Mode and Effect Analysis (FMEA) in a rigorous and structured manner. This ensures a thorough assessment of every critical component of the Halo, from the main structure to the mounting brackets and attachment connections, identifying potential failure modes and developing effective strategies to mitigate risks. Considering the points on how to do the FEA and apply them towards the design. [A]

Planning and Preparation:

Clear objectives were set and a multidisciplinary team was assembled.

The scope of the FMEA was defined and roles and responsibilities were assigned.

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Structure Analysis:

Critical components of the Halo were identified and thoroughly analysed, including the main structure, mounting brackets, attachment connections, cross members and surface finish. The function of each component was assessed and potential failure modes were identified, considering their severity and occurrence.

Risk Analysis:

Current failure prevention and detection controls were assessed for each component.

Severity, occurrence and detection scores were assigned to calculate the level of risk associated with each failure mode.

Optimisation:

Prevention and detection actions were proposed and prioritised to mitigate the identified risks.

An implementation plan was established for each proposed action and progress is monitored.

Implemented actions were periodically reviewed to ensure their continued effectiveness.

Visual tools, such as flow charts and risk matrices, are used to represent the results of the FMEA analysis in a clear and concise manner. Tables are used to summarise the identified failure modes, along with their severity, occurrence and detectability, facilitating the identification of critical areas requiring attention during optimisation. Failure Mode and Effect Analysis (FMEA) was an essential tool in our process to improve the HALO design. Through this analysis, potential failure risks in each component were identified and addressed, allowing the safety and reliability of the Halo to be strengthened. This tool directly contributes to improving the safety and quality of the Halo design for the Formula SAE vehicle [A].

Initially, only the CAD model of the Formula SAE vehicle frame lines was available. To which the silhouette of a Halo device was added, trying to stick to the original design of the device. Proposals were generated for further evaluation, shown below:

Box 13

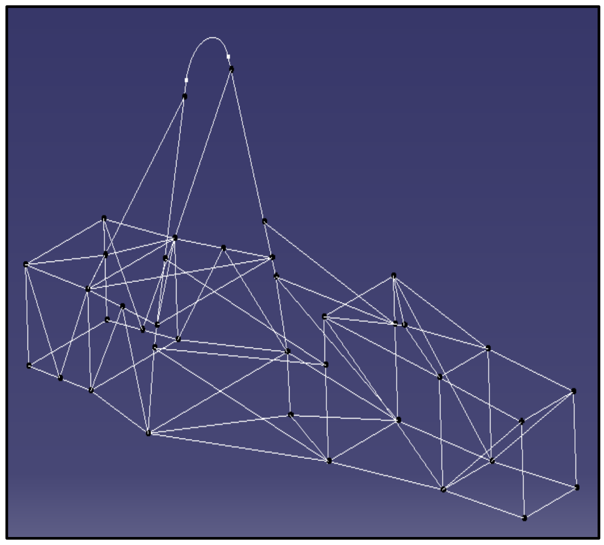


Figure 12
Demonstration image of the CAD model of the FSAE 2023 lines

Source: Own elaboration

Several proposals were made, modelled and evaluated for comparison, and the proposals generated are shown below.

Box 14

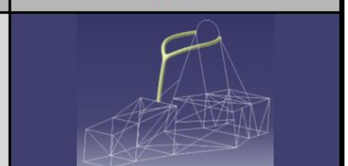
No. de Propuesta	Imagen
1	
2	
3	

Figure 13
Proposals generated

Source: Own elaboration

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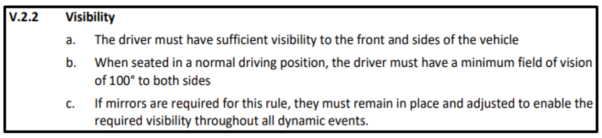
After the design stage, analyses were carried out in CATIA V5 and ANSYS software to demonstrate the functionality of the proposal. Starting with the CATIA software where the visibility tests were carried out with the dummy in order to validate the point of view, being also a requirement requested and limiting the design by the FSAE regulation in section V.2.2 which specifies as a requirement to have a visibility to the sides of 100° [5].

Box 15



V.2.2 Visibility

a. The driver must have sufficient visibility to the front and sides of the vehicle

b. When seated in a normal driving position, the driver must have a minimum field of vision of 100° to both sides

c. If mirrors are required for this rule, they must remain in place and adjusted to enable the required visibility throughout all dynamic events.

