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Parametric Design and Multi Objective Optimization of a Two-Axle Tipper Trailer Chassis for Enhanced Strength

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Abstract

The primary objective of this project is to perform a detailed analysis of the chassis frame by considering variations in cross-sectional geometry as well as material composition. The frame structure includes main longitudinal members supported by a series of cross members, and the study focuses on optimizing both these elements. Material optimization is carried out by introducing composite materials in place of conventional ones, aiming to achieve improved strength-to-weight ratio. Additionally, different loading conditions are applied to evaluate performance under varying operational scenarios. Static structural analysis is conducted using ANSYS software to assess stress distribution, deformation, and overall structural behavior. Design modelling and modifications are developed using CATIA software. Furthermore, modal analysis is performed to study the dynamic response characteristics of the frame, including natural frequencies and mode shapes. Finally, the most effective design configuration obtained from the analysis is validated as the optimized model.

Keywords: Automobile trailer, chassis frame, 2-axle frame, vibrational analysis, composite material & weight management

INTRODUCTION

The chassis of a tractor trailer serves as the primary structural framework that supports the mechanical components and cargo-carrying body of the vehicle. It is typically constructed from high-strength steel or aluminum alloys to ensure durability while minimizing weight. The design of the chassis incorporates two longitudinal beams, reinforced by cross members, which provide rigidity and resistance to torsional stress. Suspension mounts, axle brackets, and coupling points for the tractor are integrated into the chassis to support dynamic loads during transportation. Additionally, modern chassis systems may include modular features to allow for easy customization based on specific freight or operational requirements.

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LITERATURE REVIEW

Nandan and Reuben George Oommen [1] explained that the chassis serves as the fundamental structural member in commercial automobiles and carries the complete vehicle assembly during operation. Their investigation indicated that vehicle frames experience considerable loading conditions, which may produce deformation, crack initiation, or structural damage under critical working environments. The researchers also pointed out that the effect of different engineering materials on chassis performance under stress conditions has not been widely investigated, creating a requirement for additional studies in this field.

The study concluded that more detailed research is necessary for improving future chassis evaluation and design development processes. The major function of the chassis is to support mounted components, payload, and various mechanical systems connected to the vehicle structure. During the design of a heavy truck frame, several important aspects such as stiffness, material properties, structural strength, and overall weight reduction were carefully considered to obtain better performance characteristics. The research mainly concentrated on analysing the static as well as dynamic behaviour of a prototype utility vehicle ladder-frame chassis. Autodesk Fusion 360 software was utilized for developing the three-dimensional chassis model and also for carrying out the structural analysis process. In addition, the automatic meshing option available in the software was employed for generating the mesh structure required for finite element simulation and computational evaluation.

Sravan Arimadla [2] explained that the chassis acts as the primary structural member of an automobile and supports the engine, axle, and vehicle body during operation. The frame provides required strength and stability under different working conditions and is generally manufactured using steel materials. The investigation focused on the design and static structural examination of a heavy vehicle chassis using different alloy materials under varying loading conditions. Fusion 360 and CATIA V5 software were used for chassis modelling, while structural evaluation was carried out in Ansys Workbench. The study aimed to develop an improved chassis structure with reduced vehicle weight and enhanced performance characteristics under ideal operating conditions.

Murli Jha and Sujan Raut [3] developed a four-seater vehicle chassis by considering dimensional data from the Audi A8 and electrical specifications from the Mahindra e2o model. The investigation mainly focused on modelling and static structural evaluation of the chassis system using ANSYS software. Initially, a space-frame structure was examined due to its high rigidity and lower deformation characteristics. Later, a ladder-type chassis was selected because of its widespread application in India and Nepal along with a significant reduction in structural weight. The study reported only a minor variation in deflection between both chassis configurations while achieving nearly 120 kg weight reduction and identifying a suitable chassis material through theoretical and simulation results.

Hari Kumar and V. Daryanani [4] presented an important investigation on automotive chassis design and structural evaluation using finite element analysis techniques. The research examined different chassis materials including ASTM A302 and structural steel to determine improved resistance against bending, torsion, and vibration effects. ANSYS simulation software was utilized to study stress distribution and deformation behaviour under maximum payload and gross vehicle weight conditions. The authors also analysed the influence of chassis geometry, including C-section and I-section configurations, on structural performance. The study mainly focused on reducing chassis weight while maintaining sufficient load-carrying strength and durability characteristics.

