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Selection of Materials, Design and Analysis of FSAE Chassis for Different Engineering Application- A Comprehensive Review

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Review Article

Abstract

The paper addresses some important developments in tubular space frame chassis design which have been pivotal in many engineering and automobile applications. Light weight and high stiffness-to-weight ratio tubular space frame chassis have been widely studied for their performance in motorsports and high-performance vehicles. However, their tendency to fail under extreme stresses emphasizes the importance of rigorous design optimization. This study focuses on the significance of topology optimization a process that refines material distribution within a given design space to enhance structural efficiency. This approach not only improves performance but also reduces material consumption, which leads to cost savings and environmental sustainability. Material selection is the critical aspect of chassis design, where Al-SiC composites are preferred for their strength, wear resistance, and lightweight properties. The integration of methodologies such as force modeling equations, computer aided design (CAD), and finite element analysis (FEA) is emphasized as a core part of the design process. Tools like SolidWorks and ANSYS are highlighted, particularly in the areas of chassis modeling with high precision and structural analysis that ensures designs meet the high standards set by Formula Society of Automotive Engineers (FSAE). Simulation based optimization by ANSYS Mechanical will, therefore play an important role in ascertaining the validation of the structural integrity and the performance of the chassis at a real-world environment by simulating stresses, strains, and displacements so that there could be a probable prediction of failure and, consequently, design refinement. By using this methodology, safety, performance, and cost effectiveness in designing FSAE chassis would comply with FSAE regulations. The integration of cutting-edge technologies and materials ensures that chassis designs meet the evolving demands of modern applications. This comprehensive review serves as a valuable guide for researchers and engineers, emphasizing the interplay of design optimization, material science, and computational tools in achieving efficient and sustainable chassis designs.

Keywords: Aluminum Silicon Carbide [Al-SiC]; Finite Element Analysis [FEA]; Formula Society of Automotive Engineers [FSAE]; Multi-Directional Impact Analysis; Tubular Space Frame Chassis

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1. Introduction

The term "chassis" derived from French, originally referred to the frame or core structure of a vehicle. A car without its body is known as a chassis [1-2]. This skeletal framework supports and carries all the parts mounted on the vehicle, including the engine, suspension, brakes, steering, seating, and loads. If the chassis lacks adequate strength and design, it can lead to malfunctions in other mechanical components, making it a critical foundation of the entire vehicle. Like the backbone in the human body, which supports muscles, skin, and organs, the chassis provides the vehicle with rigidity and stiffness [3]. It also ensures lower levels of noise, vibration, and harshness (NVH) throughout the car [4]. As the most essential part of a vehicle, the chassis provides strength and stability in various conditions, but it also contributes significantly to the vehicle's weight. Reducing unnecessary weight is key to enhancing performance, making a lightweight chassis design important. This can be achieved by using lighter materials and innovative designs to minimize the chassis weight [5–6]. There are primarily four kinds of chassis; the ladder frame chassis was the first kind to be employed. As the name implies, the ladder chassis design includes two longitudinal rails that are connected by lateral and cross braces, like the shape of a ladder. Because of the continuous rails running from front to back, ladder frame design has strong beam resistance but lower resistance to warping and torsion [7].

The monocoque chassis design is currently the most commonly used by manufacturers. It involves a single-piece construction that defines the vehicle's overall shape. This type of chassis is highly appealing for mass production because it is easily automated, and crumple zones can be integrated directly into the structure for enhanced crash protection [8].

A less common design is the backbone chassis, named for its central structure. This design features a rectangular cross-section running through the middle, linking the front and rear suspension points. Its compact design makes it ideal for small sports cars [9].

The tubular space frame chassis resembles a truss, built from round tubes to form a lightweight yet rigid framework. This design leverages the structural strength of thin-walled, round tubes, which perform exceptionally well under torsion, compression, bending, and extension, resulting in a high strength-to-weight ratio [10].

The space-frame chassis, positioned between a ladder chassis and a monocoque, consists of small, simple components that combine to create a larger frame. Similar to a truss-style bridge, these components are arranged in triangles and experience only pure tension and compression, eliminating the need to reinforce members to handle bending loads. The space-frame chassis is a favourite in race car design due to its simplicity in construction, repair, and maintenance [11–12].

To ensure a stiff structure, the tubular space frame chassis is designed with welded struts. It utilizes different types of hollow rods, such as square and circular tubes (pipes), as struts. Although circular tubes are stronger than square ones, square tubes are commonly used due to their ease of connection. Circular pipes are primarily employed in the construction of space frame chassis. In a properly designed space frame, every direction of applied load is supported by a beam, allowing the nodes to bear substantial loads. Beam bending is minimized because the frame elements experience only tension and compression forces [13–14]. The space frame chassis is also highly crashworthy, providing enhanced safety for the driver with a factor of safety of 3. Its cage-like design offers maximum protection, making it both structurally strong in a crash and safer for the driver [15–16].

Benefits of a tubular space frame chassis: The ladder frame design was unsuitable due to its tendency to twist along its length and its lack of diagonal bracing. To increase its strength and stiffness, additional components would need to be added, which would increase the weight and require more time for positioning and welding. The backbone chassis was ruled out because it cannot provide adequate side impact and offset crash protection. Additionally, to fit between the seats, the chassis rails must be positioned closer together, leading to a loss in stiffness. It is also expensive and difficult to manufacture [17]. The carbon fiber monocoque structure was excluded from the design because once the monocoque is cast, it cannot be modified to accommodate changes in mounting locations. Furthermore, carbon fiber monocoques are costly and difficult to repair [18]. The tubular space frame chassis offers several advantages in FSAE racing. It is more affordable than other chassis designs, and modifications are simpler to make. The construction process for a space frame is also faster, and it is easier to manufacture and repair. Stainless steel is used in the race car's construction, but its intricate design and component placement can lead to wasted space, making the car bulkier. The use of stainless-steel tubing has resulted in the car being heavier and losing power [19]. Aluminum Silicon Carbide (Al-SiC) is a metal matrix composite (MMC) made from silicon carbide particles combined with an aluminum matrix. Aluminum provides high strength and low weight, while the silicon carbide particles enhance the material's hardness and durability. This combination improves mechanical properties such as stiffness, wear resistance, and strength-to-weight ratio [20].

Before entering production, a chassis must be evaluated on several critical factors, including weight, manufacturability, torsional stiffness, impact strength, and strength-to-weight ratio. It must also support the loads imposed by the engine, suspension, steering, brakes, and other components, as well as the weight of the driver. Torsional rigidity, or the resistance of a chassis to twisting forces, is a key aspect that influences the overall structural integrity, handling, and stability of the vehicle [21]. Higher chassis rigidity reduces vibrations and torsional flex, improving the vehicle's control and stability. Maximizing torsional stiffness can be achieved by selecting the right materials and optimizing the geometry and positioning of cross-members, braces, and reinforcement panels [22]. Impact strength is also crucial, especially in racing, where driver safety is a top priority. A chassis with high impact strength is better able to absorb and dissipate energy during a collision, reducing the force experienced by the driver and improving their protection. Increasing impact strength is a focus in chassis design, achieved through innovative material use, improved structural designs, and rigorous testing to ensure the frame can withstand crashes and adequately protect the driver [23]. Fatigue analysis is another essential aspect of chassis design, as it ensures long-term performance, safety, and durability. Fatigue analysis evaluates how long the chassis can endure the loads and stresses of regular driving without failing due to fatigue. Understanding loading conditions, material properties, and potential failure points is vital to designing a chassis that can withstand everyday stresses and provide reliable service throughout its lifespan [24].

Chassis can be classified into 4 type that are Ladder Frame Chassis, Monocoque Chassis, Backbone Chassis and Tubular Space Frame Chassis.

A ladder frame chassis, consisting of two longitudinal beams connected by lateral cross members, provides strength, simplicity, and the ability to support heavy loads. It is utilized in trucks, buses, and off-road vehicles because of its superior torsional rigidity and flexibility of mounting body types. Heavier and less crash-efficient than unibody designs, its reliability and modularity make it suitable for utility and commercial vehicles [25].

The body and the frame in a monocoque chassis combine as a single shell that distributes loads on it to make lightweight and improve aerodynamics. Being extremely common in modern cars, it enhances handling, improves fuel efficiency, and it is also efficient at absorption of impact energy, ideal for passenger vehicles. Though lesser suited for heavy-duty or off-road usage because the load-bearing strength of such is less than that of the ladder frame [26].

A backbone chassis has a central tubular or rectangular beam with structural rigidity that provides support to the engine, transmission, and suspension. It is utilized in sports cars, off-road, and niche vehicles due to its light design and high torsional strength. Although it is very robust and durable, it offers less interior space and crash protection compared to monocoque or ladder frames, making it compromise passenger comfort for performance and load-bearing capabilities [27].

A tubular space frame chassis is a structure, made of interconnected sections, which are essentially thin-walled tubes. These sections provide an excellent strength-to-weight ratio and are torsional stiff. They have high usage in performance and racing cars. Their design enables modification to suit the required use. The material used may be aluminum alloys or even tubular steel, with these providing high rigidity, although at a lightweight price. Its high production cost and complexity limit its application only to specialty vehicles [28].

2. Material Used for Fabrication and Their Material Properties

2.1. Material review

Recently, there has been a lot of interest in Metal Matrix Composites (MMCs) due to its prospective uses. Modern composite materials, such as Al/SiC metal matrix composite, are progressively taking center stage in production sectors including the automotive, aerospace, and automotive industries. Metal matrix composites (Al-SiC) as shown in the Figure 1 are composite materials that combine the high strength and stiffness of silicon carbide particles with the lightweight characteristics of aluminum. The material produced by this combination has higher strength, stiffness, and wear resistance, among other mechanical qualities that make it appropriate for high-performance uses in the automotive, aerospace, and military sectors. The reinforcement provided by the silicon carbide particles increases the overall toughness and hardness of the material. The endurance of the composite is increased by the dispersion of silicon carbide particles inside the aluminum matrix [29].

