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ECO-FRIENDLY TRANSPORTATION: SOLAR CAR DESIGN FOR COMPETITION- PART I, STRUCTURAL CHASSIS

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Abstract:

The design and analysis of the structural chassis for a solar-powered car are crucial aspects of ensuring driver safety and supporting the vehicle's mechanical and electrical systems. This paper is the first part of a four-part series that covers the design and development of an eco-friendly solar car for competition. The project is divided into multiple parts to provide further details of each aspect. Part I focuses on the design and analysis of the chassis, with an emphasis on achieving driver safety and a lightweight architecture. In this paper, we present the design methodology employed by the Virginia Tech Solar Car Project team during the 2022-2023 timeframe. The design process involves conducting multiple static and dynamic clearance analyses to ensure sufficient space among the chassis and other dynamic systems while maintaining optimal driver positioning. Additionally, impact and stress analyses are performed to assess the chassis' strength and identify areas for structural enhancements.

The results of the analysis demonstrate that the designed chassis meets the required safety standards as well as performance criteria. The design approach prioritizes lightweight construction without compromising the structural integrity of the chassis. Throughout the design process, various challenges are encountered, which will be discussed in detail to provide holistic insights and lessons learned.

Keywords: solar car, structural chassis, clearance study, impact analysis, stress, lightweight

Introduction:

As the demand for sustainable transportation solutions continues to grow, solar-powered vehicles have emerged as a promising alternative to traditional gasoline-powered cars. Within this context, the design of the solar car structural chassis plays a critical role in ensuring driver safety and providing a robust foundation for various mechanical and electrical systems. This paper serves as the introduction to a comprehensive four-part series on the design and development of an eco-friendly solar car for competition, with Part I focusing on the structural chassis.

The primary objective of this paper is to present a comprehensive methodology for designing and analyzing the solar car chassis, with a specific emphasis on achieving optimal performance and driver safety. The design process begins with a careful consideration of packaging and ergonomic factors to ensure optimal driver ergonomics, particularly during pedal system operation, while also ensuring a comfortable driving experience. A static and dynamic clearance study is conducted to address the driver's positioning within the vehicle, ensuring adequate space and suitable ergonomic conditions.

To assess the chassis's ability to withstand crash and collision loads, an impact Finite Element Analysis (FEA) is performed. This analysis presents significant challenges, as achieving a lightweight design is a key objective to enhance the overall efficiency of the vehicle while considering constraints such as weight and cost. Through detailed stress analysis and optimization techniques, a final chassis design is proposed that successfully meets all target specifications while minimizing weight.

The proposed methodology and design process are executed with the goal of ensuring driver safety, optimal performance, and adherence to specific design constraints. The findings and insights gained from this study contribute to the ongoing development and advancement of solar-powered vehicles. By emphasizing the importance of chassis design and analysis, this paper provides valuable guidance for future solar car design projects, with a particular focus on achieving enhanced efficiency and driver safety.

The subsequent papers in this series explore other critical aspects of the solar car design, including suspension, steering, and traction systems as Part II [1], electrical systems as Part III [2], and test and validation (Part IV). Together, these papers offer a comprehensive overview of the entire eco-friendly solar car design project, showcasing the integration of various components to achieve a high-performing and sustainable vehicle.[3]

Design methodology:

The design methodology for the solar car chassis involves a systematic approach that focuses on addressing customer needs and target specifications while considering weight and cost constraints, as shown in Appendix A. based on the previous project experiences and aiming for improvements, the project team identified the following specifications and requirements for the roll cage frame and structures, in accordance with solar car regulations: [4]

- Ground clearance: To ensure smooth maneuverability and prevent undercarriage damage, the vehicle and aeroshell were designed with a minimum ground clearance of 10 cm. Additionally, this design feature helps reduce aerodynamic lift forces. (According to item 9.3 of the regulation, Ground Clearance: When driving on a flat road, all parts of the fully laden solar car except the tires, wheels, and wheel hubs must be at least 100 mm above the ground.)

- Stability: The chassis is designed to prevent tipping over at a 45-degree bank angle, prioritizing driver safety during dynamic maneuvers.
- Crash resistance: The roll cage frame and structures are designed to withstand a 5g impact from all angles, ensuring the safety of the driver and passengers in the event of a crash.
- Low center of mass and wide wheel track: To enhance stability and minimize the risk of rollover, the chassis is designed with a low center of mass and a wide wheel track.
- Weight target: The chassis aims to achieve a specific weight target of 150-170 kg, contributing to a total gross weight (including one driver) of 330-340 kg. This weight distribution was optimized with a front-to-rear ratio of 50% and 50%, respectively.
- Torsional rigidity: A torsional rigidity of 1200-1500 Nm/deg is targeted to ensure precise vehicle control, passenger protection, and overall comfort.
- Special consideration is given to the movement of the steering wheel, seat backs, and head restraints during impact to mitigate the potential risk of injury to the occupant. By carefully designing and implementing appropriate measures, the team aims to enhance the overall safety of the solar car.

The design process for the solar car chassis involved utilizing 3D CAD design using SolidWorks software, based on a primary packaging layout. In addition, the use of SolidWorks software allows an easy visualization of the chassis design, which enabled the team to identify potential issues early in the design process and make necessary modifications. This approach helps to minimize design errors and improve the overall quality of the chassis design. Subsequently, finite element analysis (FEA) was conducted using ANSYS software to validate the design and ensure compliance with the identified targets. This step allows for the identification of any necessary design modifications prior to manufacturing and assembly stages.

It is important to note that designing an optimal chassis involves striking a balance between various factors, including cost, packaging, weight, stiffness, and safety. The design methodology employes a comprehensive approach that considered these variables, resulting in a well-engineered chassis that meets the specified requirements and performance criteria.

Chassis design:

The design is based on the packaging layout considering the integration of all interacting subsystems, including the chassis, driver cockpit, batteries, and electrical components. This approach is quite crucial in ensuring that the chassis design is fully balanced to meet the unique requirements of the solar car. By closely aligning the layout with the specific needs of the vehicle, the design team successfully created a chassis that provided a robust foundation for the entire system. The careful consideration given to the packaging layout allowed for efficient space utilization, effective component placement, and seamless integration of various systems, contributing to the overall performance and functionality of the solar car [5].

The primary objective of the chassis structure is to prioritize driver safety in the event of an accident, while also serving as a robust and stable platform for supporting other vehicle systems. In the realm of solar car racing, two dominant chassis structures are commonly employed: the tubular metal spaceframe, featuring aluminum and steel spaceframes, and the carbon fiber composite monocoque chassis. For this particular project, a tubular space frame configuration was chosen, constructed using AISI 4130 chromoly steel tubes with two distinct profiles.

Most of the chassis structure utilizes tubes with an outer diameter (OD) of 1" and a thickness of 0.065". However, areas of the chassis that are vital for structural integrity, such as those surrounding the roll cage, employ tubes with an OD of 1.5" and a thickness of 0.120". Additionally, rectangular boxes were strategically incorporated at the front and back of the chassis to serve as attachment points for the suspension wishbones. The design of these mounting areas is of utmost importance to ensure efficient shock absorption from the wheel/suspension system while maintaining the necessary stiffness.

Triangulation in the chassis assists in absorbing impact loads and providing torsional stiffness. The suspension shocks at the front and rear connect to a node at the points of a diamond shape to better disperse energy into the chassis frame. The bottom half of the chassis features a trapezoidal shape that enhances resistance to side impacts. The full chassis with a model driver inside can be observed in Figure 1. The roll cage design is illustrated in Figure 2 with a driver model that has a bubble around the helmet representing appropriate head clearance that the roll cage bars cannot intrude into (see clearance study below). To further enhance safety measures, netting will be added to the sides of the roll cage, effectively preventing excessive head movement, and providing additional protection to the driver.

By incorporating these key elements into the chassis design, the project team aims to create a structure that guarantees the highest level of safety and performance for the solar car.