OBJECTIVES

- Designing a 3D model of tractor trolley Chassis in CATIA.
- Static and Vibrational analysis using ANSYS.
- Comparison of the static analysis and vibrational analysis results for C and I sections and varying the cross members of I sections of the Chassis.
- Analyzing the better materials in terms of traditional vs composite material
- Comparing the weights of the product
- Suggesting the optimum cross section of the Chassis

METHODOLOGY

Here in this thesis we are going to consider different models of frames and sub frames of a tractor trailer. The frame is consisting of the side long members, one main long member joined with a series of number of cross-members. So here we are optimizing the cross members and the material optimizing is done by using a composite material and even the loads are being varied for the better optimizing of the product, here the static analysis is done using ANSYS software and the design considerations are done using CATIA software. And here after the static analysis, we are even going to even verify the designs using vibrational analysis and very the results. The weight of the product is also considered and the results are compared and resulted [5-7].

ANSYS ON ORIGINAL CHASSIS MODEL

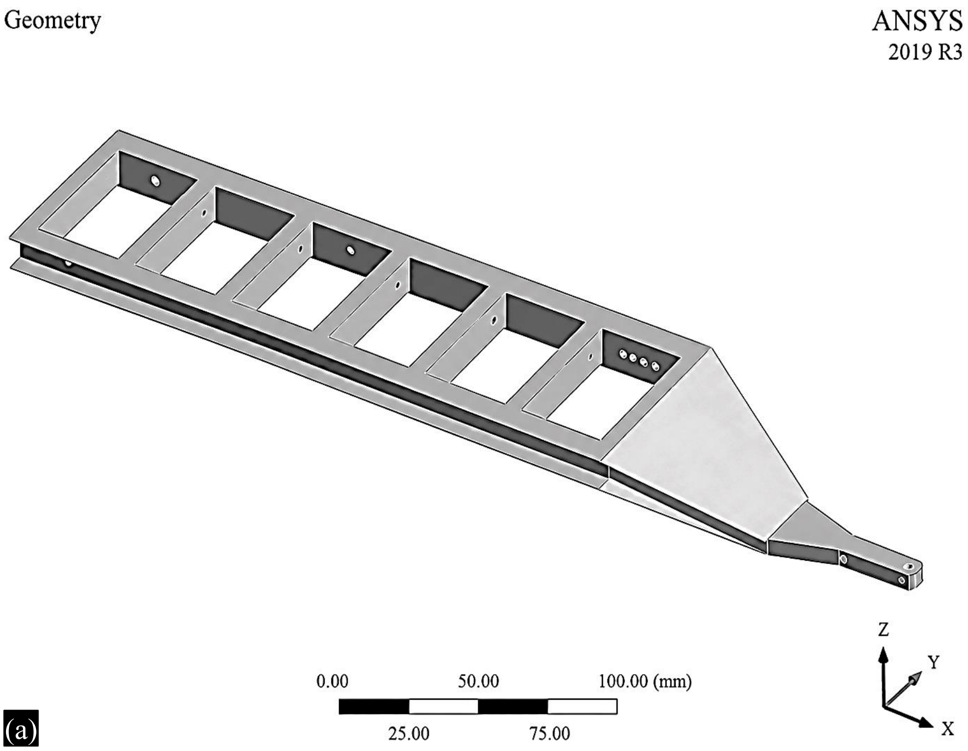
Advanced features in ANSYS, such as adaptive meshing, allow the software to refine the mesh automatically in regions where higher accuracy is needed. Users can also apply local mesh controls, such as sizing, inflation layers (for capturing boundary layer effects in fluids), and face or edge refinements. In ANSYS structural analysis, boundary conditions are essential for defining how a structure interacts with its environment. They describe constraints and external influences that affect the behaviour of the model under loading. Without appropriate boundary conditions, a structural simulation cannot be accurately or meaningfully solved.