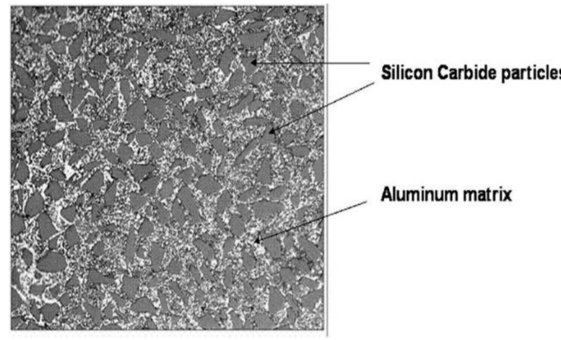

Figure 1. Microscopic structure of Al-SiC [30]

Steel, titanium, chromoly steel, and carbon fiber are used in most chassis designs because of their specific mechanical properties and applications. The value of steel lies in its low cost and high strength, but it is quite heavy, which makes it unsuitable for performance-based designs. Titanium alloys offer the highest strength-to-weight ratio along with excellent corrosion resistance, though at a much higher price [31]. Chromoly steel is a chromium-molybdenum alloy that has strength and weight, better than structural steel but still carries a lot of weight [32]. Carbon fiber stands out due to its excellent strength, stiffness, and lightweight properties. It is perfect for the high-performance vehicles but costly and complicated to manufacture so it's not widely used [33]. Optimized chassis designs make possible 35% material savings compared to structural steel and chromoly steel, and up to 20% more than that compared to titanium alloys

To fabricate Al/SiC metal matrix composites (MMCs) using the melt-stirring method, bars and circular plates with different SiC weight fractions (5%, 10%, 15%, and 20%) were prepared. The materials were homogenized by stirring at 200 revolutions per minute for 15 minutes using a graphite impeller. Mechanical characteristics such as proportionality limit, ultimate tensile strength, breaking strength, and the upper and lower yield points of tensile strength were assessed. The results showed that higher SiC weight fractions led to improved tensile strength, with increased SiC content (5%, 10%, 15%, and 20%) also contributing to greater hardness in the composites of the study was to develop aluminum matrix composites reinforced with ceramics that offer high strength and low weight, focusing on the AA6061 alloy [34]. A varienum alloys are used for technical applications and research, with the choice of alloy for MMCs being influenced by factors like composition, response to heat treatment, mechanical behavior, and corrosion resistance [35]. The investigation targeted reinforcing aluminum alloy composites with silicon carbide to create advanced structures that could eventually replace existing superalloys.

The research primarily focused on fabricating Al/SiC composites through powder metallurgy, a technique chosen for its ability to achieve uniform reinforcement distribution and localized residual porosity without triggering interfacial chemical reactions. SiC particles of various weight fractions (10% and 15%) and mesh sizes (300 and 400) were used as reinforcements, offering different mechanical properties for evaluation. Experimental findings revealed that variations in SiC weight fractions and mesh sizes directly affected the mechanical properties of the composites. The powder metallurgy method ensured uniform reinforcement dispersion throughout the matrix, helping to achieve the desired properties for the Al/SiC composites without causing chemical interactions at the interface [36].

In another study matrix composites were produced using a liquid metallurgical process. These composites, made from aluminum and SiC particles coated with nickel and copper, exhibited enhanced toughness. Copper-coated SiC particles demonstrated better hardness and metallurgical bonding compared to nickel-coated ones. The electroless process was used to coat SiC particles with nickel and copper to improve the interfacial bonding with the aluminum matrix. During fabrication, parameters such as melt temperature, stirring speed, stirring time, and preheating temperature were optimized. Different compositions of Al-SiC MMCs with SiC content ranging from 5% to 15% were tested to examine the effects of Ni and Cu coatings on hardness. The A356 alloy showed an increase in hardness as the SiC content increased in both Ni- and Cu-coated SiC MMCs, attributed to the higher volume fraction of SiC in the alloy [37].

The most balanced product material that emerges from Table 1 is therefore Al-SiC composites. They have lightweight characteristics akin to advanced materials with carbon fiber but are nonetheless cost-effective and safe under operation. This balance from the reduced weight, cost efficiency in construction, and reliable structural operation is what makes AlSiC the preferred material material in modern chassis design requirements meeting both engineering and economic capabilities.

When choosing materials for various chassis types, several prime considerations must be weighed against one another to achieve optimal performance, safety, and cost. Strength is key, as the material must resist the weight of the vehicle and dynamic forces like acceleration, braking, and cornering. For high-performance applications, titanium or chromoly steel are excellent choices because they offer high strength-to-weight ratios. Other significant aspects are Weight - more for performance variants or for EVs; where any weight reduction has positive influences on handling and fuel efficiency along with overall performance. Carbon fiber and aluminum alloys can be used based on its light weight characteristics. Finally, Cost would play a greater role where for mass market and commercial models, expensive options such as carbon fiber cannot be an option. In these applications, lower cost but still adequate strength materials like steel or aluminum are preferred. Resistance to corrosion is critical, especially for automobiles, which are exposed to high environmental conditions. Aluminum and galvanized steel are commonly used since they resist rust and corrosion well. Fabrication and manufacturing feasibility also comes into play; a material must be easy to fabricate and allow for an efficient, scalable method of manufacture. Last but not least, while off-road vehicle chassis types require particularly impact resistance and suitability to extreme conditions, ultimate selection will depend on whether the intended application can get by with those factors, matching up with performance requirements, security standards, and budget constraints [54].

Table 1. Different materials used for chassis

Sl. No	Material	Critical findings	Reference
1.	SAE-AISI 1020	Higher stress produced, higher deformation, light weight	[38]
2.	Carbon Composites	Weight was reduced, stiffness of the chassis increased, material was expensive	[39]
3.	AISI 1018	Weight was reduced, stress was negligibly reduced	[40]
4.	AISI 1144 Carbon Steel	Minimum stress tolerance and high internal resistance	[41]
5.	Polymer composite	Less weight, increase in longitudinal and lateral stiffness	[42]
6.	Chromyl Steel	Increased stiffness, material cost was expensive	[43]
7.	Stainless Steel	Less tolerance to stress and total deformation	[44]
8.	Forged steel SM45C	Optimized weight, improved fuel efficiency	[45]
9.	Magnesium alloys	Increased toughness, strengthening and less deformation, good thermal properties	[46]
10.	Titanium alloys	High yield strength, enhanced ductility, enhanced tensile strength	[47]
11.	St52 [Structural steel plate]	Increased strength, hardness and performance	[48]
12.	Austenitic steel	Increase in yield strength and ductility, increase in thermal properties	[49]
13.	Cast Iron	Improved tensile strength, good vibration absorption, increase in damping	[50]
14.	ASTM A36 steel	Increase in tensile strength and yield strength	[51]
15.	ASTM A302 Alloy Steel	Increase in tensile strength, stress was reduced	[52]
16.	Aluminum 6063 Alloy	Increase in yield strength and elongation	[53]

The use of advanced material such as carbon fiber and titanium alloy in the FSAE chassis manufacturing highly imparts the cost both on the side of material costs and the processes by which the chassis is constructed. Carbon fiber are known for their light properties and high strength that may translate to performance in the handling and fuel efficiency due to a minimized weight of the chassis overall. However, this comes at a high cost, both in terms of raw material and labor-intensive manufacturing processes like molding and curing. That would make it an expensive proposition for FSAE teams who need precision and quality control. Specialized equipment and skilled labor to work on carbon fiber further add to the costs of production [55]. Similarly, titanium alloys, although having a superior strength-to-weight ratio and high-temperature resistance, are several times more expensive than steels or aluminum. Moreover, the fabrication of titanium alloy requires specialized tools and techniques, thereby further increasing its cost. Although these materials can offer performance advantages, particularly on weight reduction and durability, these attract costs that may be hard to affect when budgets are limited as those of FSAE teams. Consequently, teams have to weigh the pros and cons of using advanced materials versus staying within budget constraints. For this reason, sometimes teams use a mix of materials such as aluminum or steel for parts of the chassis while using carbon fiber or titanium strategically at key points [56].

2.2. Material properties

Aluminium metal matrix composites (AMMCs) are lightweight materials with high strength-to-weight ratios that are widely used in industries such as automotive, aerospace, and marine due to their isotropic properties and adaptability in forming processes. Research has shown that factors like the weight percentage and size of the reinforcement particles influence the mechanical properties of AMMCs, including hardness, density, and porosity, which in turn affect tensile strength and ductility. Silicon carbide (SiC) particles, at 5% weight and 63μm in size, were selected as the reinforcement material for AA5052 due to their high hardness and elastic modulus. The reinforced AA5052 composite exhibited improved hardness and compressive strength compared to the unreinforced alloy, primarily because of the SiC's reinforcing effect [57].

Al/SiC composites, like other AMMCs, are valued for their performance at high temperatures, wear resistance, and specific strength. Ceramic composites such as silicon carbide (SiC) are preferred as reinforcements due to their superior mechanical properties, enhancing matrix performance. Powder metallurgy, combined with microwave sintering, facilitated the uniform dispersion of SiC particles within the aluminium matrix, significantly improving the mechanical properties such as toughness and tensile strength of the composite compared to pure aluminium. However, as the size of the reinforcing particles increased, a reduction in elongation was observed [58].

To prepare samples for testing, a mixture of fly ash, silicon carbide, and aluminum 7068 in powder form was compressed under pressure. The samples were sintered at 600°C for two hours before being subjected to tests for hardness, density, compressive strength, and scanning electron microscopy (SEM). Aluminium 7068 served as the base metal in the powder metallurgy process. The hardness test revealed that aluminium 7068 reinforced with 4% silicon carbide achieved a maximum hardness of 96 BHN, with hardness increasing as the silicon carbide content rose. SEM analysis demonstrated the microstructure and bonding of the silicon carbide and fly ash within the aluminium matrix, and energy dispersive X-ray (EDX) analysis confirmed the presence of these reinforcements [59].

Further studies of Al/SiC metal matrix composites (MMCs) have focused on corrosion behaviour and microstructure. An increase in the volume fraction of SiC and a decrease in its particle size were found to improve corrosion resistance. At ambient temperature, Al/SiC MMCs exhibit excellent corrosion resistance, and their density is higher than that of pure aluminium. The size of the SiC particles affects weight loss and corrosion resistance. Mechanical and microstructural studies on Al-SiC composites have demonstrated that incorporating SiC improves the ultimate tensile strength and hardness of the aluminium composites. However, the introduction of SiC particles also increases porosity due to trapped air. Overall, aluminium composites reinforced with SiC achieve significant mechanical property enhancements at a cost-effective level [60].