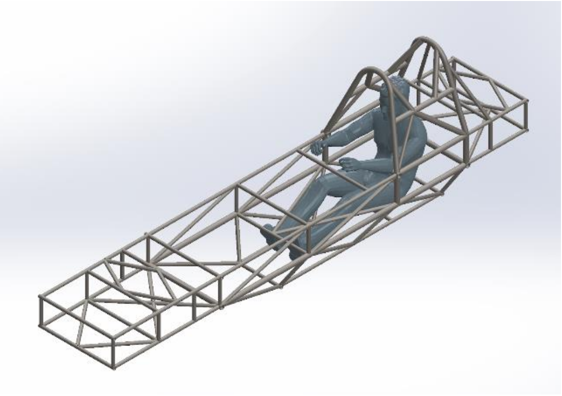

Figure 1 : Chassis design with driver inside

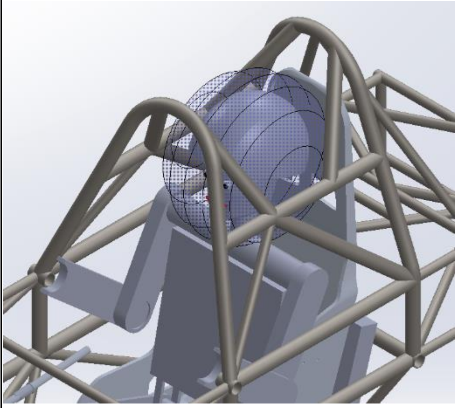

Figure 2 : Roll cage concept design

Clearance study:

Referring to regulation 10.3.A.14 of the solar car regulation, there must be 50 mm of clearance in all directions between any member of the Occupant Cell and the helmets of the occupants seated in the normal driving position. Having said that, There must be at least 30 mm of clearance between the occupant’s helmet and the padding to allow for free movement of the occupant’s head. Therefore, the roll cage has been designed to provide at least 50 mm clearance between the driver’s helmet and the roll bars. A translucent sphere with a 50.8 mm higher radius than the helmet was added to visualize this regulation. Figure 3 illustrates the clearance between the occupant's helmet and surrounding members [6][7].

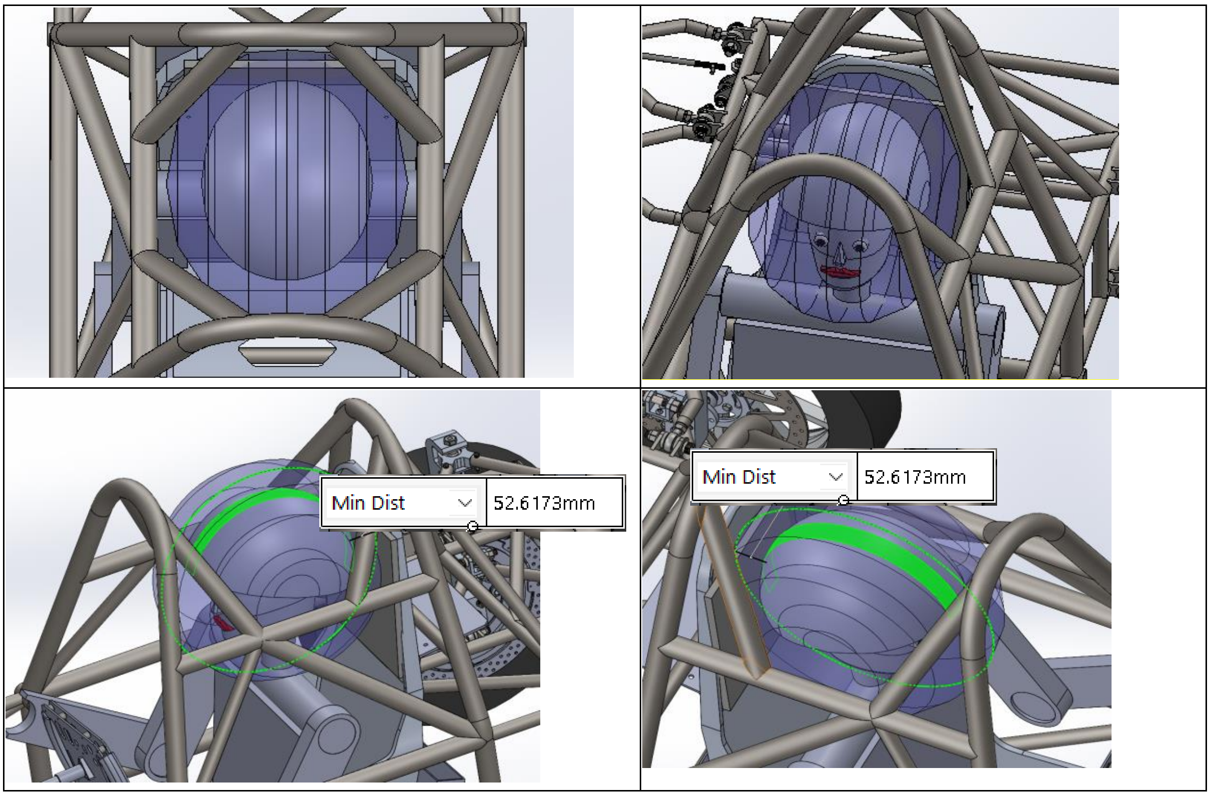

Figure 3: clearance analysis between occupant's helmet and surrounding members

To ensure ergonomic aspects of user operation, the brake and accelerator pedals are separated to provide clearance in the interior footwell. In accordance with regulation 8.8.B, the accelerator pedal is placed furthest right in the footwell, whereas the brake pedal is furthest left. Due to interior constraints such as the floor pan width, aeroshell tolerance, and crash structure, the pedals cannot be placed next to each other as the area would be too tight for single foot operation.

Seat belts integration:

The integration of seat belts is one of critical aspect of ensuring driver safety within the solar car. While the seat belts are sourced from a supplier, careful attention must be given to the placement of the attachment points between the seat belt and the roll cage structure. These attachment points play a dominating role in providing a reliable safety condition for the driver.

In accordance with the regulations outlined in 10.3.E of the FSGP 2022 guidelines, it is really mandatory for all solar cars to be equipped with a minimum 5-point lap and shoulder belt harness system for each occupant. Furthermore, the safety belts must be securely installed and attached to the structural chassis. The design of the safety belt mounts should be capable of withstanding impact loads equivalent to those the safety cell is designed for, as specified in Regulation 10.3.A.8.Specifically, the attachment point for the shoulder straps should be positioned rearwards between a horizontal orientation and a maximum of 30 degrees below horizontal, while remaining perpendicular to the occupant's spine or seat back. Figurative representation of the recommended attachment point can be observed in Figure 4. By ensuring proper integration of the seat belts into the roll cage structure, a secure and effective safety system that aligns with the necessary regulations and enhances overall occupant protection was provided.

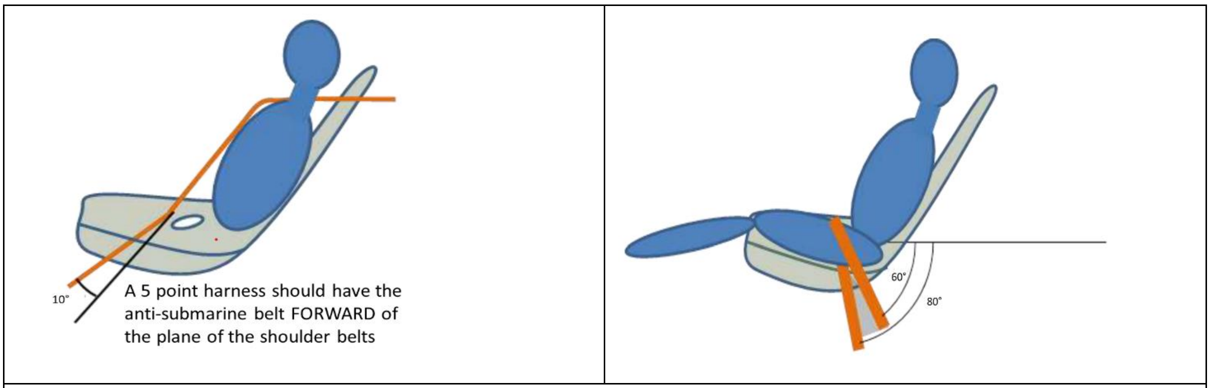

Figure 4: Configuration of seat belt attachments on the chassis . 10.3.E, FSGP 2022

The seat belts utilized in the solar car are a 5-point harness system consisting of shoulder belts, left and right hip belts, and an anti-submarine harness. These seat belts meet the SFI 16.1 certification, ensuring their compliance with safety standards. The seat belts will be securely wrapped around the nearest tubing within the vehicle structure. In alignment with regulation 10.3.E.7, the mounting points for the seat belts have been positioned to locate the shoulder mounting points at the horizontal level. This placement ensures proper positioning and functionality of the seat belts within the vehicle. Detailed information regarding the specific locations of the seat belt mounting points can be seen in Figure 5. By adhering to the prescribed regulations and incorporating the 5-point harness system with correctly positioned mounting points, the project team aims to enhance occupant safety and meet the necessary requirements for the solar car.