There are two main types of boundary conditions in structural analysis:

1. *Displacement (or kinematic) boundary conditions:* These are used to restrict movement in one or more directions. For example, fixing a face of a solid means setting the displacement in all directions to zero. You can also apply partial constraints—such as restricting movement in only the x-direction—depending on the real-world situation being modelled.
2. *Force (or dynamic) boundary conditions:* These include applied forces, pressures, torques, or moments on surfaces, edges, or points. They simulate real-world loads like wind pressure, weight, or operational forces acting on a part or assembly (Figure 1).

MODIFIED CHASSIS MODEL-1, WITH "I" SECTION FRAME

The mesh profile image illustrates the finite element mesh for the modified Model 1 tractor-trailer chassis, with an "I" section frame geometry. This specific analysis defines how the structural volume is divided into smaller geometric subdivisions to facilitate accurate mechanical calculations across the assembly. Upon analysis conducted, the discretized body is represented through a dense network of connected points and volumes. Based on the provided data, the total number of nodes is recorded at 13,858, while the element count reaches approximately 6,564 (Figure 2).



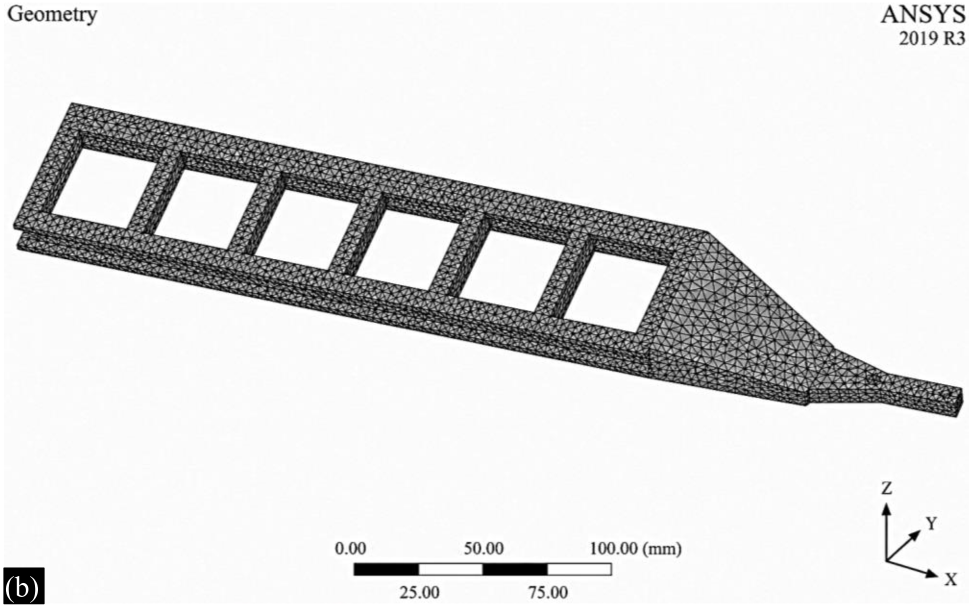


Figure 1. (a) to (b) Import and mesh model of original trailer chassis frame in to Ansys.