Because of its remarkable strength-to-weight ratio, aluminium-silicon carbide (Al-SiC) is regarded as the perfect material for tubular space frame chassis in high-performance applications. This offers a lightweight yet sturdy construction that is crucial for optimizing handling, acceleration, and efficiency. By reducing flexing under heavy loads and increasing wear resistance, such as by minimizing surface damage and maintaining structural integrity with minimum maintenance, silicon carbide particles greatly increase stiffness. Al-SiC also has outstanding fatigue and corrosion resistance, which guarantees long-term durability and reliable performance under severe circumstances, as well as outstanding thermal stability, which allows it to retain its mechanical qualities in extremely hot or cold temperatures. Al-SiC is an exceptional material for high-performance chassis design because of these qualities taken together [61].

Future breakthroughs in materials science include nanomaterials, lightweight alloys, and hybrid composites could provide unprecedented strength, stiffness, and durability combinations, whereas additive manufacturing developments may permit the fabrication of complex optimized tubular structures with integrated reinforcement.

3. Design of Tubular Space Frame Chassis

3.1. Design of chassis using rule book

The three most common tube shapes are square, rectangular, and circular. For energy absorption, round tubes outperform all others and are typically used in space frames. Round tubes are also stronger than square tubes in both compression and torsion [62]. Shear and tension strength are similar between the two, but bending strength varies depending on the direction of the applied force. Specifically, square tubes are stronger when bending forces are applied along an edge, functioning like a fully boxed I-beam. However, when bending forces are applied at a 45-degree angle to the edge, square tubes tend to flatten, resulting in a loss of strength [63-64].

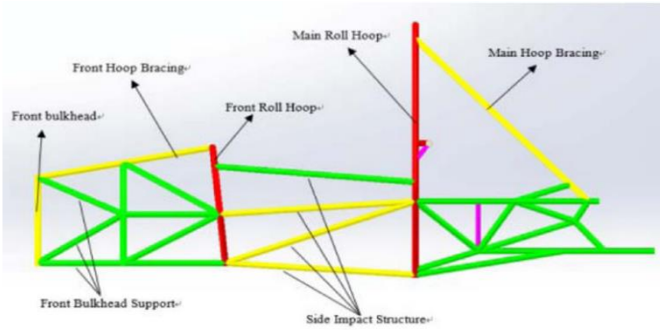

Figure 2. Showing the different parts of a chassis [65]

The front roll hoop, one of the most complex components of the chassis, connects the front and rear sections of the car and is reinforced to protect occupants during rollovers or impacts. The front hoop bracing links this component to other parts of the chassis, such as the floor panel, side sills, or rear roll cage, enhancing overall structural integrity. The front bulkhead, situated at the front of the chassis, provides crucial support and rigidity, especially during frontal impacts, and acts as a protective barrier while contributing to overall chassis stiffness. Supporting the bulkhead, the front bulkhead support connects its top to other structural elements, ensuring proper load transfer throughout the chassis [66-67]. The main roll hoop, located behind the driver's seat, arches over the car's interior to safeguard the driver in case of a rollover. Main hoop bracing, including diagonal and lateral bars, further reinforces the main roll hoop by connecting it to other chassis components like the floor panel, rear bulkhead, or rear roll cage. Lastly, the side impact structure, situated between the front hoop and the main hoop, features side impact beams in the doors, as shown in the Figure 2 reinforced pillars such as the B-pillar, and additional reinforcements in the chassis and body panels to enhance protection against side impacts [68].

Chassis design requires the careful consideration of several factors to ensure performance, safety, and durability. Structural strength and rigidity are of paramount importance, since the chassis has to bear the weight of the vehicle, support dynamic loads due to acceleration, braking, and cornering, and resist external forces in impacts. Weight optimization is another important factor: weight reduction enhances fuel efficiency, handling, and acceleration, particularly in performance and electric vehicles. Material selection is critical, and one opts for steel, aluminium alloy, or composites depending upon the strength-to-weight ratio with respect to cost and feasibility to manufacture. Crash safety is very vital, and the design ought to absorb and dissipate impact energy efficiently to safeguard people inside. Manufacturing feasibility or cost-effectiveness will establish whether the design can go into mass production without costs exceeding budget constraints. Aerodynamics also plays an important role in chassis design, especially in high-performance vehicles, where drag can be significantly reduced to achieve better performance. For utility and commercial vehicles, load-carrying capacity and modularity are significant factors. The integration of standards and regulations, such as those from FSAE or safety authorities, ensures that the vehicle is compliant and reliable. Each design choice must therefore balance these factors, addressing specific requirements for the vehicle while optimizing performance, safety, and cost [69].

3.2. Specification of tubular space frame chassis

It was necessary to establish some design criteria before the frame's first design could begin. These are taken directly from the FSAE handbook, which details each and every requirement.

The initial specifications to be determined are the track and the car's wheelbase. The narrower track must make up no less than 75% of the broader track, and the wheelbase must be at least 1525 mm, under F-SAE regulations. Only wheel sizes of 10 in and 13 in are permitted per FSAE regulations and Figure 3 shows the wheel base of the car.

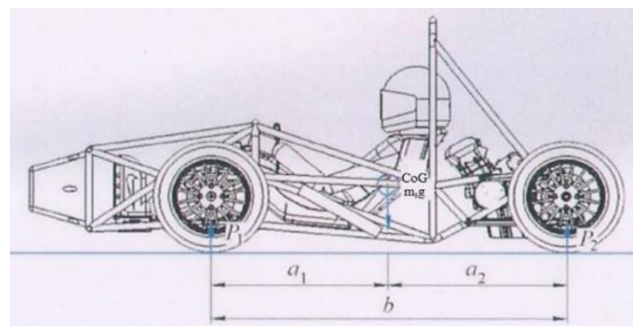

Figure 3. This figure shows the wheel base of the car [70]

The Front Hoop shall be no closer than 250 mm rearward from the steering wheel. When viewed in side view, every part of the Front Hoop above the Upper Side Impact Structure shall be angled less than 20 degrees from vertical. Front Hoop Bracing: The front hoop shall be provided with two forward-raking braces one left-hand and one right-hand. Front hoop bracing shall be secured as close as possible to the top surface of the front hoop, but not deeper than 50 mm is shown in the Figure 4. The front bulkhead must be positively retained all the way back to the front hoop by a minimum of three frame members on each side of the vehicle. To secure the upper support member to the front hoop, one must utilize the zone which falls within 100 mm above and 50 mm below the upper side impact member. The top surface of the front bulkhead should be a minimum of 50 mm below the upper support member's point of attachment.

The Main Hoop needs to be one continuous, uncut length of closed-section steel tubing that meets. Less than 10° must separate the portion of the Main Hoop above the top Side Impact Tube connection point from vertical. The Main Hoop and the chassis bottom tubes must be no less than 380 mm apart. The Main Hoop Braces have to be fastened 160 mm or less below the Main Hoop's uppermost surface. The Main Hoop and Main Hoop Braces must create an included angle of at least 30° is shown in the Figure 5 (a). On each side of the car, at least two Frame Members must support the lower end of the Main Hoop Braces back to the Main Hoop.

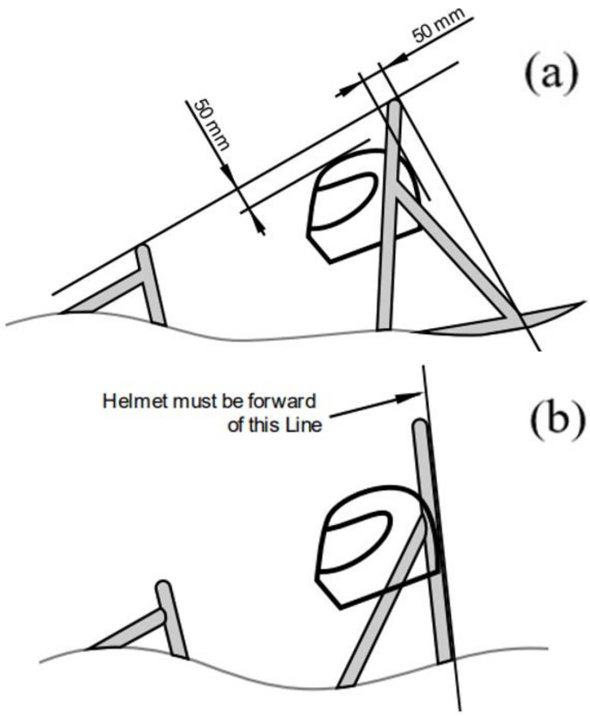

Figure 4. Measurements of driver's position(a), Positioning of the driver (b) [71]

As the driver remains in the standard driving position, the Side Impact Structure has to be made up of three or more tubular elements that are placed on either side of the driver and the driver position is shown in the Figure 5(b).

It shall be completely in a zone parallel to the ground between 240 and 320 mm is as shown in the Figure 6 above the lowest point of the top surface of the Lower Side Impact Member, connecting the Main Hoop and the Front Hoop.

To prevent toppling, the vehicle's center of gravity must be kept as low as feasible. Low center of gravity can be achieved, for example, by mounting heavy parts directly on the chassis, such as the engine and driver's seat. Preserving the structural integrity is also essential. This is accomplished by using bends rather of welds, which lowers the cost [71–72– 73].

Electric vehicle (EV) chassis design has some unique challenges when compared to internal combustion engine (ICE) vehicles. Probably one of the most obvious is battery placement and integration. EVs require large, heavy battery packs often mounted on the floor of the vehicle to lower the centre of gravity and improve stability. This requires a chassis design that can accommodate the size and weight of the battery while providing structural integrity and safety, especially in crash scenarios. ICE vehicles have a compact engine and transmission, allowing for more traditional chassis designs. Weight distribution is also a challenge for EVs, as the batteries cause an uneven weight distribution, which impacts handling and performance. Thermal management of the battery is also necessary in an EV chassis, requiring space that is not necessary in a chassis for an ICE. Durability and modularity play a role in an EV chassis, since they might be required to change more often due to changes in size and configuration for different models. Electric drivetrains also have no gearbox as part of their configuration and therefore require a different design for suspension tuning and mounting points. Finally, EVs have higher torque output at lower speeds, which puts different stresses on the chassis compared to an ICE vehicle, requiring reinforcements and optimization for these forces. Thus, EV chassis designs must balance weight, strength, safety, and component integration in ways that differ from conventional ICE vehicles [74].