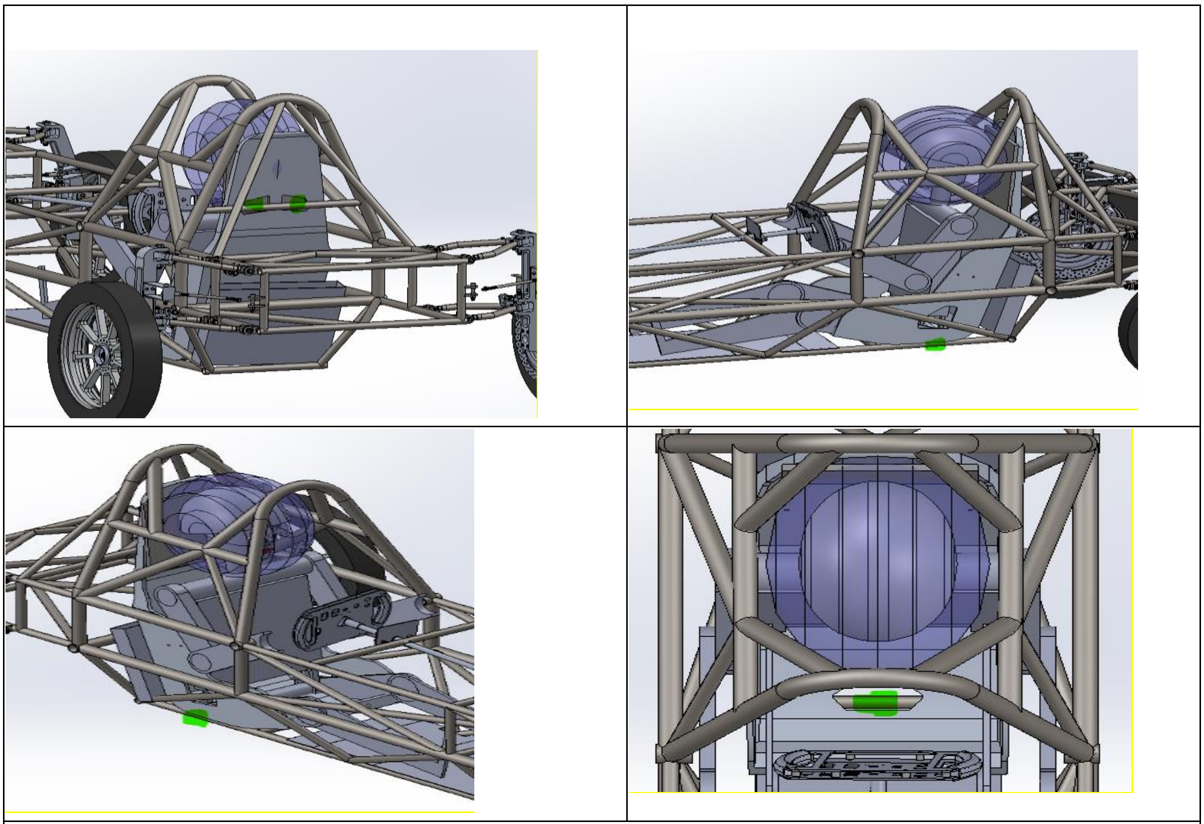

Figure 5: mounting points of the seat belts on chassis

Appendix B displays the results of the finite element analysis (FEA) conducted using ANSYS to evaluate the strength of the bars responsible for securing the seat belts. The analysis reveals that the maximum stresses experienced by the members are significantly below their yield strength of 435 MPa. This indicates that the bars designed to hold the seat belts in place possess ample strength and structural integrity to withstand the expected loads. The stress distribution throughout the nodes further validates the robustness of the design. The forces are calculated using our max driver weight (150 lbs) multiplied by a scaling factor: 2.5 for side and shoulder straps and 1.5 for anti-submarine belt.

By ensuring that the seat belt attachment points can withstand the calculated forces and remain within acceptable stress limits, the project team has prioritized occupant safety and met the necessary standards and regulations for the solar car.

Vehicle impact analysis:

The structures team used ANSYS finite element analysis (FEA) to perform impact analysis on the chassis in accordance with 10.3.A.8. This was done using a structured iterative approach: The first loop of the design, performing FEA, identifying failure points, reinforcing or updating the design, and so on until the chassis and roll cage reached the required minimum factors of safety. The project setup for the occupant cell and the roll cage in ANSYS Workbench is as shown in Figures 6a and 6b respectively.

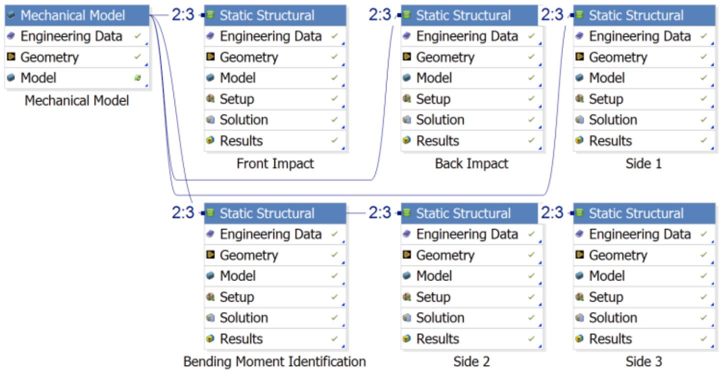

Figure 6a: Occupant Cell impact project setup in Workbench

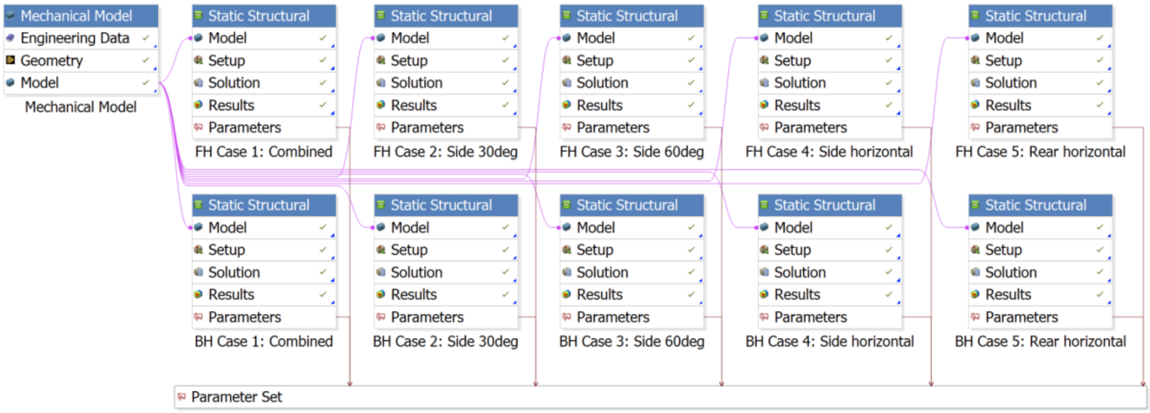

Figure 6b: Roll Cage impact project setup in Workbench

For the occupancy cell tests, beam elements are used to discretize the chassis. The impact load cases based on F.3.3.1, FSGP 2022A are used. This load are being distributed over the mesh nodes within the contact area of the bumper at a height of 350 mm off the ground in accordance with F.3.3.1.

Figure 7 describes the impact load cases for the occupant cell, which include five distinct load cases: a 5g load applied at the front, rear, and three distinct locations on the side. These load cases are analyzed to assess the structural integrity and performance of the solar car's roll cage under impact conditions. Similarly, Figure 8 shows the combined Roll Cage impact load case based on F.3.3.1, FSGP 2022. Other load cases are 5g backwards, sideways horizontal, sideways at 30 degrees, and sideways at 60 degrees. Nonetheless , this comes to five load cases applied to the front and rear roll hoop for a total of 10 load cases, as shown in the setup in Figure 6b.