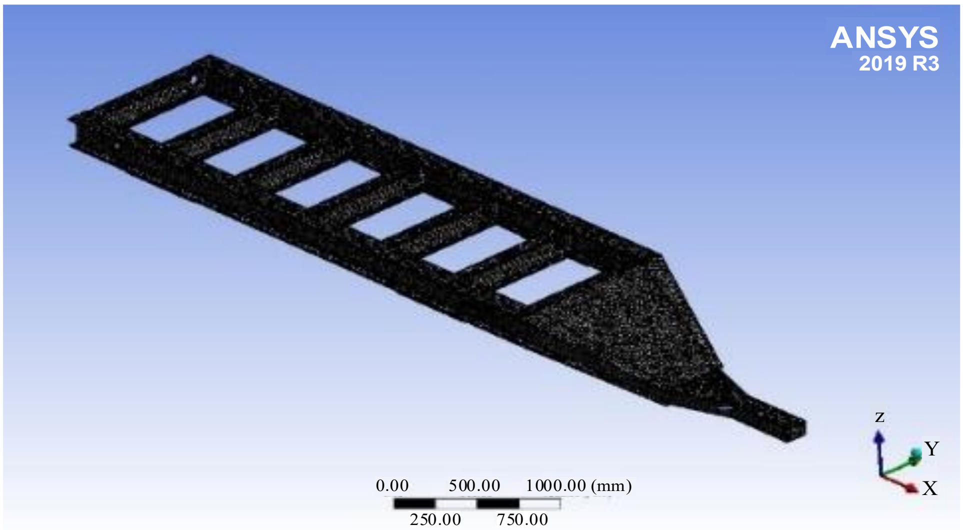


Figure 2. Mesh model of modified model 1 trailer chassis frame in to Ansys.

MODIFIED CHASSIS MODEL-2, WITH "I" SECTION FRAME AND SUB FRAME

The physical structure belonging to tractor trailer chassis Model-2 was computationally discretized utilizing finite element meshing procedures. The geometric configuration, featuring robust 'I' section frames and an updated sub frame layout, was prepared for numerical simulation with high-strength steel material properties assigned. This visual representation highlights the intricate mesh pattern applied across the entire complex assembly to accurately facilitate subsequent engineering analyses (Figure 3).

RESULTS AND DISCUSSIONS

The structural performance analysis comparing the high-strength steel (HSS) and the aluminum composite material across two loading levels reveals distinct mechanical advantages for each configuration. Under the primary load of 19,110 N, the HSS chassis demonstrates a peak stress of 7.93 MPa. When the same structure is subjected to the higher force of 28,665 N, the stress magnitude rises proportionally to 12.757 MPa. Despite this increase, the overall stress distribution remains stable, with the most significant concentrations appearing at cross-member joints and transition zones. The deformation also scales significantly with the weight, jumping from an initial 44.888 mm to 78.734 mm under the heavier load. These results confirm that while HSS handles massive vertical forces predictably, it allows for considerable physical deflection in the central longitudinal span (Table 1).

TABLES

The integration of Aluminum 6061 with 6% glass fiber reinforcement produces a much more rigid and lightweight assembly compared to the traditional steel model. At the 19,110 N load, the composite frame maintains a peak stress of roughly 7.88 MPa, which is slightly lower than the HSS counterpart. However, the most dramatic improvement is found in its structural stiffness. The total deformation for the composite material reaches only 0.11244 mm, representing nearly zero geometric distortion compared to the 44.888 mm recorded for steel. Even when the force is increased to 28,665 N, the composite maintains consistent vibration frequencies, proving that the structural integrity remains unaffected by the weight scale (Tables 2 & 3).

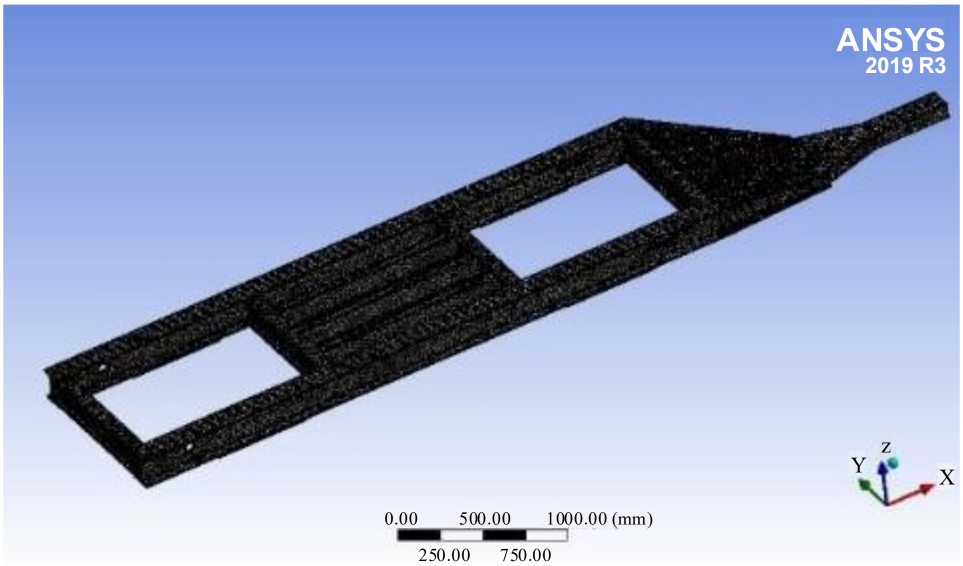


Figure 3. Mesh model of modified model 2 trailer chassis frame in to Ansys.