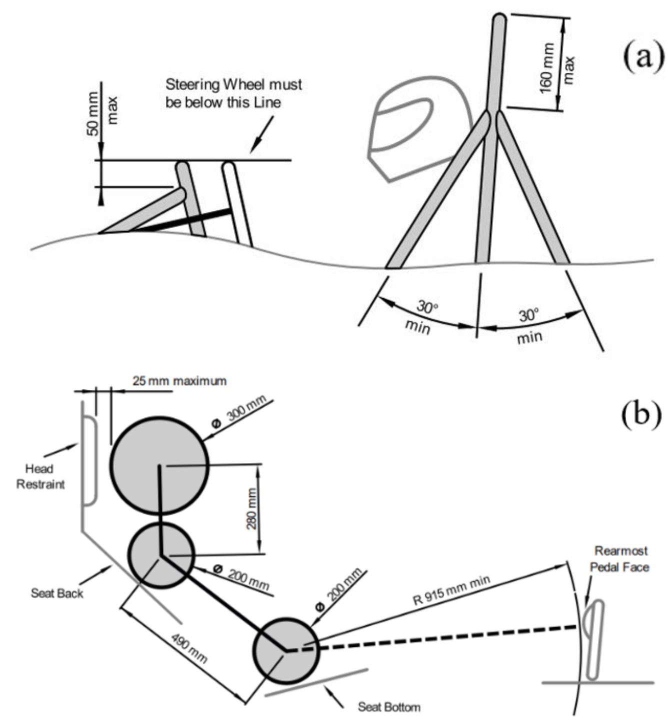

Figure 5. This figure shows the design of (a) main hoop and (b) driver position [71]

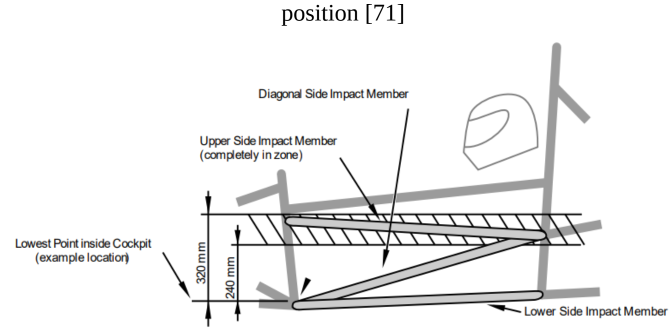

Figure 6. Position and placement of side impact structures [71]

4. Modelling of Tubular Space Frame Chassis

4.1. Modelling of a chassis

In SolidWorks, designing a chassis involves several essential steps. First, plan the design by determining the size, material, and load requirements. Then, create a basic layout. Begin by opening a new part or assembly file in SolidWorks, setting the units accordingly. Draw the general outline of the chassis on a selected plane and apply the necessary dimensions. Use the Extrude Boss/Base feature to define the foundation thickness. With additional sketches and features like Extrude and Cut-Extrude, construct structural elements such as beams and supports. When working in an assembly, ensure that components are properly aligned and fitted together. To fine-tune the design, add fillets, chamfers, holes, and slots. For realism, assign materials and appearances to the model. You can also evaluate the chassis under load conditions using simulation tools and adjust the design accordingly. Finally, generate detailed drawings and export the design for manufacturing [75] and complete model of a tubular space frame chassis is shown in the Figure 7.

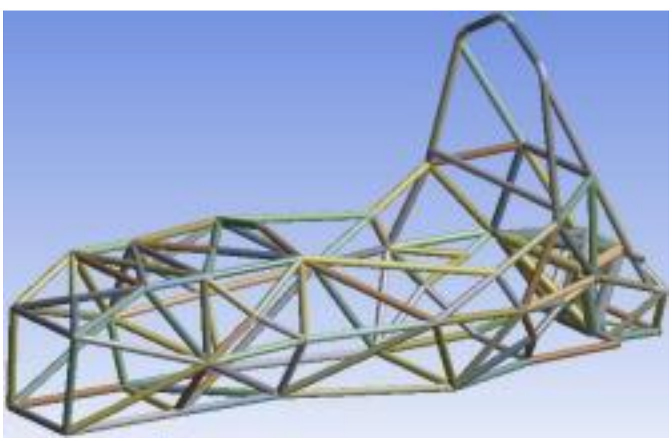

Figure 7. A complete model of a tubular space frame chassis [60]

In the 2023 chassis design process, SOLIDWORKS 2022 was used. As depicted in Figure 3, the design process started by creating reference planes at predetermined locations for the front bulkhead, front roll hoop, main roll hoop, and rear bulkhead. The chassis was divided along the Y and Z axes by a central plane [75].

4.2. Modelling Software Assisted chassis design

Finite Element Analysis is essential in identifying weak points in chassis design and ensuring that the structure withstands real-world forces by simulating mechanical behaviors under various conditions. It analyzes stress and strain distributions to pinpoint areas of potential failure, evaluates the effects of static and dynamic loads, and predicts fatigue to address long-term durability. It enables material and weight optimization to make a lightweight, yet strong chassis suitable for high-performance applications. Additionally, through the simulation of extreme conditions, such as a crash, it offers both safety and standard compliance. Development time and costs reduce considerably through virtual testing without a reduction in reliability, however, when it functions appropriately under real conditions [76].

4.2.1 Ansys software

Ansys is a comprehensive simulation software widely used in engineering fields such as mechanical, civil, electrical, and aerospace engineering. It enables engineers to simulate and analyze various physical phenomena, including structural integrity, fluid dynamics, heat transfer, and electromagnetic fields. By offering tools like Finite Element Analysis (FEA) for structural stress and deformation, Computational Fluid Dynamics (CFD) for fluid flow and heat transfer, and electromagnetic simulation for electrical and magnetic systems, Ansys allows engineers to test and optimize product designs before creating physical prototypes. This saves both time and costs during product development. Additionally, Ansys supports Multiphysics simulations, combining different types of analysis to model complex systems that involve multiple interacting physical phenomena. Its versatility makes it popular across industries such as automotive, aerospace, energy, electronics, and healthcare, helping companies improve product performance and reliability. The ANSYS workbench program is ideal for efficient product design and engineering problem complexity estimation. FEA is a technique that can generate and optimize simulations while obtaining resolution [77].

The modeling of systems and products in a virtual environment with the aim of identifying and resolving possible (or current) structural or performance problems is known as finite element analysis, or FEA. The above table specifies the condition of tubes to chassis in Table 2 Engineers and scientists employ the finite element method (FEM) to mathematically model and numerically solve extremely complex structural, fluid, and multi-physics problems [78].

4.2.2 Mesh construction

Meshing in Ansys is the process of dividing a complex geometry into smaller, simpler elements, which together form a mesh. This mesh is crucial for running simulations because it enables Ansys to perform calculations on the behavior of the model under different conditions. By breaking the model into smaller elements, meshing allows for more accurate simulations, as the governing equations such as stress, strain, or fluid flow are solved at each point of the mesh. Meshing is especially important for handling complex geometries, as it simplifies the simulation process by analyzing smaller, manageable parts. Additionally, it makes simulations more efficient by focusing computational resources on critical areas where higher precision is needed, such as regions with high stress concentrations.

Table 2. Specifies the conditions of tubes to be followed [71]

Tubes	Minimum area under Moment of Inertia (mm^4)	Minimum Cross-Sectional Area (mm^2)	Minimum Outside Diameter or Square Width (mm)	Minimum wall thickness (mm)	Sizes of round tube examples (mm)	Applications
Size A	11320	173	25	2.0	25 *2.5	Front Hoop, Main Hoop, Shoulder Harness Mounting Bar.
Size B	8509	114	25	1.2	25.4*1.6	Front Bulkhead, Front Hoop Bracing, Main Hoop Bracing, Side Impact Structure.
Size C	6695	91	25	1.2	25.4*1.2	Structural Tubing, Main Hoop Bracing Supports, Front Bulkhead Support.
Size D	18015	126	35	1.2	35*1.2	Bent / Multi Upper Side Impact Member.

In Multiphysics simulations, meshing also ensures proper interaction between different physical phenomena. Without meshing, simulations would either lack the necessary detail or be too computationally expensive to run effectively.

In Ansys, various types of mesh elements are used depending on the complexity of the geometry, the type of analysis, and the desired level of accuracy. 1D elements are used for simple geometries like beams or cables, suitable for one-dimensional analyses such as structural beams or trusses. 2D elements such as triangles and quadrilaterals are applied to surfaces or thin structures, ideal for simulations where the thickness is negligible compared to other dimensions, like plates or shells. For more complex, three-dimensional models, 3D elements are common, with tetrahedral elements being suited for intricate geometries and hexahedral elements providing higher accuracy and stability in certain cases. Pyramidal and prismatic elements are used in hybrid meshing, often in boundary layers of fluid dynamic simulations

Elemental sizes that were gradually reduced were used in the analysis. The ideal mesh size is often defined as the elemental size with a sequential stress error of less than 5%. It implies that the accuracy of the results will only be somewhat improved by any additional size reduction. The stress values for various mesh sizes [79]. Before the simulation can be done, the meshing procedure is the last step in the SolidWorks application's modeling of static strength analysis. In order to get high precision in the outcomes, the phases of the meshing procedure were designed to ascertain the number of elements, node points, and coordinate points [80].

Convergence of Mesh outlines the connection between the quantity of components and the precision of the outcomes. To confirm the findings and demonstrate that the analysis result is independent of the number of pieces, mesh interdependence can be examined. demonstrates that the deformation change for progressively smaller mesh sizes is of the order of 0.002. Therefore, any additional reduction in mesh size would merely cause the solver's computing time and complexity to grow without little altering the outcome [81].

4.2.3 Boundary conditions

Even though they take the smallest amount of time, boundary conditions are the most important FEA step. The use of boundary conditions is a difficult issue that depends on both pure engineering judgment and common sense for the following analyses: All rear in-board wishbone mounting points have had their degrees of freedom limited, while equal and opposite loads have been applied to the front in-board points [82]. The boundary conditions were created by setting up the rear suspension points and delivering a remote load at the front hubs along the push rods in opposite directions to simulate the chassis twisting during cornering. A remote load through the push rod positions at the front left and right axles is introduced in opposing directions to simulate [81].