Figure 14
Constraint V.2.2

Source: FSAE Regulation 2023

Using a percentile dictated by the same regulation in section F.5.6.5 [5], the visibility test was carried out on the 6 proposals to finally select the one with the highest visibility, using the following position:

Box 16

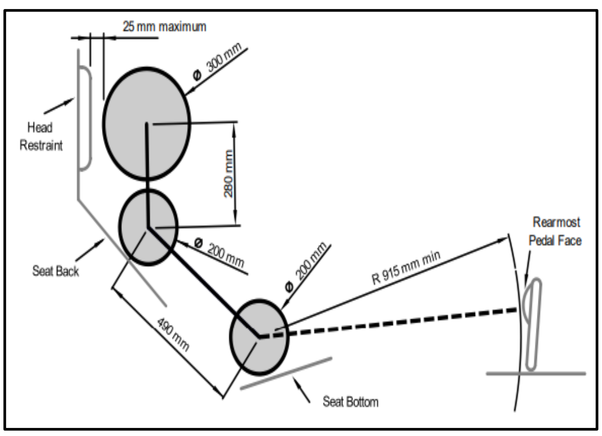


Figure 15
Pilot position determined

Source: FSAE Regulations 2023

With the Point of View (POV) tool, the following results are obtained from the proposals:

Box 17

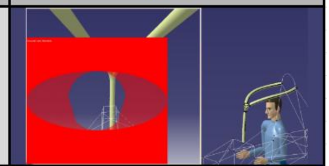
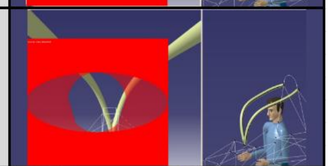
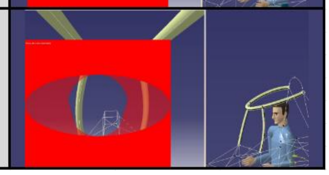
No. de Propuesta	Imagen
1	
2	
3	

Figure 16
Comparison of the results obtained in CATIA V5 POV

Source: Own elaboration

Where it was observed that proposal number 1 was the best as it obstructed visibility the least, thus meeting the 100° visibility requirement without complications. Therefore, the design stage was resumed based on the proposed geometry number 1.

Box 18

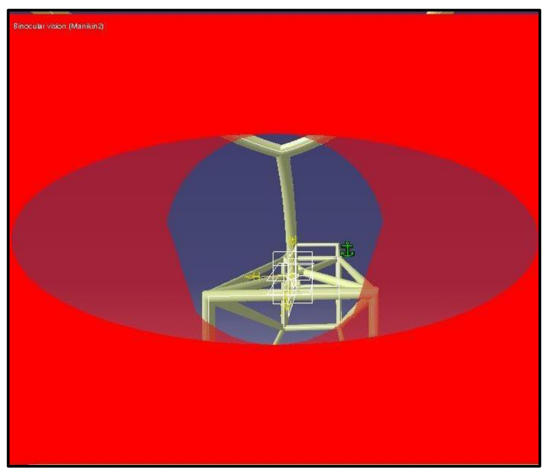


Figure 17
Results of the right-eye view on the modified CAD proposal

Source: Own elaboration

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DOI: https://doi.org/10.35429/JME.2024.8.21.1.16

Box 19

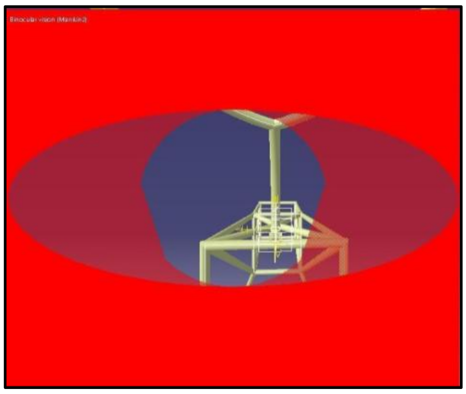

Figure 18
Results of the left-eye view of the modified CAD proposal

Source: Own elaboration

Therefore, a model was generated from the following sketches:

Box 20

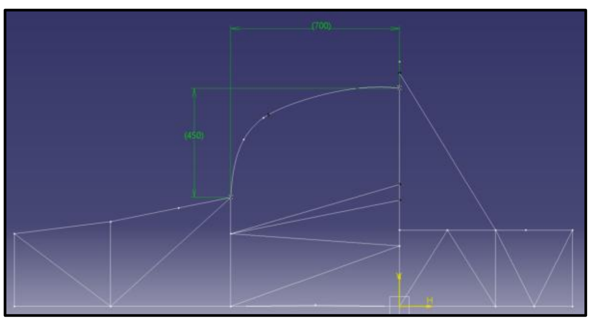

Figure 19
Lateral dimensional image

Source: Own elaboration

Box 21

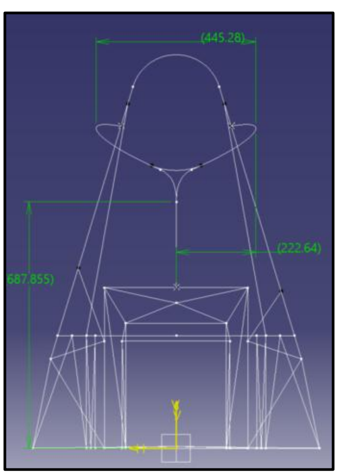

Figure 20
Front dimensional image

Source: Own elaboration

Box 22

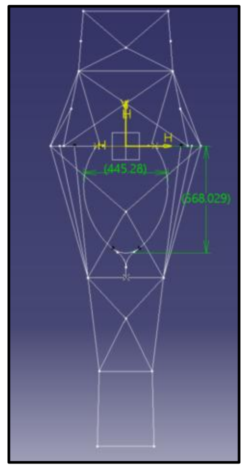

Figure 21
Front dimensional image

Source: Own elaboration

The second software used was ANSYS Workbench 2023 R2 for the analysis and validation of the chosen proposal. The analysis proposed was a modal analysis and a structural analysis following the mechanics and magnitudes of the Quasi Static Test 1 to the original frame as a starting point for comparison and to the modelled proposal. These analyses consist of a modal analysis and a structural analysis. These analyses were carried out under the conditions mentioned below. For the structural analysis, we used the Quasi Static Test 1 [1] conditions and A36 Steel or Structural Steel as the material chosen for the fabrication of the Halo.

Analysis Approach

As mentioned, tests were performed on the HALO device to validate its stiffness and strength, the tests consist of a modal analysis and a structural analysis following the evaluation method used in the real F1 HALO device. Called Quasi Static Test 1 and Quasi Static Test 2, it consists of the application of force at a point in such a way that a controlled deformation is generated on the device. In the case of modal analysis, this consists of the analysis of those frequencies that could enter into 'resonance' with the frame.

Meshing characteristics

The characteristics of the mesh used for the analyses carried out are as follows.

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Box 23

Table 2
Table of location of supports and loads on structural analysis

Study	Modal	Structural
Element size	7	7
Element type	1D	1D
Number of mesh elements	1466	1466

Source: Own elaboration

The material used was A36 steel, better known as structural steel, which was selected due to its properties, accessibility and validity according to the FSAE competition regulations. These properties are shown below:

Box 24

Table 3
Material properties table Steel A36

Property	Value	Unit
Density	7.85e-0	kg/mm^3
Young's modulus	2e+05	MPa
Poisson's Ratio	0.3	-
Shear modulus	76923	MPa
Compressive yield strength	250	MPa

Source: Own elaboration

Modal analysis

The first analysis performed is the modal analysis, carried out to determine and locate the natural frequencies and vibration modes to avoid in order to keep the frame away from resonances and/or structural failures. This ensures that the frame does not have natural frequencies that coincide with engine or ground excitations, improving durability and performance. The conditions of the analysis are shown below:

Box 25

Table 4
Table of location of supports and loads on structural analysis

Type of load/holding	Location
Fixed Support - Front	Front suspension
Fixed Bracket - Rear	Suspension rear