Table 1. Structural analysis results.

			Stress (MPa)	**Strain**	**Total Deformation (mm)**	**Directional Deformation (mm)**
Original model	Force – 19110N	HSS	7.93	0.047121	44.888	3.9936
		AL 6061 + 6% Glass fiber	7.8843	0.00011885	0.11244	0.010145
	Force – 28665N	HSS	12.757	0.07722	78.734	6.6073
		AL 6061 + 6% Glass Fiber	11.827	0.00017829	0.16868	0.015219
Modified model 1	Force – 19110N	HSS	4.9532	0.029129	21.876	2.6162
		AL 6061 + 6% Glass fiber	4.7653	7.0276e-5	0.054195	0.006418
	Force – 28665N	HSS	7.5104	0.044404	33.286	3.9969
		AL 6061 + 6% Glass fiber	7.1481	0.00010542	0.081296	0.0096275
Modified model 2	Force – 19110N	HSS	5.5752	0.032524	27.793	2.7551
		AL 6061 + 6% Glass fiber	5.3603	7.821e-5	0.069167	0.0067045
	Force – 28665N	HSS	8.4342	0.049484	42.213	4.2571
		AL 6061 + 6% GLASS FIBER	8.0406	0.00011732	0.10375	0.010057

Table 2. Modal analysis results.

Original model							
Load – 19110N				***Load – 28665N***			
HSS		*AL 6061 + 6% Glass fiber*		*HSS*		*AL 6061 + 6% Glass fiber*	
Frequency (Hz)	*Deformation (mm)*	*Frequency (Hz)*	*Deformation (mm)*	*Frequency (Hz)*	*Deformation (mm)*	*Frequency (Hz)*	*Deformation (mm)*
4.8956	2.6827	170.54	4.6333	4.577	4.9274	170.53	4.6334
6.3704	4.2193	218.39	5.7079	5.979	5.0227	218.38	5.7078
6.4797	6.4649	225.47	8.2058	6.289	5.3768	225.45	8.2066
8.4248	30.076	375.04	12.059	10.597	29.183	375.04	12.06
8.483	30.532	391.26	4.7872	10.752	16.65	391.24	4.7947

Modified model - 1							
Load – 19110N				***Load – 28665N***			
HSS		*AL 6061 + 6% Glass fiber*		*HSS*		*AL 6061 + 6% Glass fiber*	
Frequency (Hz)	*Deformation (mm)*	*Frequency (Hz)*	*Deformation (mm)*	*Frequency (Hz)*	*Deformation (mm)*	*Frequency (Hz)*	*Deformation (mm)*
3.7944	2.8313	133.9	4.8109	3.7177	2.8333	133.9	4.8109
7.0112	3.4796	242.92	6.0055	6.932	3.4615	242.91	6.0054
8.0705	3.6565	280.52	6.2394	7.9681	3.6757	280.51	6.2393
9.4112	2.5596	329.3	4.4222	9.2425	2.5473	329.28	4.4222
10.323	7.2785	358.02	11.107	10.057	7.9987	358.02	11.107

Modified model - 2							
Load – 19110N				***Load – 28665N***			
HSS		***AL 6061 + 6% Glass fiber***		***HSS***		***AL 6061 + 6% Glass fiber***	
Frequency (Hz)	*Deformation (mm)*	*Frequency (Hz)*	*Deformation (mm)*	*Frequency (Hz)*	*Deformation (mm)*	*Frequency (Hz)*	*Deformation (mm)*
3.4334	5.4265	124.01	7.9821	3.1473	6.3478	124.01	7.9767
3.5364	6.5207	127.67	9.2784	3.1920	8.7835	127.67	9.2863
3.5393	7.8201	129.75	8.971	3.1992	7.3713	129.74	8.973
4.9622	3.2795	175.78	5.5428	4.7636	3.537	175.77	5.5422
5.2787	3.5438	181.75	6.1499	5.2081	3.495	181.75	6.1498

Table 3. Weights of the Component.