5. Analytical and Numerical Analysis of Tubular Chassis

5.1 Static Analysis

Static analysis on a chassis involves evaluating its structural integrity and stress distribution under static loads without considering motion or dynamic forces. This process uses computational methods like Finite Element Analysis (FEA) to simulate how the chassis responds to forces such as weight, braking, or cornering loads. Engineers apply boundary conditions and material properties to assess stress, strain, and displacement in critical areas [53]. The analysis helps identify weak points, ensuring that the design can withstand operational stresses while minimizing material usage. It is crucial in optimizing the chassis for durability, safety, and performance. By addressing potential failures early in the design phase, static analysis reduces prototyping costs and enhances reliability. [81].

Analyzing static and dynamic loads on a chassis, it is a combination of the computational and experimental methods aimed at ensuring structural integrity and performance. The most effective computational approach for both static and dynamic load assessments would be Finite Element Analysis (FEA). Static analysis evaluates the chassis response to constant forces like weight distribution and payload, identifying stress, strain, and displacement patterns. Dynamic analysis focuses on transient forces such as acceleration, braking, cornering, and road vibrations. Modal analysis is essential in understanding the natural frequencies of the chassis and thus avoiding resonance. Time-domain simulations and frequency-domain analyses help in evaluating responses to real-world scenarios, including impact loads. Experimentally, strain gauge testing and vibration analysis using accelerometers validate computational models. Combining these methods with advanced tools such as CAD software for design and multibody dynamics simulations ensures a comprehensive understanding of the chassis behavior under various loading conditions [83].

5.2 Impact test analysis

Impact test analysis for an FSAE tubular chassis involves simulating how the chassis responds to sudden, high-energy collisions to ensure safety and durability during accidents. This analysis is crucial for evaluating whether the chassis can effectively absorb and distribute crash forces, protecting the driver and critical components. Key aspects include front, side, and rear impact tests, as well as roll-over analysis. In a front impact test, the focus is on how the chassis absorbs energy in a head-on collision, with crumple zones designed to deform and dissipate energy to reduce the force transmitted to the driver. Side impact analysis examines how the chassis withstands lateral forces, ensuring structural members like the roll hoop provide adequate protection. Roll-over analysis tests the chassis ability to support the car's weight if it flips, while rear impact analysis ensures that rear components like the engine and fuel tank are shielded from damage. Finite Element Analysis (FEA) is typically used to simulate these crash scenarios, helping engineers assess stress concentrations, deformation, and failure points in the chassis. The goal is to optimize the design for better energy absorption and crash performance, ensuring compliance with FSAE safety regulations.

Newton's second law, which says that the net force acting on a body is equal to the product of mass and acceleration of the body front, was used to compute the impact forces. Consequently, the impact time will be longer roughly 0.3 seconds because the wall is thought of as a hard, non-deformable body. As a result, the impact time will be clearly less than in the example above. It goes without saying that the impact force in the wall example will be greater than in the previous two situations. The car was thought to be traveling at 45 kmph and impacting the object in 0.13 seconds [84]. The driver and engine loads were delivered at the appropriate points for the front collision. The locations of the rear wheels and suspension mounting points were maintained. The front impact was computed with a 60 kmph maximum speed. It is possible to compute 5g force using the impulse momentum equation. Because applying forces at one end of the chassis while restricting the other leads to a more cautious approach to analysis, the loads were only applied at the front end of the chassis. Based on industry standards, the impact time is 0.3 seconds. For a speed of 60 kmph, force is computed similarly to front impact in the worst-case scenario of a rear hit. The 5g force's value has been computed. The rear end of the chassis was loaded while the front end and front suspension mounting locations. According to industry standards, the impact time is 0.3 seconds [85]. Every Formula Student Vehicle is required by the rule book to have an Impact Attenuator installed. The Impact Attenuator (IA) is a device designed to deflect energy from an automobile in the event that it collides head-on with a wall or barrier. An Anti-Intrusion plate (AIP) composed of aluminum (minimum 4mm) or steel (minimum 1.5mm) is used to attach it to the chassis. Either the Impact Attenuator and Anti Intrusion plate combination is mounted to the chassis (a minimum of eight 8 mm metric grade 8.8 bolts) or it is welded to the front bulk head. Upper SIS, Diagonal SIS, and Lower SIS are the minimum number of steel tubes that make up the side impact structure (SIS). The top component needs to join the main hoop and the front hoop. The lower part is required to join the front and main hoop's bottoms. Furthermore, the upper and lower members must be triangulated by a diagonal member [86].

5.2.1 Experimental analysis

The experimental analysis of a Formula SAE (FSAE) tubular chassis is crucial for evaluating its structural performance under various load conditions, ensuring both strength and safety. The process begins with the design and fabrication of the chassis, typically made from steel or aluminum tubing, which forms the framework for mounting components like the engine and suspension while protecting the driver. After designing the chassis using CAD software, finite element analysis (FEA) is conducted to simulate how it responds to torsional, bending, and impact loads. FEA helps identify potential weak points in the design and allows engineers to optimize the structure before physical testing.

Once the chassis is built, load and deflection testing is carried out to evaluate its torsional stiffness, bending deflection, and vibration characteristics. These tests simulate real-world racing conditions, ensuring the chassis can withstand the forces it will experience. Strain gauge testing is also conducted, where gauges are placed at critical points on the chassis to measure localized stresses. This real-time data ensures that the stresses stay within safe limits. Additionally, impact and crash tests may be performed to assess the chassis ability to protect the driver in the event of a collision.

Each Formula Student Vehicle is required by the rule book to be equipped with an Impact Attenuator (IA), a device that deflects energy away from the vehicle in the case of a head-on collision with a wall or barrier. An anti-intrusion plate (AIP) made of aluminum (minimum 4mm) or steel (minimum 1.5mm) connects it to the chassis. The Impact Attenuator assembly and Anti-Intrusion plate can be bolted to the chassis or welded to the front bulk head. The upper, diagonal, and lower steel tubes are the minimum number of tubes required for the side impact structure (SIS). The upper section has to connect the front and main hoops. The lower section is required to connect the front and main hoop's bottoms. Moreover, a diagonal component needs to triangulate each of the higher and lower members [86]. Newton's second law, which says that the net force acting on a body is equal to the product of the mass and acceleration of the body front, was used to determine the impact forces. Impact: As it happens, the car will hit a wall, a tree, or another vehicle. The bodies of the tree and the second car in the first two situations are malleable. Because the wall is thought to be non-deformable, or a rigid body, the impact time will be longer roughly 0.3 seconds. Consequently, the impact time will be a lot less than it was in the case above. Newton's second law, which states that the net force exerted on a body is equal to the product of mass and force, was used to determine the impact forces [86].

5.2.2 Numerical analysis

The moment of impact was 0.13 seconds, and it was estimated that the automobile was traveling at 45 kmph [84]. The driver and engine loads were applied at certain points in time for the front collision. The locations of the rear wheels and mounting points for the rear suspension did not change. A 60 kmph optimum speed was used to compute front impact. An equation for impulse momentum produced a force of 5 g. Since applying forces to one end of the chassis while restricting the other produced a more conservative analysis, the loads were only applied to the front end of the chassis. According to industry regulations, the impact time is 0.3 seconds. The force is predicted to be similar to a front impact crash at a worst-case rear impact collision speed at 60kmph.

$$F = ma \quad (1)$$

$$F = \frac{\Delta p}{\Delta t} \quad (2)$$

$$J = m \times v \quad (3)$$

The purpose of the front impact analysis is to evaluate both the driver's safety and the stiffness of the roll cage in the event of a head-on collision. A car's side impact study is performed to determine how strong the rollcage will be in the event of a side-impact collision with another vehicle. The impact occurs a little bit later than the front impact since both bodies are pliable. In the event of a side hit, the car was regarded as being stationary. The purpose of the rear impact test is to evaluate the rear part's structural integrity in the event of a rear-end accident. Additionally, in this kind of examination, the front and back the load is applied to the back four nodes once the suspension points are established as indicated by the green arrow [87].

For reliable results, the impact test is run with the ANSYS 19.0 R2 program as shown in Figure 8. The purpose of these tests, which are conducted in accordance with SAE impact test guidelines, is to guarantee both driver and passenger safety. When a collision occurs, if any, the starting boundary conditions for FEA are determined and shown based on real-time situations. Since determining the overall deformation and stress as the analysis's primary objective, it is important to examine how the chassis behaves in light of these simulated findings

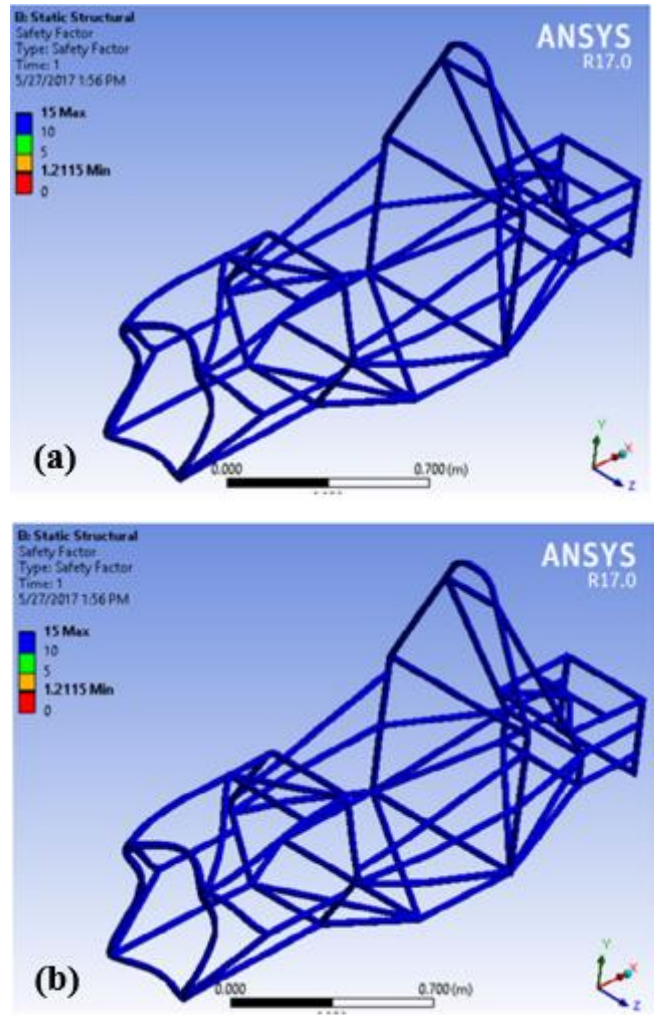

Figure 8. a) FOS for frontal impact, b) Equivalent stress for frontal impact [89]

Given that both conditions produce comparable results, either the firewall beams or the rear suspension mounts are fixed in this state. The above Table 3 is boundary condition of impact. In this case, force is delivered to the front toe bar. In this scenario, the front swing arm mounts are fixed, and force is applied to the rear side of the vehicle [79].

