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Mechanical Analysis of Different Composites Used in Automotive Chassis Design

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Abstract

Background: *In the rapidly changing automobile sector, the necessity for lightweight yet durable chassis materials is essential. The incorporation of composite materials offers the benefit of decreasing the total weight of vehicles while preserving adequate load-bearing capacity. This research examines three materials: ASTM A148 Gr 80-50 steel, P100/6061 aluminum alloy, and Graphite Al GA 7–230 Metal Matrix Composite (MMC). These materials were chosen for their ability to improve vehicle performance by optimizing strength, flexibility, and impact resistance.* ***Methods:*** *The chosen materials underwent stringent mechanical testing to evaluate their appropriateness for chassis applications. The evaluated key mechanical parameters comprised tensile strength, flexural strength, elongation, and percentage area reduction. Tensile and flexural tests were conducted to assess the materials capacity to endure various stress types, while elongation and area reduction measurements offered insights into their ductility and deformation properties under load.* ***Results:*** *ASTM A148 Gr 80-50 Steel demonstrated significant load-bearing capacity, featuring a tensile strength of 390 MPa and a flexural strength of 810 MPa. It exhibited commendable ductility, with 22% elongation and a 35% reduction in cross-sectional area, signifying its appropriateness for heavy-duty chassis applications. P100/6061 Aluminum alloy provides a balance of strength and weight, featuring a tensile strength of 320 MPa and a flexural strength of 640 MPa. It exhibited improved ductility with 30% elongation and a 41% reduction in area, rendering it suitable for applications where weight sensitivity is paramount. Despite possessing inferior tensile (76.9 MPa) and flexural strengths (159 MPa), graphite aluminum GA 7–230 MMC demonstrated superior ductility with 51% elongation and 68% area reduction. These characteristics demonstrate superior energy absorption during deformation, rendering it appropriate for impact-resistant applications.* ***Conclusion:*** *This study emphasizes the unique benefits of each material for car chassis applications. ASTM A148 Gr 80-50 steel has shown to be a viable option for severe load-bearing applications owing to its superior strength and commendable ductility. The P100/6061 aluminum alloy demonstrated efficacy as a lightweight chassis design choice, achieving a balance between structural integrity and weight reduction. Graphite Al GA 7-230 MMC, albeit exhibiting reduced strength, showcased enhanced energy absorption properties, rendering it appropriate for applications necessitating impact resistance. Future study may investigate the application of hybrid composites or the further optimization of these materials to improve vehicle performance while reducing weight.*

Major Findings: *The study compared three materials- ASTM A148 Gr 80–50 steel, P100/6061 aluminum alloy, and Graphite Al GA 7–230 MMC- for automotive chassis applications through rigorous mechanical testing. ASTM A148 Gr 80–50 exhibited superior strength and ductility, making it ideal for load-bearing applications. P100/6061 demonstrated a balance of strength and lightweight properties, suitable for weight-sensitive designs. Graphite Al GA 7–230 MMC showcased exceptional ductility and energy absorption, favoring impact-resistant applications. These findings underscore the materials' diverse advantages in enhancing chassis performance.*

Keywords: *Automotive Chassis, Composite Material, Flexural Testing, Tensile Testing*

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1.0 Introduction

The foundation of the vehicle is its chassis. The chassis is only the vehicle's support structure in a more limited sense. The frame (*i.e.,* the support structure) along with the suspension, steering, and attachments that are directly affixed to the frame is what is commonly indicated by the term "chassis" in the context of vehicle technology[1]. The truck chassis is the foundation of the vehicle. The bulk of modern big trucks use what is known as a "ladder frame" as its supporting structure. The frame consists of cross members and side members, the latter of which should be affixed to the former as rigidly as possible. This attachment's rigidity accounts for the majority of the frame's torsional stiffness, which makes it the only component capable of responding to torques applied along the vehicle's X axis. When viewed from above, side beams have various shapes; the smaller portion can support the steering and dual wheels, while the bigger portion is designed for the mounting of the engine and the driver's cabin. Because of the wide range of payloads, side beams are likewise tapered (as seen from above), allowing the suspension stroke of the rear wheels. Even though an open section is not the best choice for high torsional stiffness, the side beam's cross section is formed like a C. Open cross sections, which are frequently used, are easily bendable starting with steel sheets of greater resistance and thickness. Their cross section is strengthened when needed by the addition of more substantial C beams or plates.