	HSS (kg)	AL 6061 + 6% Glass fiber (kg)
Original model	1645.3	567.43
Modified model 1	1647.9	568.33
Modified model 2	1690.2	582.9

From a dynamic standpoint, the composite material offers superior resistance to dangerous resonance. The first natural frequency for the reinforced aluminum is measured at 170.53 Hz, which is significantly higher than the 4.577 Hz observed for the HSS frame [8-12]. This higher frequency threshold means the composite chassis is less likely to experience intense oscillations during standard road operations. While the HSS design is undeniably durable and capable of managing extreme loads without immediate failure, the Aluminum 6061 and 6% glass fiber composite emerges as the best output choice [13]. It provides a superior balance of minimal physical deflection, high-frequency stability, and efficient stress management, making it an ideal candidate for long-term heavy-duty transport applications (Figure4-7).

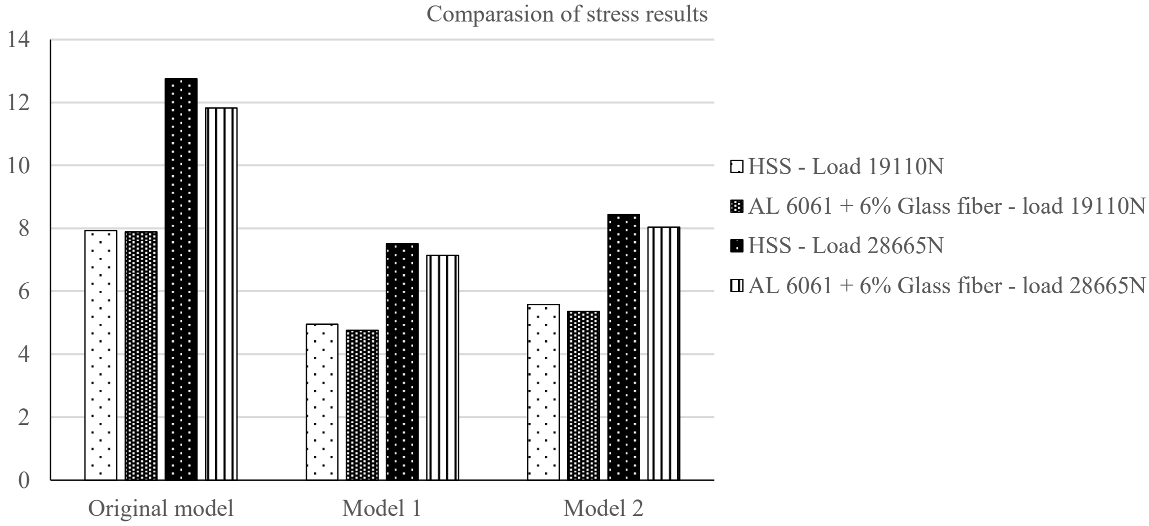


Figure 4. Comparison of stress between original and modified models.