According to the limits in the regulation, the maximum speed of the car is supposed to be 60 km/hr, or around 16.66 m/s. [90].

For a perfectly inelastic collision, the impact force is as calculated from Eq. (1).

$$W_{net} = \left(\frac{m \times v^2}{2}\right)_{final} - \left(\frac{m \times v^2}{2}\right)_{initial} \quad (4)$$

Where, W net is network done on account of an inelastic collision.

$$W_{net} = -\left(\frac{m \times v^2}{2}\right)_{initial} \quad (5)$$

Table 3. Impact testing conditions [88]

Types	Loading Conditions	Boundary Condition	Load Applied
Front Impact	Uniformly distributed load on front bulkhead	The bottom nodes of both sides of the main roll h oop, as well as the sites where the main hoop and shoulder harness tube join, are fixed displacement (x,y,z), but not rotated	120000 Newton
Side Impact	Uniformly distributed loads on side members	The bottom nodes on both sides of the front and main roll hoops have fixed displacement (x,y,z), but not rotation.	7000 Newton
Rear Impact	Uniformly distributed load on rear bulkhead	Clamp-front suspension mounts	4704 Newton

But,

$$W_{net} = Impact\ force \times d \quad (6)$$

$$Impact\ force = \frac{W_{net}}{d} \quad (7)$$

$$Impact\ force = \left(\frac{m \times v^2}{2}\right)_{initial} \times \frac{1}{d} \quad (8)$$

(OR)

$$v = \frac{d}{t} \quad (9)$$

$$d = v \times t \quad (10)$$

$$Force = \frac{0.5 \times m \times v^2}{d} \quad (11)$$

5.3 Optimization

Optimization techniques, although not always widely known or implemented in industry, offer highly promising approaches for systematic design improvements in mechanical engineering. Despite this, there is a vast body of work that covers both the theory and practical applications of optimization. For automotive manufacturers, reducing vehicle weight is a key objective, as it enhances structural performance while also improving fuel efficiency. However, creating a lighter chassis often comes at the expense of rigidity and crashworthiness, requiring a careful balance between these factors.

To achieve this balance, optimization techniques are now integrated into the design process to identify the lightest possible vehicle structure that still meets manufacturer specifications and vehicle certification standards. However, optimization can be computationally intensive, sometimes taking days or weeks to complete. Reducing computing costs and improving flexibility in the early stages of vehicle design is therefore essential.

One way to address this challenge is by treating the automobile chassis as a truss structure and optimizing its design for a specific vehicle type [92].

5.3.1 Structural Optimization

Enhancing a chassis design to strike the ideal balance between stiffness, strength, and weight is known as structural optimization in Figure 9. Determining the functional and load-bearing requirements, such as load distribution, crash safety, and torsional stiffness, usually starts this procedure. Then, engineers model stress and strain under various scenarios using a variety of techniques, such as topology optimization and finite element analysis (FEA). Choosing the right material is essential since lighter materials, such as composites or aluminum, may reduce weight without sacrificing strength. In order to improve vehicle performance, the optimization aims to reduce weight while making sure the chassis can sustain forces like cornering, acceleration, and braking loads. Changes to cross-sectional forms, reinforcement of important sections, or removal of superfluous material are examples of design iterations. High stiffness-to-weight ratio, durability, and cost-effectiveness in production should all be guaranteed by the optimized chassis. This enhances the vehicle's overall performance, handling, and efficiency [93].

Key structural optimization methods include: (i) topology optimization; (ii) topometry optimization; (iii) topography optimization; (iv) size optimization; and (v) shape optimization [94-95]. The different types of optimization techniques are as follows:

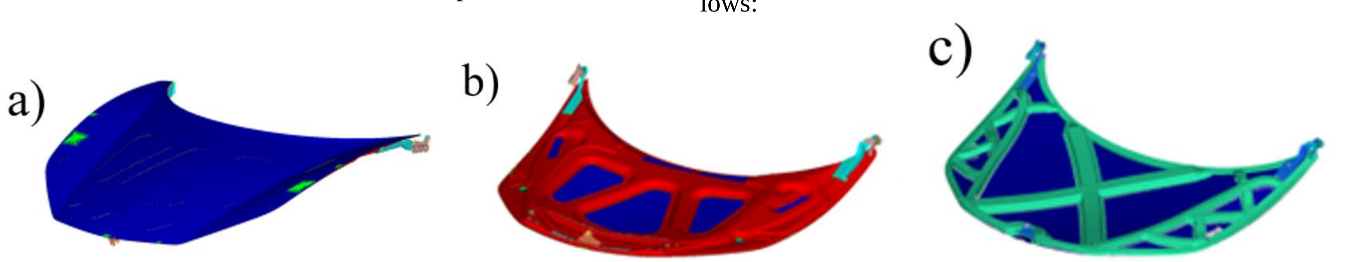

Figure 9. Reference model a) top view, b) side view, and c) optimum layout

Ferrari F458 Italia front hood: reference model and new layout from the optimization results. The optimization was performed in three stages: topology, topometry, and size. A series of topometry optimizations followed to find the optimal thickness distribution and identify the most critical areas. The solution was refined through size optimization. In the end, the performance requirements.

5.3.2 Topology Optimization

Chassis topology optimization is a sophisticated computational design technique that aims to maximize performance through effective material distribution inside a structure is as shown in the Figure 10. Achieving the lightest and most structurally efficient chassis while preserving strength, safety, and rigidity is the primary objective. All possible load routes are included in the baseline design space at the start of the process. After that, engineers provide the limitations, including load scenarios (such as torsional, bending, and crash loads), boundary conditions, and optimization goals like mass reduction or stiffness maximization. Based on the applied loads, the program iteratively reinforces high-stress locations and eliminates material from low-stress areas using topology optimization methods. The procedure simulates a number of events the chassis may experience, including collision scenarios, acceleration, braking, and cornering forces, using finite element analysis (FEA). The result of judicious material reduction is a robust, lightweight skeleton. This design methodology frequently produces buildings with void sections, trusses, or organic-like forms that are optimized for performance, resulting in non-intuitive designs that would be challenging to obtain using standard design processes [96].

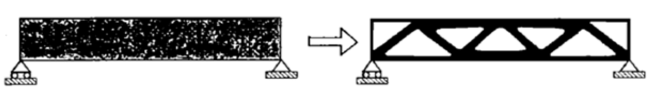

Figure 10. Topology optimization original problems on the left and the optimal solutions on the right [97]

By achieving a high stiffness-to-weight ratio, topology optimization reduced the vehicle's total mass and enhances handling, acceleration, and fuel efficiency. By carefully positioning materials where they will be most required in the event of a collision, it can also improve crashworthiness. It also lowers production costs and material waste by reducing superfluous material. Manufacturability must be balanced in the final design, which frequently calls for further smoothing and adjustments to guarantee that it can be manufactured using methods like CNC machining, 3D printing, or welding. This strategy may provide motorsports, like Formula SAE, a competitive edge by producing a chassis that is stronger, lighter, and more performance-focused. [98].

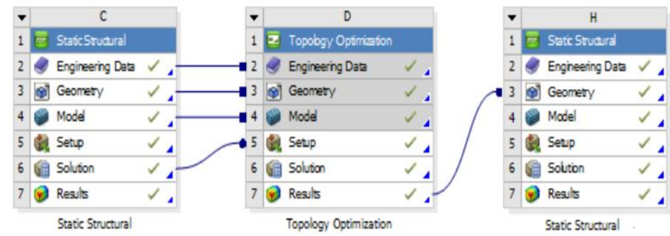

Figure 11. Structural analysis and topology optimization scheme [99]

The ANSYS workbench application's static structural tool was used to conduct a structural study of the vehicle chassis made in the SOLIDWORK three-dimensional modeling program. Topology optimization was carried out utilizing the findings of structural analysis as shown in the Figure 11. The geometry produced by topology optimization was rearranged to repeat the static structural analysis.

A mathematical model that optimizes the material design area based on the constraints and boundary conditions specified under applied loads is known as topology optimization. The primary goal of topology optimization is to generate strong and light parts with same properties while also reducing the quantity of material in the parts. The stress-free areas of the chassis were removed in order to minimize weight by reworking the optimal chassis shape. The loads and boundary conditions used in the initial analysis were utilized in the same manner and from the same locations during the structural analysis of the geometry, which was derived following topology optimization. This allowed for a more relevant comparison between weight and shape [97].

The structural study of the new chassis model, which was derived via topology optimization, revealed that the deformation had increased by around. Nonetheless, it was discovered that the von-Mises stress value rose by about. For the truck chassis subjected to several load types simultaneously, topology optimization was used to reduce the chassis weight. The results of the structural study showed that the vonMises stress value was around 194 MPa, and the mass of the non-optimized model was found to be 2685 kg. Following topology optimization, it was determined that the chassis weighed around 2316 kg and had a von-Mises stress value of about 220 MPa. According to the study's findings, the truck chassis' weight was lowered by about 369 kg without compromising the necessary strength levels [99].

Topology optimization could benefit from advanced algorithms that account for multi-objective criteria, such as stiffness, weight, and manufacturability, allowing for highly efficient and innovative designs.