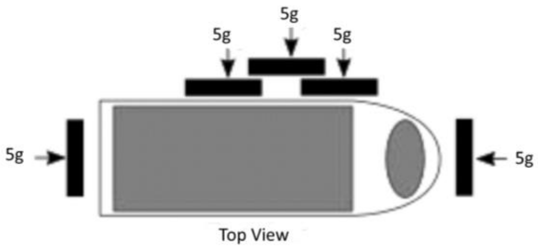	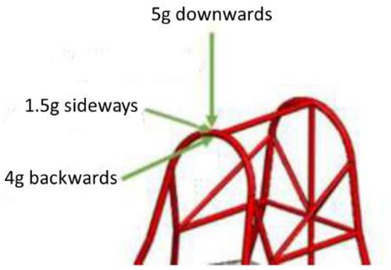
Figure 7: Occupant cell Impact load case (F.3.3.1, FSGP 2022)	Figure 8: Roll Cage Impact load case (F.3.3.1, FSGP 2022)

For the roll cage, 3D elements are being used to discretize the model after 5 mm fillets are applied to all joints and gussets in SOLIDWORKS. In ANSYS, structural members unrelated to the roll cage (below shoulder level) were removed except for those needed to apply elastic boundary conditions. AISI 4130 steel was applied to the structure, the contact patches for the applied force are created from nodes at the top of the front hoop and back hoop within the specified in F.3.3.2, FSGP 2022, and the model is meshed with an element size of 1 mm at the joints and the default size for the rest. The model is constrained with displacement supports using the 3-2-1 method as well as elastic supports, and the inertia relief option was used. Simulations were performed with the impact configurations outlined in regulations.

The chassis meets impact requirements with a factor of safety above 1.1 and with less than 25mm of deformation for all cases. The methodology and corresponding results which are summarized in Table 1 have already been confirmed by Brian Call and Bill Elliot who are dedicated experts for assessment of solar car and racing projects championships.

Table 1: FEA Results for occupant cell Impact

Test	Front	Back	Side 1	Side 2	Side 3
Factor of Safety	1.725	1.566	1.398	1.659	1.181
Deformation (mm)	1.977	2.245	6.224	1.557	2.305

further details of FEA Results for occupant cell Impact have been shown in Appendix C. In compliance with the guidelines specified in 10.3.A.8, the primary objective is to ensure that the roll cage does not yield, while all other components of the occupant cell do not deform by more than 25 mm and do not exceed their ultimate strength limits when subjected to the specified load cases. It is crucial to note that the load cases were determined based on the total gross mass of the vehicle, denoted by "g". Decreasing the weight of the chassis and car therefore decreases the force needed for the load cases and increases the ability of the chassis and roll cage to meet the required safety factors. The details of the stress and deformation analysis have been displayed in Appendix D.

All ten impact load cases for the front and rear roll hoops exceeded the required factor of safety of 1.1 using a yield strength of 435 MPa for 4130 steels. Table 2 summarizes FEA Results for roll cage Impact. Of utmost importance is the provision of adequate protection for the driver under these impact conditions. It is imperative to consider the movement of body panels and the solar collector to ensure that these components do not breach the space occupied by the driver during an impact event. This entails careful evaluation and implementation of design measures to prevent any potential penetration or hazards to the driver's safety.

Table 2: summary of FEA Results for Roll cage Impact

Safety Parameter	Front Hoop Case 1	Front Hoop Case 2	Front Hoop Case 3	Front Hoop Case 4	Front Hoop Case 5	Rear Hoop Case 1	Rear Hoop Case 2	Rear Hoop Case 3	Rear Hoop Case 4	Rear Hoop Case 5
Factor of Safety	1.47	1.25	1.41	1.40	1.95	1.16	1.17	1.63	1.15	1.17
Maximum Equivalent Stress (MPa)	294	345	307	308	221	373	371	266	376	369

The details of the stress and deformation analysis are shown in Appendix D. The ongoing efforts to refine and optimize the design will continue to prioritize the safety of the driver, ensuring that the solar car's occupant cell remains robust and resilient in various impact scenarios.

Conclusion

The design and analysis of the solar car chassis have been successfully executed, resulting in a lightweight and safe vehicle. The systematic design methodology employed in this project played a vital role in addressing customer needs and meeting target specifications. By adopting a systematic approach, the design process prioritized key factors such as torsional rigidity, strength against impact loads, packaging considerations, and clearance requirements for all components. Through the utilization of advanced software tools like SolidWorks and ANSYS, the design was optimized and verified to ensure optimal performance and safety.

Furthermore, the integration of seat belt design, compliant with FSGP safety requirements, further enhanced driver safety. The completed chassis design, developed by the Virginia Tech Solar Car Project Team, not only meets the essential criteria for performance, safety, and efficiency in solar car racing but also showcases the effectiveness of a systematic design methodology.

It is essential to emphasize that the design methodology employed in this project provided a systematic and structured approach to address customer needs and target specifications. By focusing on these aspects, the team was able to deliver a solar car chassis that not only meets the required standards but also ensures driver safety and overall vehicle performance.

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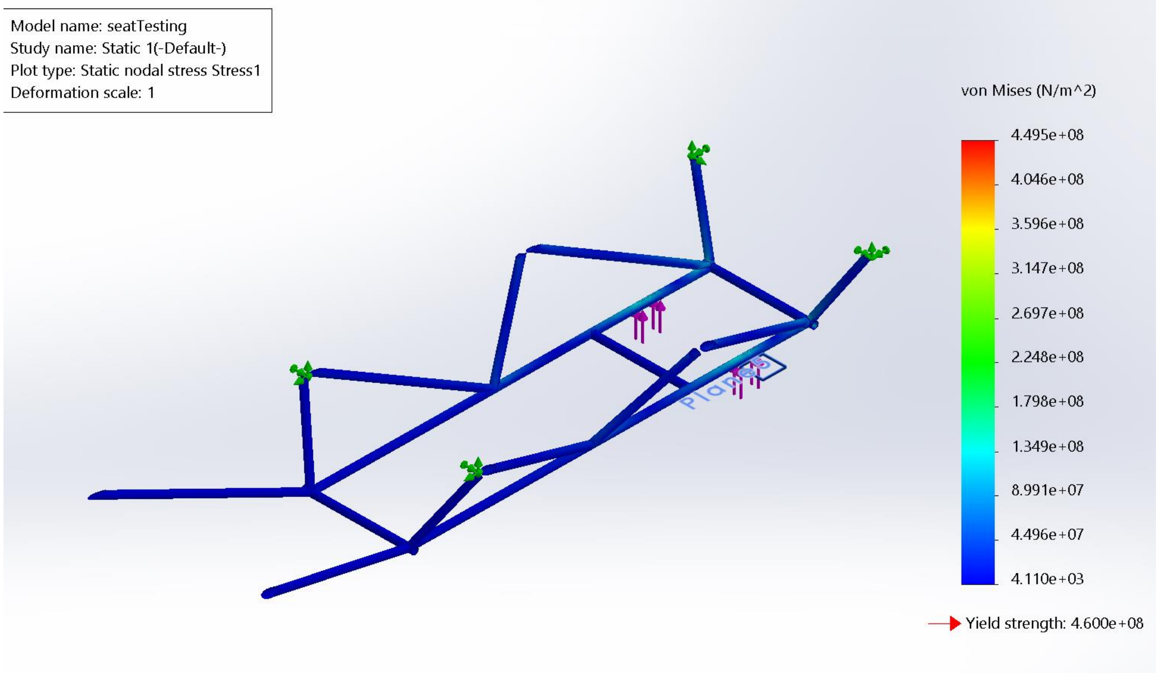
Appendix A: Summary of customer needs and target specifications for chassis design