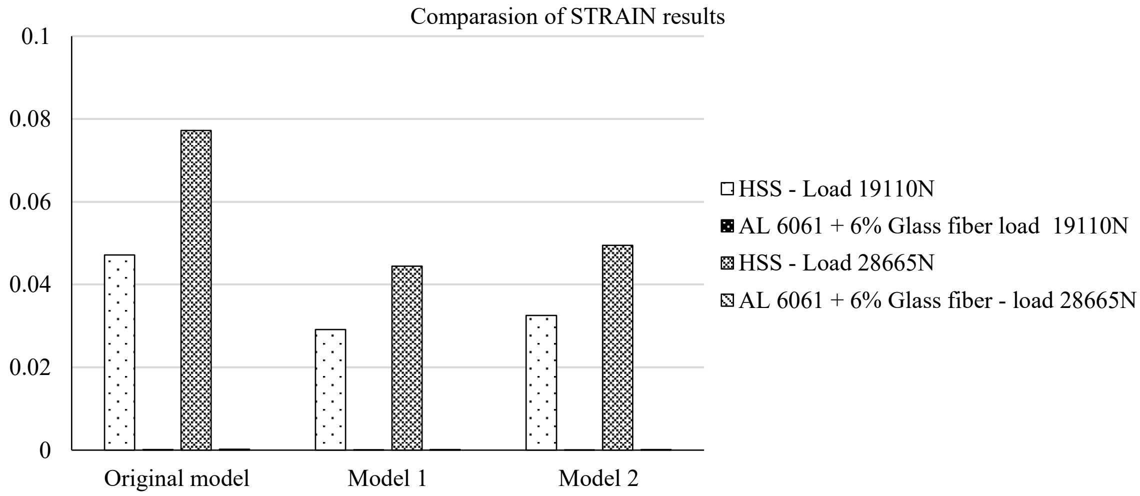


Figure 5. Comparison of strain between original and modified models.

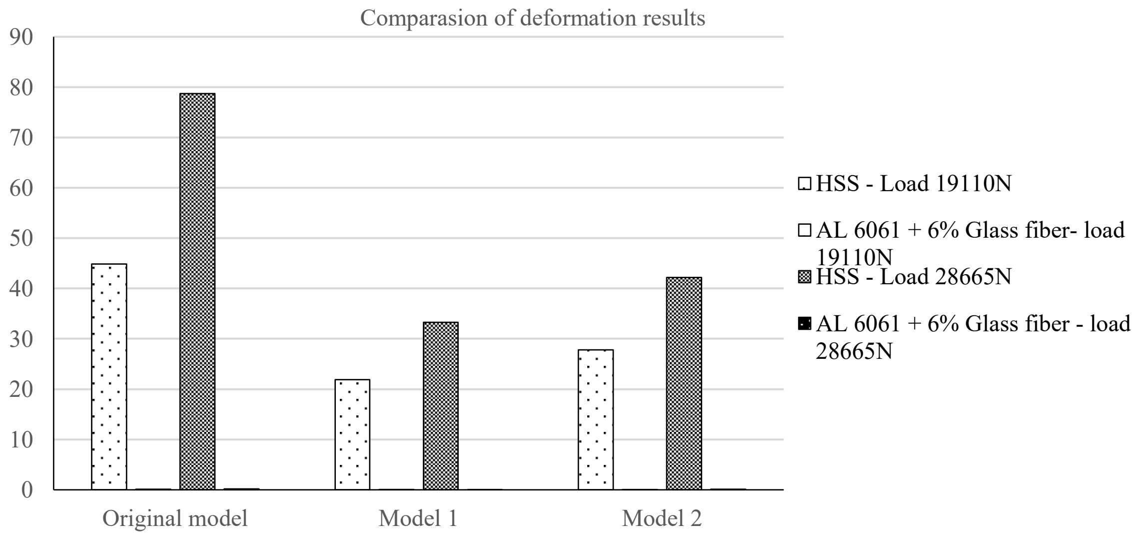


Figure 6. comparison of deformation between original and modified models.

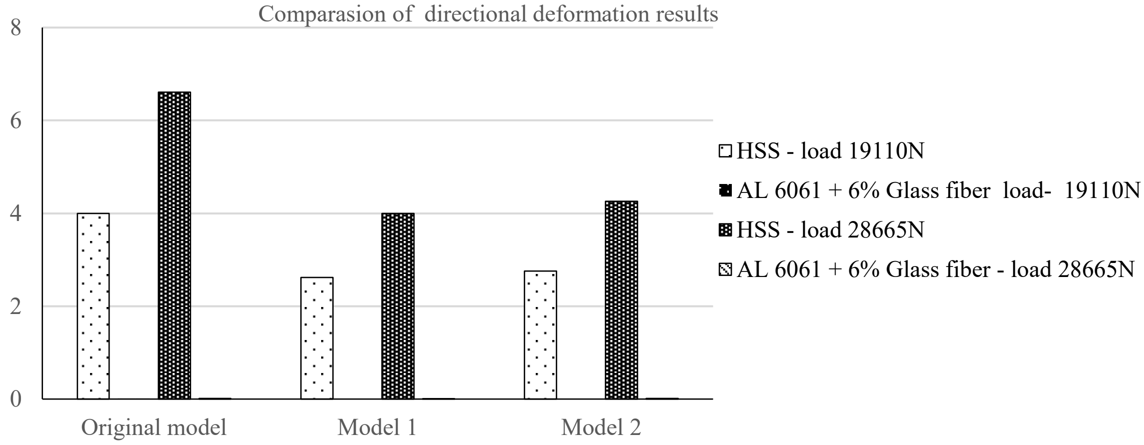


Figure 7. Comparison of directional deformation between original and modified models.