5.3.3 Topometry Optimization

Instead of changing a chassis general topology or structure, topometry optimization is a specific structural optimization approach that focuses on changing the thickness or cross-sectional characteristics of its pieces. By varying the thickness of distinct components or sections within the framework, this technique improves the distribution of materials. Enhancing the chassis' rigidity, strength, and overall performance while reducing its weight and making sure it satisfies all load and safety standards is the main goal.

Engineers establish the design space and performance objectives, such as decreasing mass or optimizing structural stiffness under particular load scenarios, such as cornering, braking, or crash impacts, via the conventional topometry optimization method. The optimization procedure assesses the distribution of stress and modifies the thickness of each element in response to the loads that are applied using finite element analysis (FEA) techniques. The program fine-tunes the structure to enhance performance by repeatedly increasing or decreasing the material in locations that are experiencing high or low stress, accordingly [100].

By providing more accurate control over the material distribution without changing the overall geometry, topometry optimization has several benefits. This method produces a very effective design that uses less unneeded material and has a superior stiffness-to-weight ratio. Additionally, it enhances the chassis' dynamic response, which improves handling and performance especially in racing applications like Formula SAE, where structural integrity and weight reduction are crucial. The final optimized design balances excellent performance and manufacturability while being modified to the vehicle's unique specifications [101].

5.3.4 Topography Optimization

Adding or changing ribs, grooves, and other structural reinforcements on a chassis surface without changing the overall geometry is the goal of the design process known as "topography optimization." This technique keeps the chassis lightweight while enhancing rigidity, strength, and vibration resistance. Topography optimization improves the structural performance of the current design by fine-tuning surface features, as opposed to topology or topometry optimization, which concentrate on material distribution or thickness modifications [102].

Engineers provide load conditions, boundary limitations, and optimization objectives like increasing stiffness or lowering material consumption during this procedure. Finite element analysis (FEA) software is used to test the design under real-world stress scenarios, including as crashes, braking, and turning. In order to more effectively and equally distribute stress and avoid deformation under load, the algorithm then recommends the best surface alterations, such as the addition of ribs, flanges, or depressions in strategic locations.

In automotive and racing applications, like Formula SAE, where stiffness and weight reduction are essential, topography optimization is particularly advantageous. The chassis can withstand more loads without gaining much bulk by carefully positioning reinforcements, which improves handling, performance, and crashworthiness. Furthermore, because surface features are simpler to integrate into conventional manufacturing procedures like stamping, shaping, or casting, the method improves manufacturability [103].

5.3.5 Size Optimization

A chassis size optimization aims to strike the ideal balance between weight, strength, and stiffness by modifying the measurements of particular structural components, such as beams, tubes, or frame members. Size optimization improves the cross-sectional dimensions is as shown in the Figure 12 (such as diameter and wall thickness) of pre-existing components, as opposed to topology or topometry optimization, which alters material distribution or thickness. The objective is to reduce the bulk of the chassis while making sure it can sustain the many forces it comes into contact with, including impact, bending, and torsion loads.

Before establishing performance goals, which usually involve lowering weight while preserving or improving structural integrity, engineers first define load situations, such as cornering, braking, and collision forces. The program evaluates the stress and strain on individual components using computational technologies such as finite element analysis (FEA) and iteratively modifies their sizes to maximize performance. While less crucial areas might be made smaller to conserve material, high-stress areas can need thicker or bigger components [104].

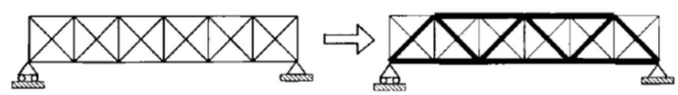

Figure 12. Sizing optimization original problems on the left and the optimal solutions on the right [104]

A highly efficient chassis design is produced via size optimization, with each structural part providing precisely the right amount of stiffness and strength without using too much material. In motorsport applications like Formula SAE, where every gram of weight saved may enhance handling, acceleration, and fuel efficiency, this method is very helpful. Furthermore, dimension optimization guarantees that the chassis design can be manufactured with conventional materials and production techniques, maximizing performance while reducing weight [94].

The accuracy and efficiency of optimization are greatly increased by this size optimization technique. According to the findings of the size optimization stage, the frame's major components have a 78.4 kg thinner thickness, and even though the frame's maximum stress increased from 152.28 MPa to 177.07 MPa, it is still within the permitted stress range of 235 MPa. Subsequent frame experiments confirmed that the size optimization was correct [105].

5.3.6 Shape Optimization

In order to improve performance through better stress distribution and weight reduction, shape optimization of a chassis entails fine-tuning the outward geometry of structural components is as shown in the Figure 13. Without changing the overall topology of the design, this method concentrates on modifying the form of specific components, such as beams, joints, and load-bearing sections, to better withstand forces like bending, torsion, and impact. The goal is to develop a more effective structural shape that uses less material and maximizes stiffness and strength [106].

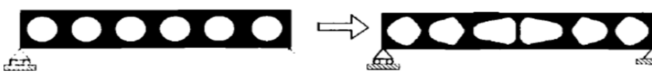

Figure 13. Shape optimization original problems on the left and the optimal solutions on the right [106]

Determining the design constraints, including load conditions, boundary limits, and goals like mass minimization or stiffness maximization, is the first step in the process. The response of diverse forms to loads, including turning, braking, and impact forces, is simulated using computational methods such as finite element analysis (FEA). The program iteratively modifies the angles, curves, and contours of components based on these simulations in order to lessen high-stress locations and more equally distribute loads.

In motorsport applications such as Formula SAE, where chassis weight reduction directly impacts vehicle performance in terms of handling, acceleration, and fuel efficiency, shape optimization is particularly useful. Engineers can enhance structural integrity, lower aerodynamic drag, and boost energy efficiency by fine-tuning designs. This process frequently produces creative, simplified designs that improve performance and manufacturing feasibility, resulting in a lightweight and highly optimized chassis.

Punching holes where there is more fos and lowering the moment of inertia such that its permissible stress achieves the value of permitted bending stress are the two main methods of form optimization. Punching the holes close to around 20 holes across the chassis. By closely examining the Ansys data, It was able to punch holes where the chassis was over constrained or where the Fos was higher than anticipated. It was able to lower the classis's weight by 26 kg as a result of this outcome. lowering the transverse members' moment of inertia. The present chassis features four transverse elements in total. After lowering the weight by 12 kg, our design is still safe because the permissible bending stress is less than the acceptable bending stress [107].

5.3.7 Optimization of automobile chassis

An automotive chassis is designed using topology optimization, with the goal of reducing weight while meeting performance criteria related to handling and safety standards is as shown in Figure 14. These criteria include: (i) global bending and torsional stiffness; (ii) crashworthiness, particularly in the case of a front-end collision; (iii) modal analysis; and (iv) local stiffness at suspension joints, the engine, and gearbox. The newly designed chassis consists of numerous structural tube bars, with specialized methods for securing all auxiliary components.

Using the defined mass distribution and critical dimensions, early CAD and FEM models were developed to evaluate the structural behavior of the vehicle. Over time, various chassis optimization technologies have been introduced to enhance torsional stiffness while reducing mass. Multiple iterations were conducted, including adjustments to the design variable definitions, to determine the optimal solution. The result was impressive: the optimized chassis exhibited lower mass and greater torsional stiffness than the initial model.

In line with Formula Student guidelines, a CAD model of the chassis was created, incorporating minor rulebook updates. These modifications included reinforcing the front bulkhead and adding extra links in the midsection to increase torsional resistance. Increasing the outer diameter of the pipes not only improves torsional rigidity but also boosts the chassis maximum load-carrying capacity. While the minimum size is restricted by Formula Student constraints, there is no maximum limit.

Optimizing the lightweight design of passenger car seat frames is essential to improving vehicle safety and efficiency. This is especially important in the context of contemporary car design, as weight reduction may result in better performance and fuel economy. Grey relational analysis (GRA) and optimized coefficient of variation (OCV) are used in this research to present a unique optimization design approach. By addressing the difficulties involved in multi-objective lightweight optimization, this strategy seeks to successfully balance weight reduction and safety [108].

Most Formula Student teams aim for a torsional stiffness between 2000 to 5000 Nm/° by either increasing the number of pipes or the thickness of the tubes used in the chassis. This paper analyzes torsional stiffness using ANSYS, considering three sets of pipe profiles. The study identifies the frame with the highest torsional stiffness achieved through profile optimization according to Formula Student standards. Comparing the torsional stiffness-to-weight ratio across the three frames, the third set of profiles had the best performance, with a torsional stiffness of 9091 Nm/°. This optimized chassis model is now ready for production [109].

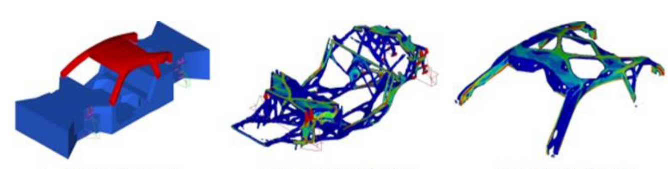

Figure 14. Automotive chassis topology optimization. In the results, the density ranges from 0.1 (blue) to 1.0 (red)

Among other factors, the major failures that cause the failure in the tubular space frame chassis include material fatigue, overstress concentrations, weld joint failure, corrosion, and buckling under compressive loading. Fatigue is initiated normally under operational dynamical repeated loading that has causes progressive cracking with time. This often happens at the concentration points such as sharp corner and abrupt change in the geometrical shape or path to loading design. Weld joints are vulnerable due to residual stresses, mismatched welds, and improper alignment of the weld joint. Corrosion attacks, especially in severe exposure, deteriorate the material structural integrity, while buckling arises from insufficient stiffness in tubular members when subjected to compression.

Design optimization addresses these weaknesses by improving the layout of the chassis, material selection, and manufacturing processes. Engineers can use Finite Element Analysis to identify and reduce stress concentrations so that loads are evenly distributed. Optimizing joint designs and weld quality enhances durability, while corrosion-resistant materials or protective coatings reduce environmental damage. Reinforcing or redesigning structural elements can also improve stiffness and reduce the risk of buckling. Weight optimization achieved by the strategic placement of material in areas of most need will enhance performance and maintain structural integrity. By doing so, design optimization improves significantly the reliability and life expectancy of tubular space frame chassis [110].