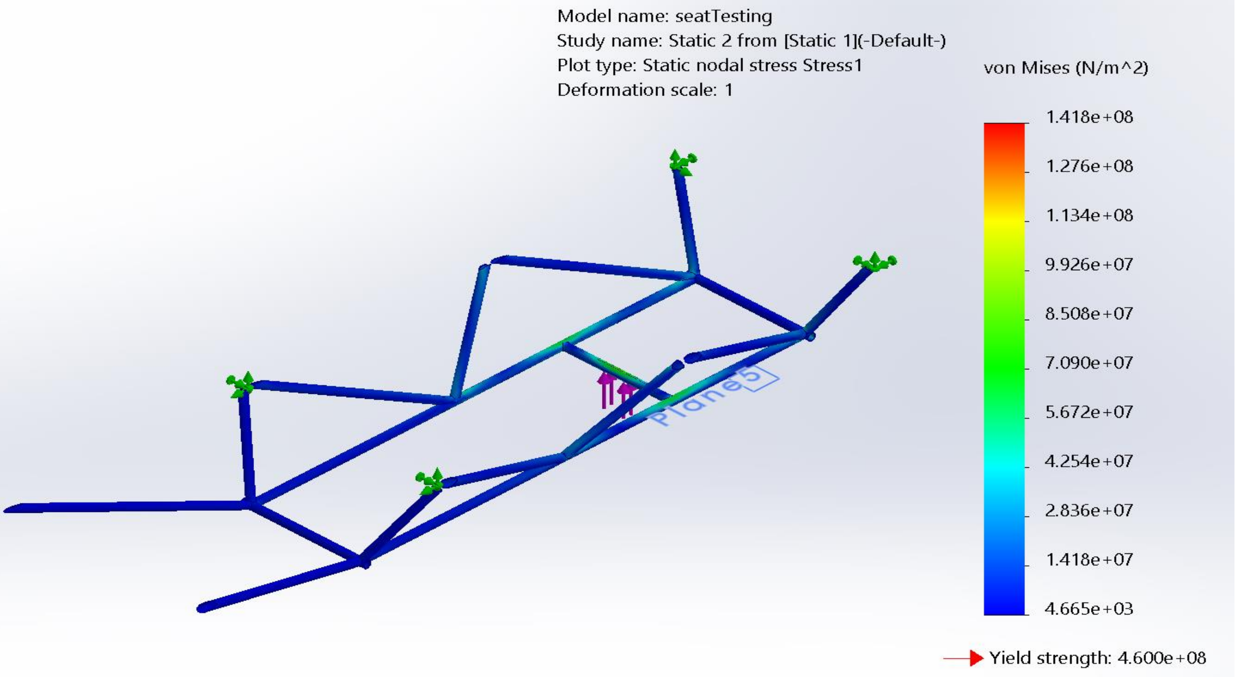
		Structures Engineering Characteristics		2	3	6	7	8	9
Customer Needs	#	Description	Customer Weighting (5-1)	Gap size (cm)	Angle (degree)	Deformation (mm)	Weight (kg)	Radius (mm)	Gravit-ation Acceleration (G)
	1	Chassis has to satisfy the dimension regulation	4	1	3	1	3	9	3
	2	Gap between the car body and ground must be >10cm	5	9	1	3	3	3	1
	3	Vehicle must not tip over at a 45 degree angle	5	1	9	1	3	1	3
	4	Roll cage must be above shoulders	5	1	1	3	1	1	9
	5	Max. deformation of roll cage is 25 mm and cannot fail	5	1	1	9	1	1	9
	6	Occupancy space must have an 835 mm radius at all points from driver	5	1	1	1	1	9	9
	7	Bolts meet SAE grade 5, metric grade M8.8	5	1	1	1	3	1	3
	8	Meets all the load/impact (G) requirements for chassis/roll cage	5	1	1	9	3	1	9
	9	Frame has to be light	3	1	1	1	9	1	1
	10	Frame has to be comfortable to the driver	3	1	1	1	1	1	1
	11	Chassis should have triangle in every segment	2	1	1	9	1	1	1
		Absolute Score		87	95	163	119	129	235
		Importance Ranking 1st, 2nd, 3rd…		6	5	2	4	3	1

Structures Target Specifications Table					
Customer Need #s	**Eng. Characteristic**	**Importance Ranking**	**Units**	**Marginal Value**	**Ideal Value**
1,2,5,7,10	**Gravitation Acceleration (G)**	**1st**	**G**	**3-5G**	**5G**
1,2,3,4,5	**Deformation (mm)**	**2nd**	**mm**	**25mm**	**25mm**
1,2,6	**Radius (mm)**	**3rd**	**mm**	**50.00**	**50.00**
8,9	**Weight (kg)**	**4th**	**kg**	**57.00**	**50.00**
7	**Angle (degree)**	**5th**	**degree**	**45.00**	**50.00**
7	**Gap size (cm)**	**6th**	**cm**	**12.00**	**15.00**

Appendix B: stress analysis of mounting points of the seat belts on chassis



Model name: seatTesting
Study name: Static 1(-Default-)
Plot type: Static nodal stress Stress1
Deformation scale: 1



Model name: seatTesting
Study name: Static 2 from [Static 1](-Default-)
Plot type: Static nodal stress Stress1
Deformation scale: 1

Appendix C: FEA results of impact analysis (occupant cell)