CONCLUSION

From the above outcomes, a clear trend can be observed when both loading conditions and material choices are compared across the initial and improved configurations. The original chassis, when subjected to 19110 N, shows comparatively higher deformation values, especially for HSS, where displacement is noticeably large. Even though the stress levels remain within limits, the strain and total deformation indicate that stiffness is relatively lower in the base design. When the load is increased to 28665 N, both materials experience a rise in stress and deformation, but the increment is more significant in HSS than in the composite material. The aluminum alloy reinforced with glass fiber demonstrates much smaller strain and displacement values, suggesting better rigidity under similar conditions.

After the first design modification, there is a visible improvement in structural response. For both loads, the stress values are reduced compared to the original case, and deformation is also controlled to a certain extent. Particularly, the composite material exhibits very minimal strain, almost negligible when compared with HSS. However, although Model 1 improves stiffness and reduces deformation, the weight slightly increases for both materials, which affects overall efficiency when lightweight design is a priority.

The second modification presents a more balanced outcome. Even though stress values are slightly higher than Model 1 in some cases, the deformation remains reasonably controlled. Under 19110 N, both materials show reduced displacement compared to the original structure, and under 28665 N, the results remain stable without excessive variation in deformation. The aluminum–glass fiber combination again performs better in terms of strain control and directional deformation. At the same time, this model maintains structural integrity without a drastic penalty in weight, even though it is marginally heavier than the previous designs.

When modal characteristics are examined, the natural frequencies in the modified models shift upward compared to the original configuration, indicating improved stiffness. Lower deformation amplitudes at similar frequency ranges in the optimized designs suggest better vibration resistance. Among all cases, Model 2 provides a consistent pattern where deformation remains moderate while frequencies are reasonably high, which is desirable for avoiding resonance issues.

Considering the weight data, HSS models are significantly heavier than the aluminum composite versions. The aluminum with 6% glass fiber reduces mass by nearly two-thirds in every configuration, which is a major advantage for applications where fuel efficiency and payload capacity matter. Even though Model 2 has the highest weight among the three designs, the difference is not excessive, and the structural benefits compensate for this increase.

Based on the combined evaluation of stress, strain, deformation, vibration response, and weight, the second modified model can be treated as the most optimized design. It offers a good compromise between strength and stiffness while maintaining acceptable deformation under higher loads. In terms of material selection, the aluminum 6061 reinforced with glass fiber emerges as the better choice due to its low weight and improved deformation behavior compared to HSS. The comparison is essentially made by observing how each model responds to increasing load in terms of mechanical parameters and then correlating those findings with weight efficiency and dynamic stability.

Future Scope

The present investigation opens several directions for further improvement and deeper study of the tractor–trailer chassis system. One possible extension is the inclusion of additional hybrid materials and layered composites, where varying fiber content or orientation may further enhance stiffness while keeping mass low. Instead of limiting the study to aluminum with a fixed glass fiber percentage, future work can explore combinations such as carbon fiber blends or functionally graded materials, which may provide better resistance against both static and dynamic loads.

Further refinement can also be achieved through advanced optimization techniques. The modified models already show improvement, yet shape optimization using algorithms such as genetic methods or topology optimization could remove unnecessary material from low-stress regions. This approach may lead to an even lighter structure without compromising safety. In addition, integrating manufacturing constraints into the design stage would help in developing models that are not only efficient but also practical to produce.

Another scope lies in experimental validation. While simulation provides reliable trends, physical testing of scaled or full-size prototypes would strengthen the credibility of the findings. Strain gauges, vibration sensors, and load testing rigs can be used to compare real-time data with numerical predictions and identify any deviations.

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