Source: Own elaboration

Box 26

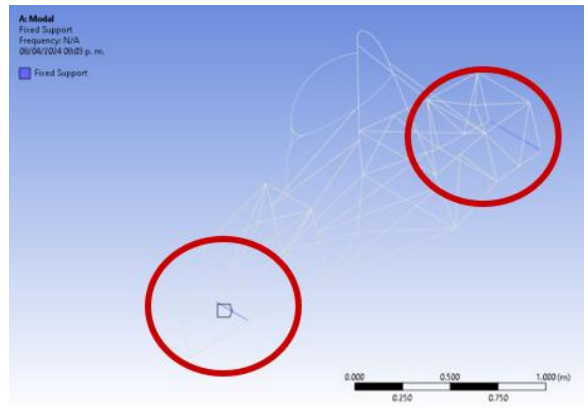

Figure 22
Image showing the location of the supports

Source: Own elaboration

Box 27

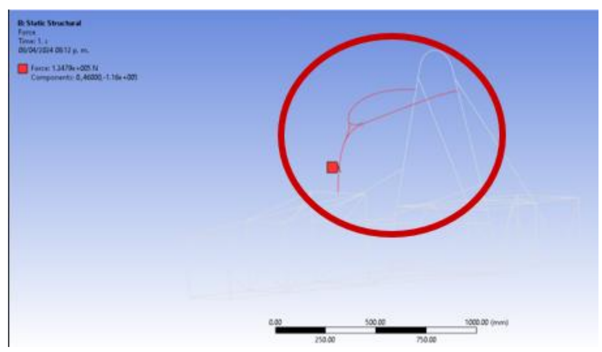

Figure 23
Image showing the load used for structural analysis

Source: Own elaboration

As mentioned above, the modal analysis was carried out to avoid that the frequencies induced to the frame coincide with the frequencies produced by the vibration of the engine, mentioned below:

Box 27

Table 5
Table of results of the modal analysis on the original FSAE model

Force Induced	Value	Units
Engine Revolutions	**13000**	rpm

Source: Own elaboration

Modal analysis studies were carried out before and after the modifications in order to obtain a comparison between the two. The following results were obtained:

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DOI: https://doi.org/10.35429/JME.2024.8.21.1.16

Box 28

Table 6
Table of results of modal analysis on the FSAE model

No. of Frequency	Value (Hz)
1	47.768
2	72.249
3	74.955
4	88.846
5	104.26
6	116.94

Source: Own elaboration

Box 29

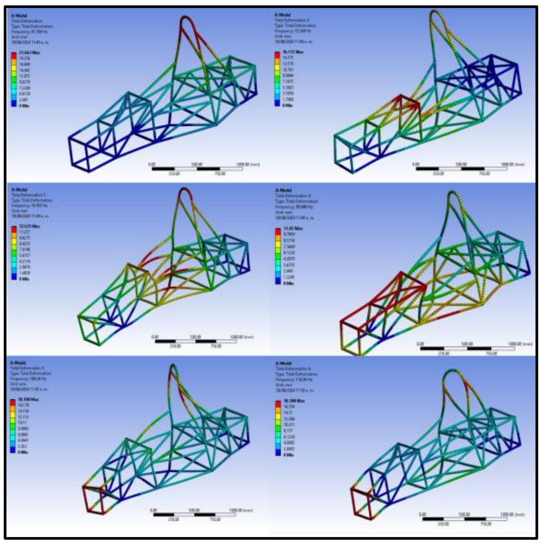

Figure 24
Deformation results obtained from modal analysis (A36 STEEL) prior to Halo modification

Source: Own elaboration

Once the modifications to the frame had been made, the analysis was carried out again, obtaining the following results:

Box 30

Table 7
Table of results of modal analysis on the FSAE model

No. of Frequency	Value (Hz)
1	43.636
2	71.349
3	79.554
4	80.394
5	101.58
6	109.87

Source: Own elaboration

Box 31

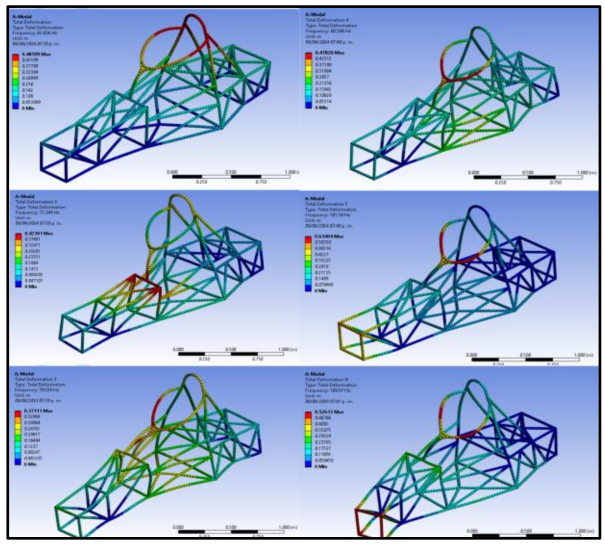

Figure 25
Deformation results from modal analysis

Source: Own elaboration

The values of frequencies that could cause the proposed structure to resonate (216 Hz frequency of the electric motor) can be found. As can be seen, the results vary little.