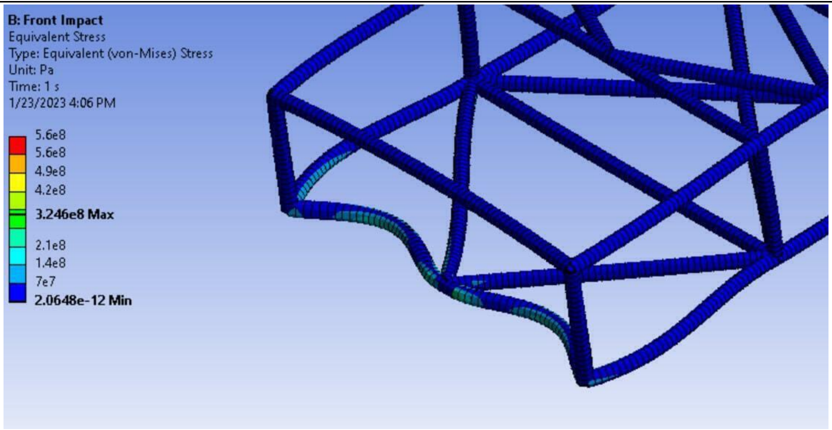


Figure C.1.A: FEA of front impact – equivalent stress

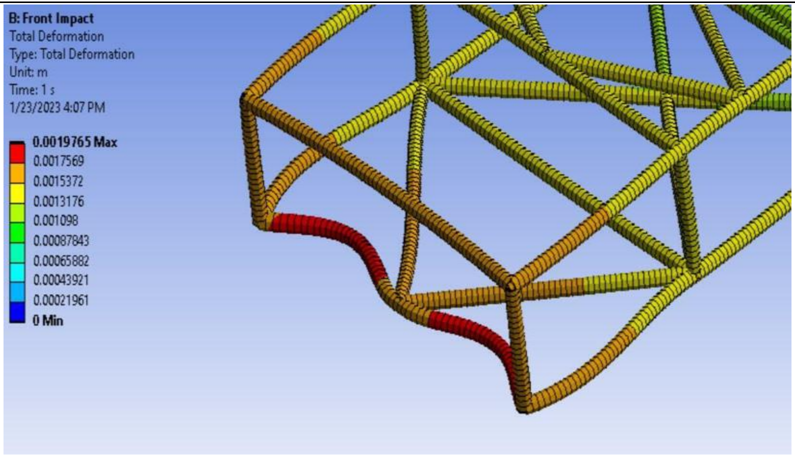


Figure C.1.B: FEA of front impact – total deformation

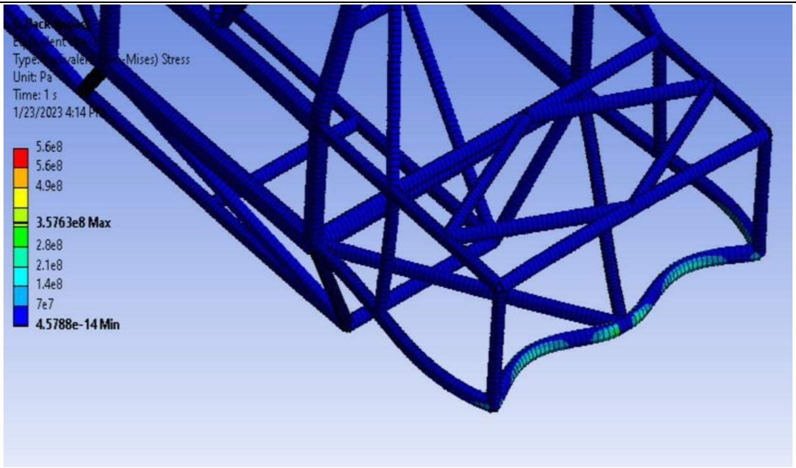


Figure C.2.A: FEA of back impact – equivalent stress

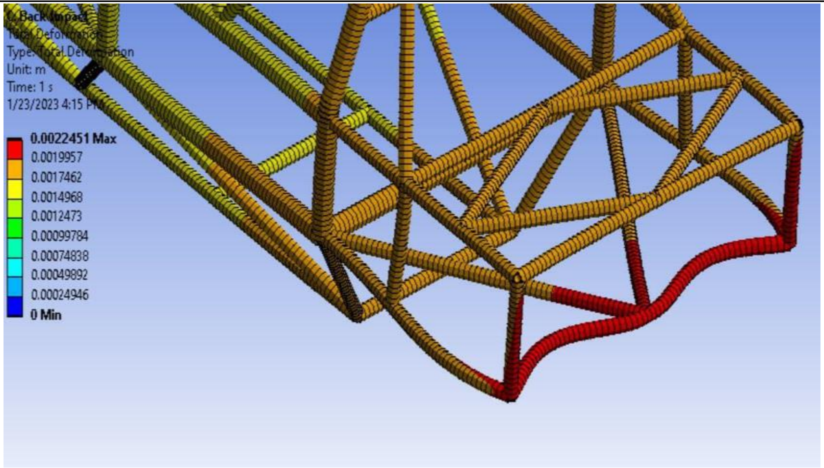


Figure C.2.B: FEA of back impact – total deformation

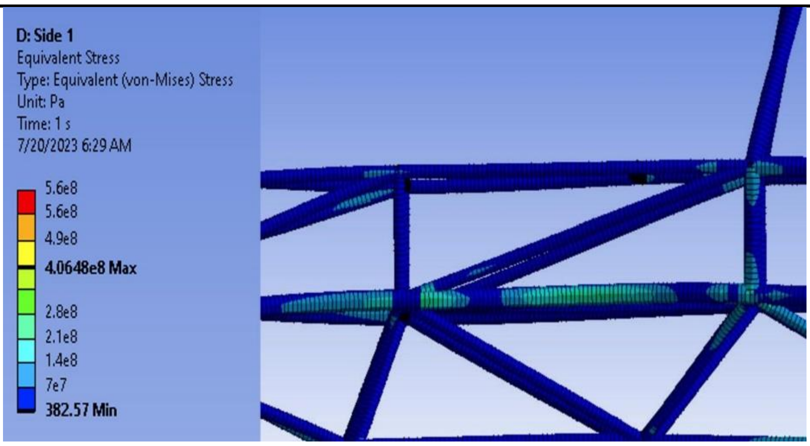


Figure C.3.A: FEA of side impact 1 – equivalent stress

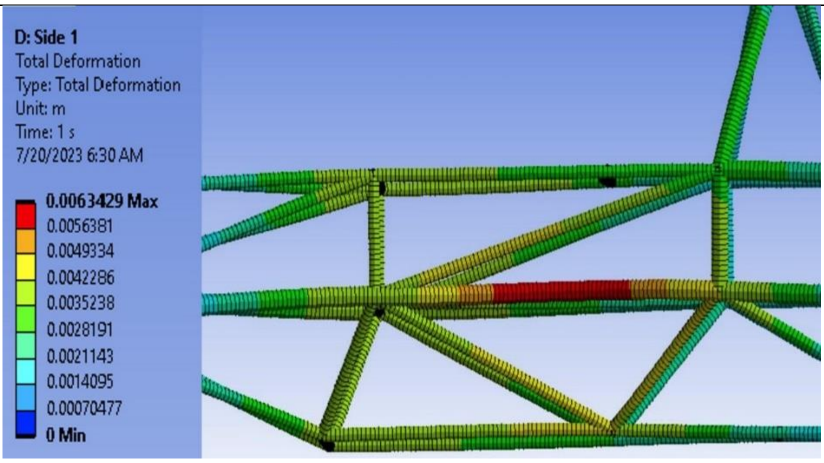


Figure C.3.B: FEA of side impact 1 – total deformation

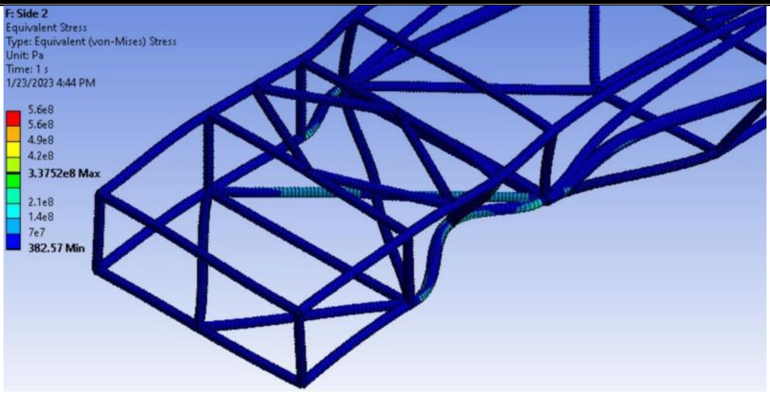


Figure C.4.A: FEA of side impact 2 – equivalent stress

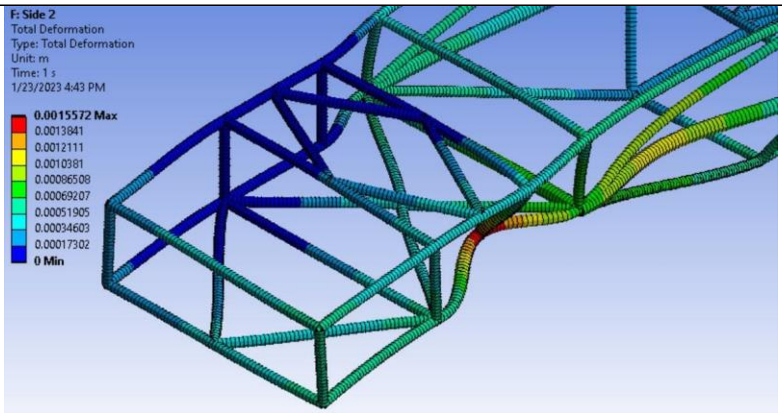


Figure C.4.B: FEA of side impact 2 – total deformation

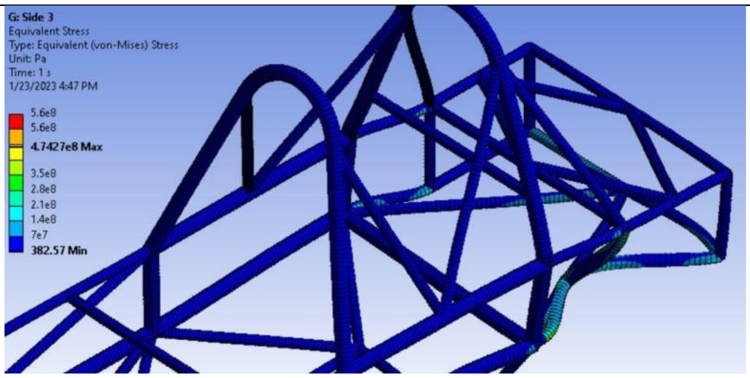


Figure C.5.A: FEA of side impact 3 – equivalent stress

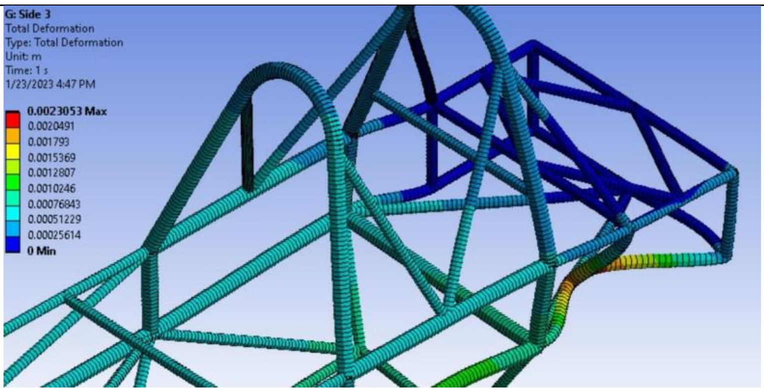


Figure C.5.B: FEA of side impact 2 – total deformation

Appendix D: Front and Rear Hoop analysis results (Roll cage)