5.4 Torsional stiffness

Torsional stiffness refers to a structure's resistance to twisting when subjected to a torque or rotational force. In automotive engineering, particularly in the design of a vehicle's chassis, torsional stiffness is a crucial performance parameter that affects handling, stability, and ride quality. A chassis with high torsional stiffness can resist twisting forces more effectively, improving cornering performance and allowing for more precise vehicle control, especially during sharp turns or on uneven road surfaces. On the other hand, a chassis with low torsional stiffness may experience undesirable flex or deformation, reducing the vehicle's responsiveness and potentially compromising safety [81].

Torsional stiffness is usually measured by applying a known torque to one end of the chassis while the other end is fixed, and then measuring the resulting angular deformation. Engineers strive to optimize torsional stiffness without adding excessive weight to balance performance, safety, and efficiency in vehicle design. It is defined as the amount of torque required to produce a one-degree angular displacement of the chassis along its roll axis. According to Lonny L. Thompson, increased torsional rigidity in a race car's chassis enhances handling by enabling the suspension system to better control the vehicle's kinematics [82].

The degree of stiffness needed is dictated by the dynamics of the vehicle's design. Longitudinal and lateral load transmission is influenced by the chassis rigidity. A chassis with low stiffness can delay weight transfer between the front and rear wheels during acceleration, or between the inner and outer wheels during cornering, which increases the vehicle's response time. Furthermore, the chassis must be robust enough to handle dynamic suspension loads, such as when the car encounters alternating bumps. For example, when the left wheel experiences upward movement (jounce) and the right wheel moves downward (rebound), spring forces act in opposite directions, creating a torque at the front of the car.

Torsional rigidity is a key factor in determining a chassis ability to withstand twisting loads under challenging dynamic conditions. A weak chassis can negatively affect the vehicle's suspension system and overall performance. To assess torsional rigidity, torque is applied about the chassis longitudinal axis at its front suspension pickup points, while the rear suspension points remain fixed, simulating critical load conditions. This torque is distributed in opposite directions across both front pickup points to generate the required twisting force [111].

5.4.1 Numerical and Analytical approach

Once the frame is built, it is critical to validate the mathematical models and determine the precise qualities that the structure has achieved. The following offers a straightforward analysis and method for calculating a frame's torsional rigidity the torsion tube is as shown in the Figure 15. Torsional loads are the greatest and most significant loads transferred through the frame. They are caused by cornering forces or a rough road surface. A fundamental method for analyzing the torsional rigidity of an automotive frame is to imagine the car as having one fixed end and the frame as a hollow tube with a moment given to one end [112]. A schematic illustration of this is presented below:

To calculate torsional stiffness, divide the torque applied to the frame (the tube) by the angular deflection frame Finite Element Model loading case is as shown in Figure 16. The actual computation is performed as follows, with the image below depicting the view from the front of the suspension bay.

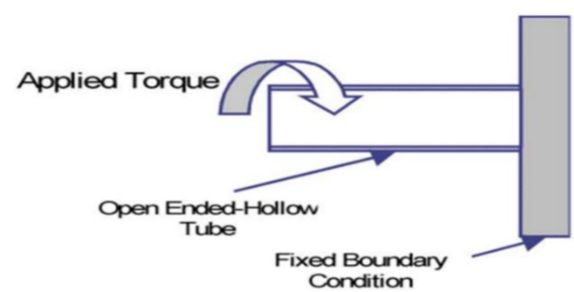

Figure 15. Torsion Tube This concept, when applied to the real car frame would look like follows [112]

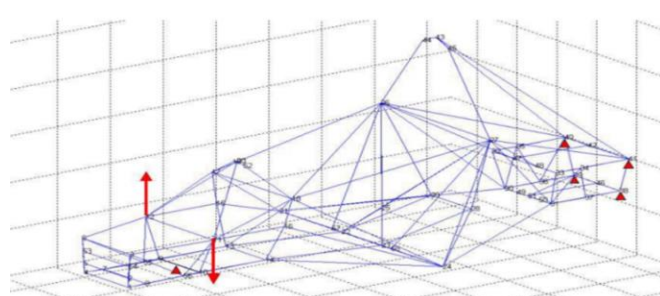

Figure 16. Frame Finite Element Model Loading Case [112]

$$K = \frac{T}{\theta} \quad (12)$$

$$K = \frac{F_S L}{tan^{-1}\left[\frac{(\Delta y_1+\Delta y_2)}{2L}\right]} \quad (13)$$

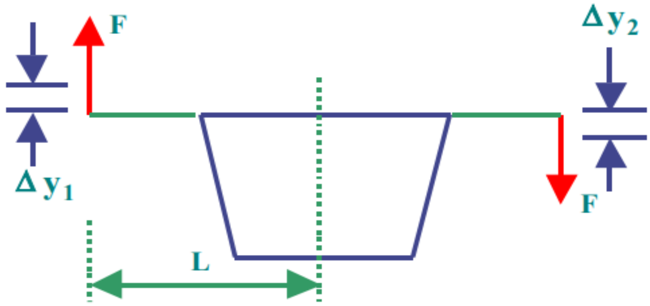

Figure 17. Front Suspension Bay Testing Loads [112]

The torque above is defined here as force applied at one corner multiplied by distance between the point of application and centerline of the vehicle the front suspension bay testing loads is as shown in Figure 17. The deflection is an angle formed between the center of an automobile and the point of deflected corner. It makes sense that both deflections are present in the above equation because the average of left and right deflections to get a best estimate of the total angular deflection. The above example is challenging to replicate in lab as it involves generating a vertical force opposite to gravity. It would be much easier to just suspend a known weight from one corner of the car and let it pivot about a roller [112]. This is done as follows.

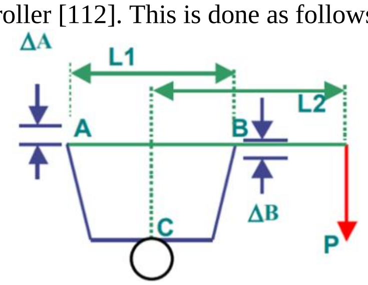

Figure 18. Front Suspension Bay Testing Loads [112]

In the picture above, the lever arm is a tube clamped to the frame at locations A and B is as shown in the Figure 18. A weight is then suspended from the end of the tube. At point c, a roller supports the frame along its centerline. The torque operating on the car and resisted in the clamped rear bay is just the force, P, multiplied by the lever arm, L2. The angle of twist can be simply determined from the average deflection and the half bay width,

$$\theta = tan^{-1}\left(\frac{\Delta_A+\Delta_B}{L_1}\right) \quad (14)$$

Now it can be simply need to utilize the definition of torsional stiffness and substitute it into our formulas for torque and angular deflection.

$$K = \frac{T}{\theta} \quad (15)$$

$$K = \frac{P(L_1+2L_2)}{tan^{-1}\left(\frac{\Delta_A+\Delta_B}{L_1}\right)} \quad (16)$$

This frame testing method is comparatively simple, and the advantages are that it allows frame stiffness to be calculated without including suspension components. The major disadvantages of this method are that artificially produced load routes do not load the frame as the track does. Also, depending on the extent of the discretion one has as a user for example, in terms of rear nodes to be fixed and front nodes on which the load is applied can greatly modify the results. Full car chassis torsion tests may, therefore, be the best way to arrive at true vehicle rigidity [112].

AI-driven simulations and real-time multiphysics modeling promise to accelerate and refine numerical analyses, enabling faster and more accurate predictions of structural performance under diverse conditions.

6. Conclusion

This review paper highlights the significance of numerical analysis and topological optimization for design and improvement of tubular chassis. Through an in-depth examination of existing literature, it becomes evident that computational techniques play a crucial role in enhancing the performance, durability, and efficiency of chassis in various applications. The integration of topology optimization with structural analysis is an efficacious approach to pursuing next-generation high-performance, and lightweight structures. From the existing literature, it is found that Al-Sic material is preferably used to manufacture as this material offers a good balance of strength, toughness, and wear resistance, making it suitable for high performance. It is also noticed that the FSAE standard establishes the criteria for designing and measurement of chassis. Most of the researchers used SolidWorks as a powerful CAD software option for creating detailed designs and assemblies of chassis with its user-friendly interfaces and extensive modelling features. Further, this article reviews the use of FEA as an appropriate numerical approach to carry out static structural analysis. Software like ANSYS with the ability to integrate structural behaviour under different loading conditions with a generated CAD model is essential for finite element analysis. Topology optimization proves beneficial in improving the performance and durability of chassis while concurrently minimizing weight and material usage. Specialized software like ANSYS Mechanical provides a wide range of simulation tools for various engineering disciplines, including structural analysis, and Opti Struct from Altair Engineering's Hyper Works suite, which offers topology optimization capabilities empowering to optimize designs effectively through simulation-based approaches. These processes ensure that the final design meets the required structural constraints and achieves optimal efficiency, resulting in improved functionality and longevity for chassis in various practical applications. The automotive industry will continue to benefit from ongoing research and development efforts, as innovative analysis methods and technology-driven solutions help optimize chassis designs that will contribute to safer and more efficient race car production. In conclusion, this review paper emphasizes the indispensable role of numerical analysis and topological optimization in elevating the capabilities of chassis, and it serves as a valuable reference for researchers, engineers, and industry professionals striving to enhance construction equipment efficiency and sustainability.

Nomenclature

F	: Force (N)
m	: Mass (kg)
a	: Acceleration (m/s^2)
Δp	: Change in momentum (N)
Δt	: Change in time (sec)
v	: Velocity (m/s)
J	: Impulse (Ns)
W_{net}	: Net work done on account of an inelastic collision (J)
F_i	: Impact force (N)
d	: Distance travelled during impact (m)
t	: Time of impact (sec)
K	: Torsional Stiffness (Nm^2)
T	: Torque (Nm)
θ	: Angular deformation
F_s	: Shear Force (N)
L,L_1,L_2	: Lever arm length (m)
y1,y2,A,B	: Translational displacement (m)

Conflict of Interest Statement

The authors declare that there is no conflict of interest in the study.

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Suprith S: Writing-original draft, Methodology, Software, Validation.
Manish M: Conceptualization, Writing-original draft, Validation.
Mahesh S: Writing-original draft, Data curation, Visualization.
Mantesh B Khot: Supervision, Conceptualization, Resources.

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