Structural Analysis

The next analysis performed was the structural analysis, carried out to determine the total deformation according to the determined forces. In this case, as mentioned, the analysis is based on the Quasi Static Test 1 [1] performed on the Halo devices for F1. Thus ensuring that the Halo complies with the maximum allowable deformation of 90 mm. The conditions of the analysis are shown below:

Box 32

Table 8
Table of location of supports and loads on structural analysis

Type of load/holding	Value	Location
Constant force on Y-axis	-46 kN	HALO Impact Zone
Constant force on Z-axis	-116 kN	Halo Impact Zone

Source: Own elaboration

From this analysis, the total deformation and the directional deformation were sought, and the following results were obtained:

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Box 33

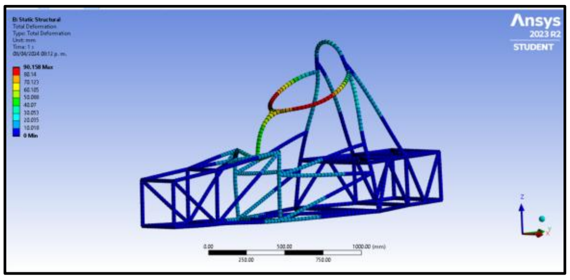

Figure 26
Total deformation of structural analysis on the FSAE model

Source: Own elaboration

Box 34

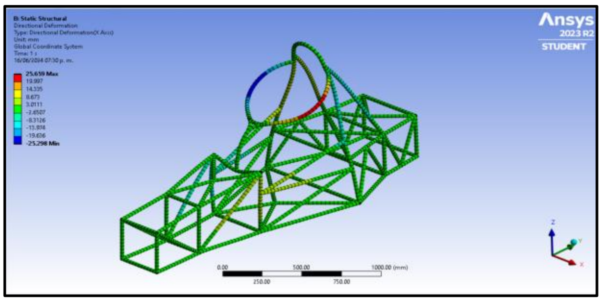

Figure 27
Directional deformation of the structural analysis on the FSAE model

Source: Own elaboration

Box 35

Table 9
Results obtained from the Structural Analysis

Structural static analysis	
Type	Final Model
	Value
Total deformation	90.158 mm
Directional deformation	25.659 mm

Source: Own elaboration

From this analysis, the total deformation was found to be 90.158 mm at its maximum point, which shows that the impact on the main hoop generates a deformation that exceeds by 0.158 mm the tolerance values initially proposed under these test conditions.

Physical Tests

For the validation and corroboration of the results a physical model was generated by 3D printing, this device was scaled at a ratio of 1:8 because this scale was the one that best fit the printing bed of the 3D printer.

The material Onyx [B] was chosen due to its mechanical properties and the current availability of the material.

These mechanical properties and under the environmental conditions shown below:

Box 36

Table 10
Properties of Onyx

Condition	Value	Unit
Young's modulus	2400	MPa
Elongation at break	25	%
Flexural strength	81	MPa
Flexural modulus	2900	MPa

Source: Own elaboration

Box 37

Table 11
3D printing conditions

Condition / Material	Valor / Number	Model/Unit
3D printer	Marforged	Mark Two
Temperature	24	°C
Curing time	45	min

Source: Own elaboration

Box 38

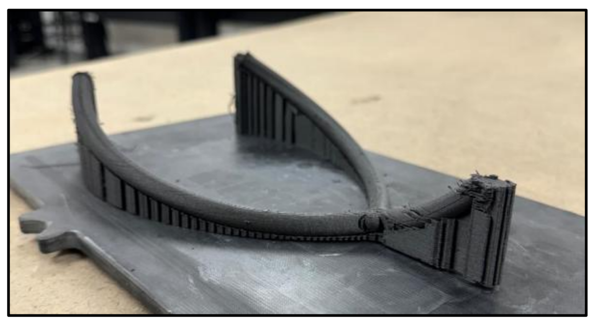

Figure 28
3D printing at Onyx

Source: Own elaboration

However, some problems arose in the printing, details such as marks and a weakened node invalidated the print, so another option had to be implemented.