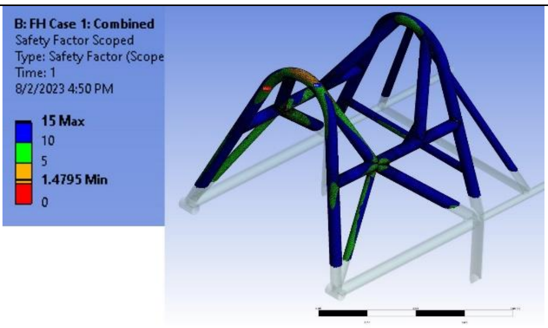


Figure D.1.A: Front Hoop Case 1 Factor of Safety

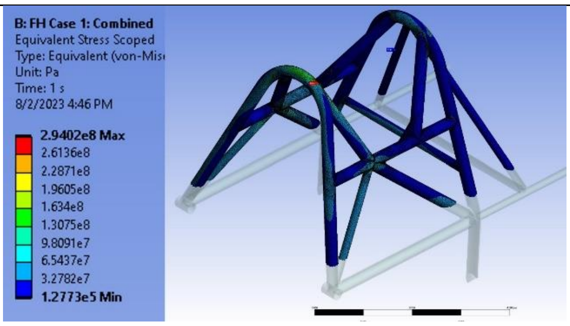


Figure D.1.B: Front Hoop Case 1 Equivalent Stress

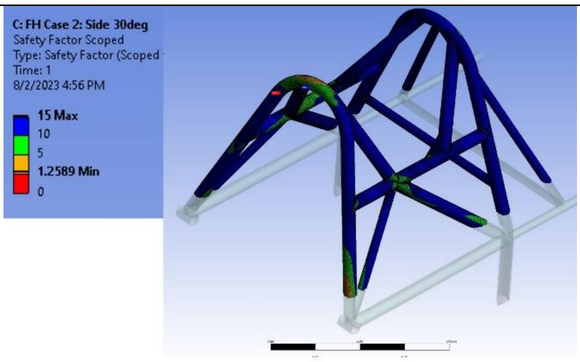


Figure D.2.A: Front Hoop Case 2 Factor of Safety

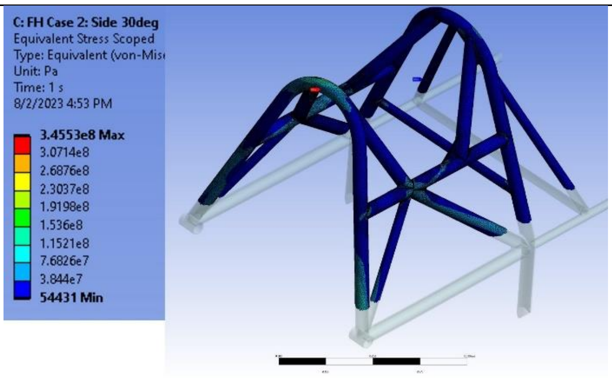


Figure D.2.B: Front Hoop Case 2 Equivalent Stress

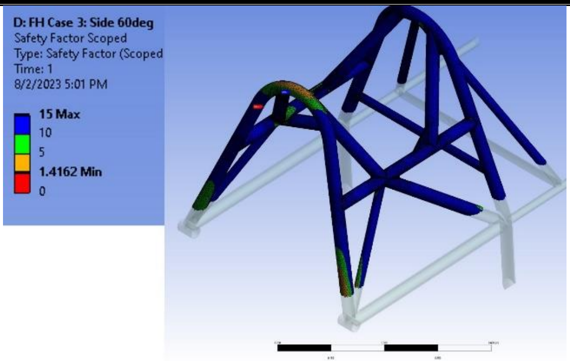


Figure D.3.A: Front Hoop Case 3 Factor of Safety

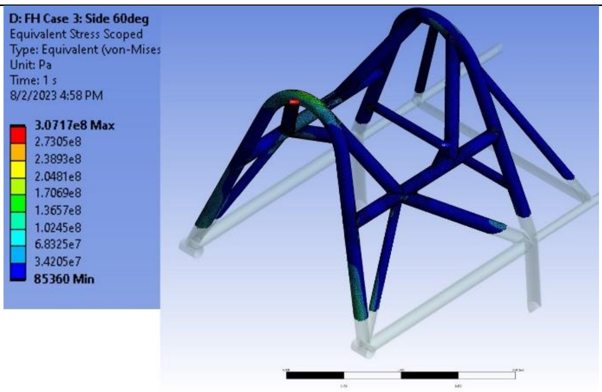


Figure D.3.B: Front Hoop Case 3 Equivalent Stress

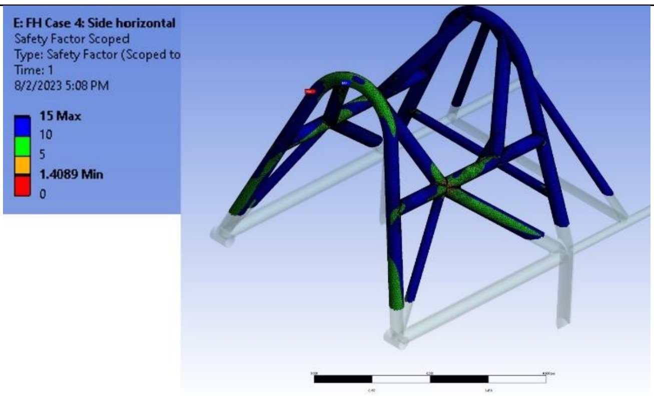


Figure D.4.A: Front Hoop Case 4 Factor of Safety

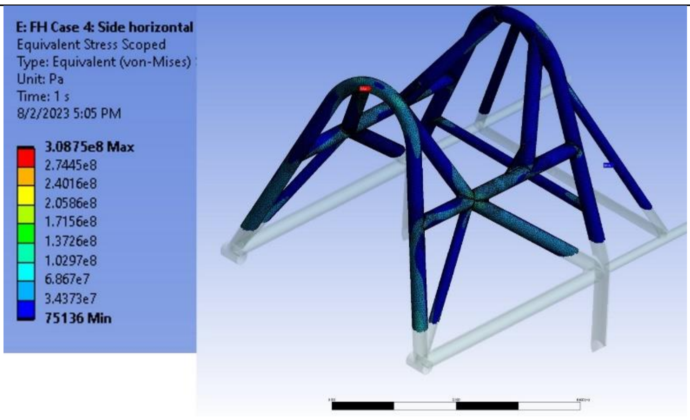


Figure D.4.B: Front Hoop Case 4 Equivalent Stress

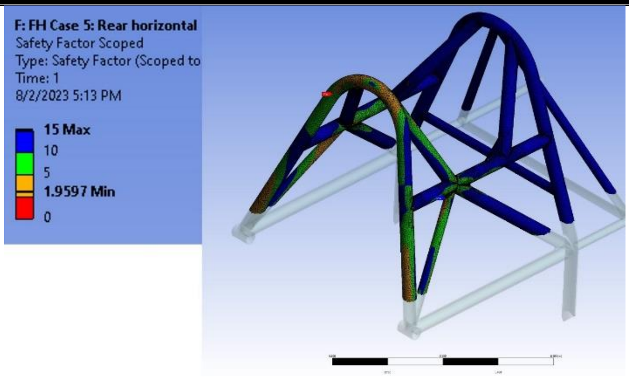


Figure D.5.A: Front Hoop Case 5 Factor of Safety

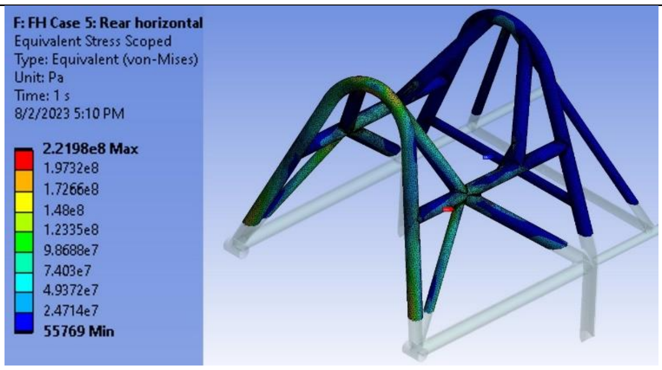


Figure D.5.B: Front Hoop Case 5 Equivalent Stress

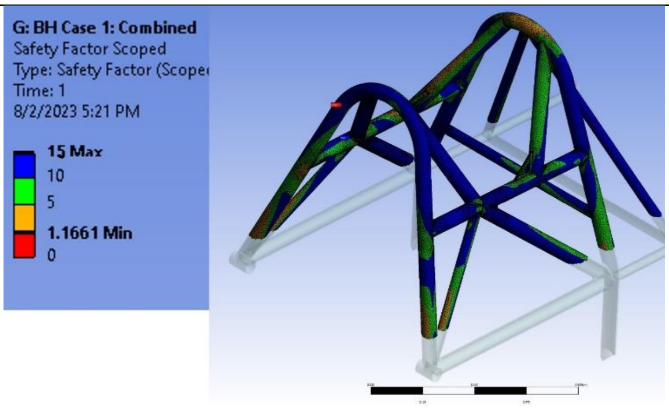


Figure D.6.A: Rear Hoop Case 1 Factor of Safety

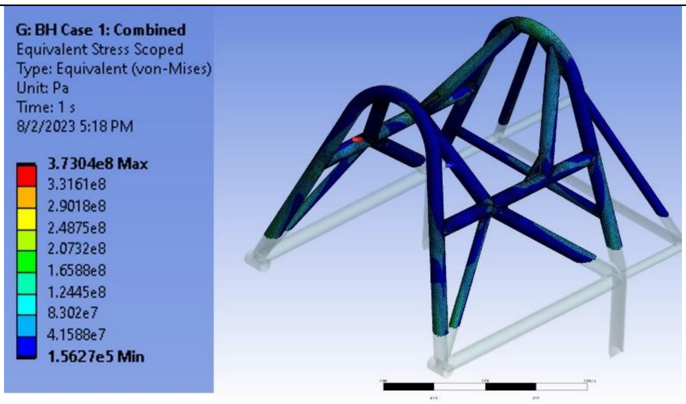


Figure D.6.B: Rear Hoop Case 1 Equivalent Stress

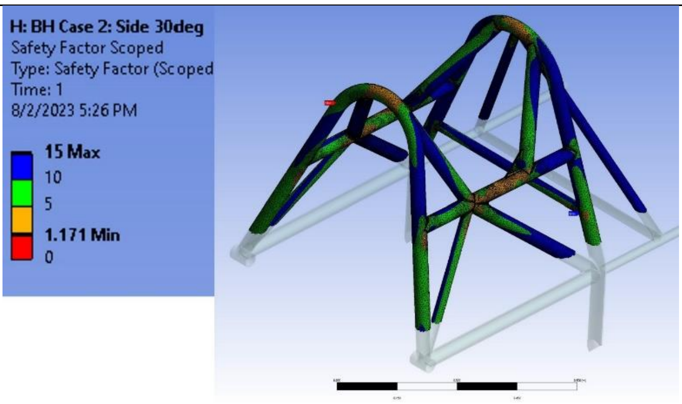


Figure D.7.A: Rear Hoop Case 2 Factor of Safety

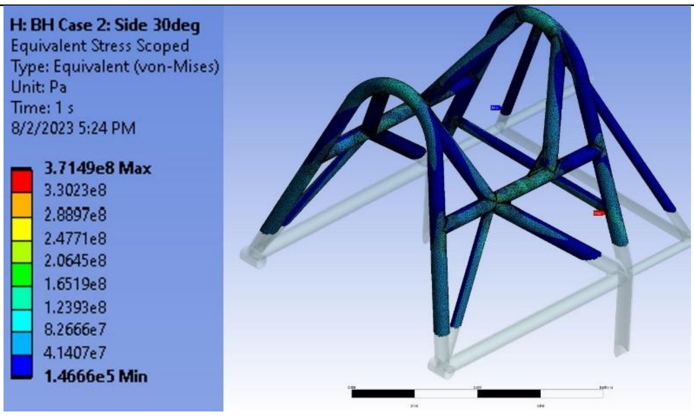


Figure D.7.B: Rear Hoop Case 2 Equivalent Stress

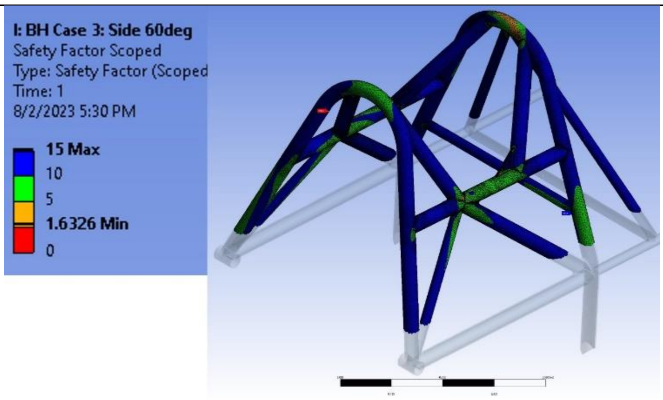


Figure D.8.A: Rear Hoop Case 3 Factor of Safety

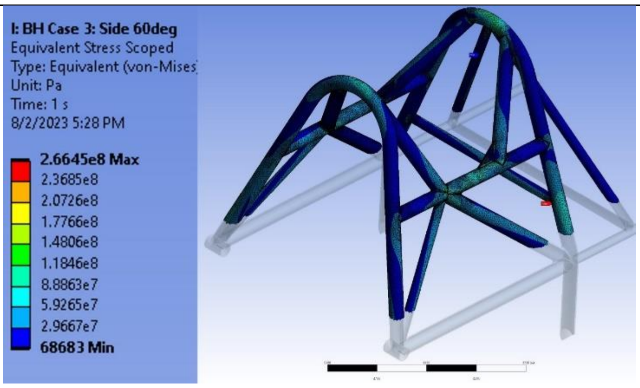


Figure D.8.B: Rear Hoop Case 3 Equivalent Stress

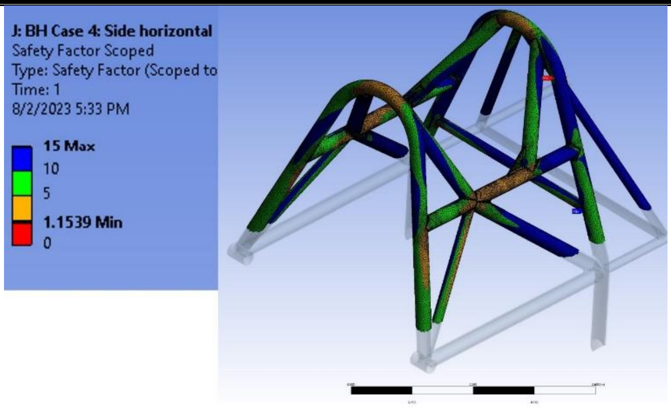


Figure D.9.A: Rear Hoop Case 4 Factor of Safety

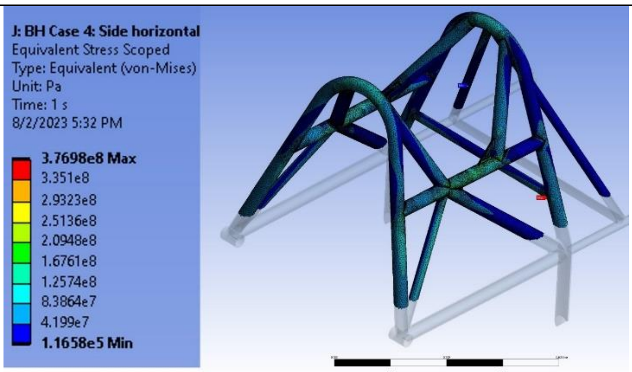


Figure D.9.B: Rear Hoop Case 4 Equivalent Stress

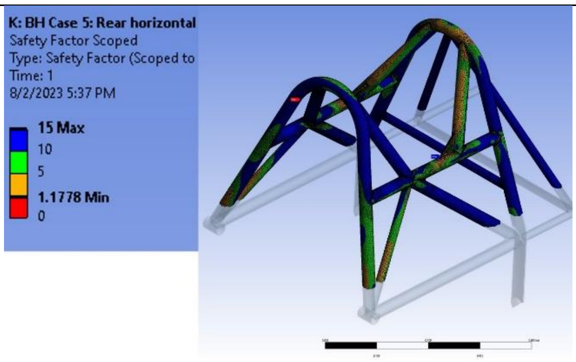


Figure D.10.A: Rear Hoop Case 5 Factor of Safety

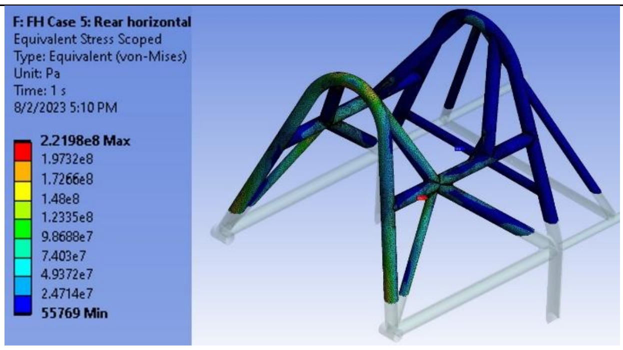


Figure D.10.B: Rear Hoop Case 5 Equivalent Stress