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DOI: https://doi.org/10.35429/JME.2024.8.21.1.16

Box 39

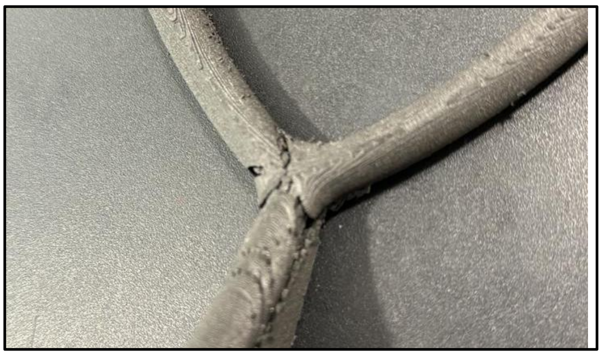

Figure 29
3D printing at Onyx

Source: Own elaboration

Due to the printing failures and the lack of more Onyx material, it was decided to print with clear V5 resin [B], with its mechanical properties shown below.:

Box 40

Table 12
Properties of V5 resin

Condition	Value	Unit
Young's modulus	2750	MPa
Elongation at break	10	%
Flexural strength	92	MPa
Flexural modulus	2450	MPa

Source: Own elaboration

The following results were obtained from this print. For this print, the HALO was rescaled to a ratio of 1:9 to fit the printer bed.

Box 41

Figure 30
Printing of HALO in Resin V5

Source: Own elaboration

The print was subjected to a cleaning process in a vat of ethyl alcohol for 40 minutes and a curing process of 45 minutes at 70 °C. Subsequently, physical tests were carried out using a universal stress machine. This equipment allowed to progressively apply force on the Halo as a function of time.

Box 42

Figure 31
3D printing at Onyx

Source: Own elaboration

Once positioned, the upper plunger of the machine was positioned at a height almost touching the Halo protection device to obtain accurate measurements and to avoid non-contact data between the plunger and the Halo. The machine was programmed to lower by 10 mm every minute, thus measuring the force at which the Halo deformed and/or failed.

Box 43

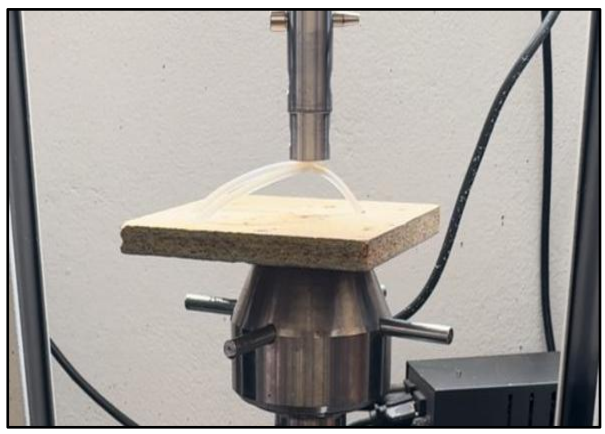

Figure 32
3D printing at Onyx

Source: Own elaboration

The tests showed that the failure effect occurred at 137.05 N of force applied on the V5 resin Halo, with a deformation of up to 20.81 mm extension

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Box 44

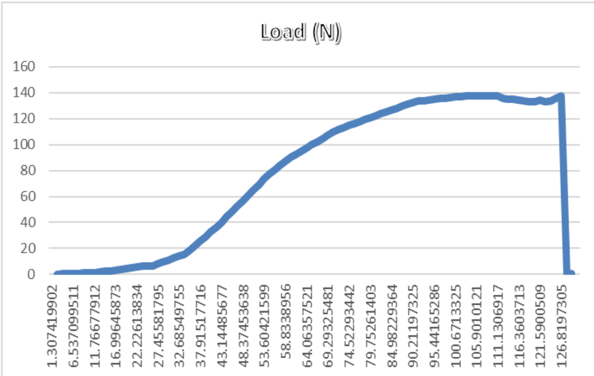

Figure 33
Behaviour of force applied on the HALO

Source: Own elaboration

Box 45

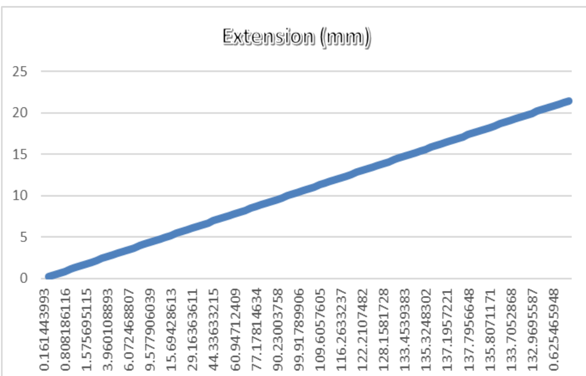

Figure 34
Elongation behaviour against applied force

Source: Own elaboration

These results demonstrate that, under the test conditions described, the HALO printed on V5 resin presents a deformation capacity and specific resistance that is crucial for its evaluation in future applications.

Analysis Results

The modal analysis is performed to validate the structural stiffness of the frame and to visualise the interaction between the frequencies of the medium and the frame, the structural analysis is performed to validate the structural toughness against a possible impact, and as a requirement/complement the visual comparison in order to fulfil the design requirement, adding value towards the inclusion of the device. As mentioned in the modal analysis, it is maintained over the frequency range that would cause the frame to resonate, demonstrating that the stiffness of the structure is preserved.

In the case of the point of view analysis it is observed that the field of view is only obstructed at the centre and was therefore not considered relevant compared to the structural and safety benefits observed. As expected due to the characteristics of the material, the steel is a tough and resistant option to the test, however it fails the tests under the conditions of Quasi Static Test 1 exceeding the tolerance defined by a difference of less than 0.158 mm of deformation, this is a point that is considered for future improvements and starting point for redesign of the geometry or even the choice of material, in this case being of experimental subject is considered as valid because in this geometry and with this material is discarded for professional use.

Conclusions

After the research and analysis carried out in the project, it was concluded that the inclusion of a Halo type device in a Formula SAE type vehicle represents a benefit as it maintains the rigidity and resistance without compromising the aesthetics of the vehicle, at the same time as it increases pilot safety in the event of any eventuality in a competition or test. It is concluded that if it is desired to open the competition to a wheel-to-wheel type, the Halo device would be of great use as part of the safety and damage prevention elements. The results of the physical tests allowed a comparison to be made with the initial graph showing the behaviour of the steel, it is assumed that the proposed Halo structure could withstand a possible impact under 124, 787.82 Newton at 338.37°. It is important to note that these assumptions are based on the study and knowledge of the behaviour of each material. However, in order to obtain more accurate and realistic results, it is recommended that a prototype be made using the proposed material. Digital analysis suggests that the A36 Steel Halo construction is effective in providing protection against critical deformations, ensuring the safety and integrity of the driver in collision situations.

Conflict of interest

The authors declare that they have no conflicts of interest. They have no known competing financial interests or personal relationships that could have influenced the article reported in this paper.

Authors' contribution

The contribution of each researcher in each of the points developed in this research was defined based on:

Noguez-Jimenez, Victor-Manuel: He contributed to the construction of the CAD models and their analysis, ensuring compliance with the theoretical analyses and their numerical validation. As well as the generation of the physical experiments on the 3D model.

Perez-Carrillo, Daniel: Contributed to the elaboration and evaluation of the CAD models, the analysis of the models presented, as well as the evaluation and execution of the 3D printing of the models.

Cordero-Guridi, José de Jesús: Contributed to the development of the research method as a guide and validation of the project.

García-Tépox, José Domingo: Contributed to the diversification of ideas on the generation of the physical tests and the generation of the 3D printed physical model.

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Abbreviations

CAD - Computer-Aided Design

FEA - Failure Modes and Effects Analysis

FMEA - Failure Modes and Effects Analysis

FEA - Finite Element Analysis

HIC - Head Injury Criterion

FIA - Federation Internationale de l'Automobile

FSAE - Formula SAE

POV - Point of View

Annexes

[A] Design Failure Mode and Effect Failure Analysis (PMFE) - Halo Design for Formula SAE

[B] Clear Resin V5 Datasheet

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Background

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