Cross beams, mostly made of steel, continue to distribute the local loads generated by suspensions and the power train; which are specific to industrial vehicle suspensions, provide layout examples[2,3]. Cross beams also help to make the frame more rigid against torsional loading. In fact, the moment of inertia of the frame would be twice that of a single section if the two side beams were totally severed from one another. Due to the fact that this section is constructed using rectangular pieces with thicknesses that are significantly lower than their lengths. Ideally, cross beams force the side beams to stay parallel. The bending stiffness of the cross beams limits the torsional deformation of the side beams, enhancing the torsional stiffness of the assembly. To strengthen the linkage with the side beams, cross beams can be regionally reinforced with C profile cuts that are welded at its ends or it can be produced with a straightforward C shape, with its ends bent and without plat bands, and put inside the side beams. A tubular cross section that is welded to flanges at the ends of the cross beams can also be used when it is required to minimize their dimensions.

It should be noted that due to the great size of the frame, all joints with side and cross beams are constructed with rivets or bolts if these are to be removed for repairs. Due to the tremendous heat introduced during arc welding, there would be substantial deformation and resultant residual stress, which would be challenging to remove with heat treatment. The preparation of small components or cross beams is the only use for arc welding.

1.1 Literature Review

A study by Beermann introduces a hybrid approach to analysis that incorporates analytically calculated beam elements for the cross-member and side member sections with idealized joint areas created using finite elements[4]. Warping torsion force displacement relationships are included in the beam element. Along with the compatibility of their displacements, the joints flexibility is taken into consideration. One bi-moment is implemented as a supplementary statically indeterminate force at every joint where two members are joined. The matrix force method has included flexibility coefficients or nodal substructures for the larger joint area, and these are employed in the total computation. The proposed method is used to calculate displacements and internal forces, and good agreement with experimental results is obtained.

A big motor vehicle chassis is being analyzed in a study by Agarwal and Mthembu using computational and experimental techniques[5]. The ANSYS software is used to carry out the CAD design and the FE analysis. The Central Composite Design (CCD) scheme and Optimal Space Filling (OSF) design are then employed as optimization approaches in a Taguchi Design of Experiments (DOE) to improve the chassis design. It is therefore desirable to have the optimization strategy that results in the greatest weight reduction. Using the CCD approach yields a mass reduction of the chassis of about 5.3%, while using the optimal space filing method yields a mass reduction of 4.35%. In order to expand the capacity of passenger truck chassis, a research carried out by Jembere *et al*., focuses on an ideal state and analyzes stress for various cross-sections under various loading situations while taking

stress concentration factor into account[6]. The goal of the current investigation was to identify key locations under loading by determining the maximum stress and maximum deflection. Different cross-sections (such as 'C' and 'I') were used to analyze stress under various loading scenarios. In this investigation, modifying the pre-existing chassis profile has reduced the important stress and deflection characteristics. In this study, the simulation-based examination of the passenger truck chassis stresses and deflections was divided into three groups. As a result, it can be seen through a comparison of cross-sections and material between classical and simulation methods that using I cross-section with ASTM A148 Gr 80–50 mild steel reduces stress and deflection.

Applying the Box-Behnken design scheme, the study conducted by Agarwal and Mthembu aims to optimize the design of chassis[7]. The materials examined were P100/6061 Al and Al GA 7-230 MMC. The experiment design was used to produce several design points. For every design point, equivalent stress, deformation, and mass were assessed. Cross member width was the parameter chosen for optimization using the Box-Behnken algorithm. ANSYS software was used for the heavy motor vehicle chassis FE simulation and CAD modeling. By using the aluminum metal matrix composites P100/6061 Al and Al GA 7-230 MMC, the chassis weight was reduced by 68% and 70%, respectively, without significantly affecting the chassis strength. The goal of a work carried out by Gawande *et al*., was to create a stiffness model that would allow the selection of the best cross section for a given torsional stiffness[8]. A stiffness equation was created using an adaptation of Johnson's optimization technique, and a portion was chosen with a predetermined torsional stiffness and necessary mass constraint. Modeling was done with the 'Creo' software, while Finite Element Analysis (FEA) was done with 'Hypermesh'. A close match between the stiffness determined by the created stiffness model and FEA demonstrates the viability of the suggested model. The tubular section with a thickness of 4 mm turned out to be superior than the hollow square section and the tubular section with a thickness of 5 mm in terms of torsional stiffness. According to the FEA results, the front and rear torsional stiffness was increased by 44%, whereas the front and rear lateral stiffness was increased by 10%, for the identical chassis weight. According to the strain energy contribution, in both front and rear torsion load conditions, the tubular section absorbs greater strain energy than the current C-section cross member.

An investigation carried out by Sithik *et al*., explains how to reduce the weight of the chassis frame while maintaining present durability performance by converting complex durability load cases into similar static load cases and cascading life targets down to simple stress targets[9]. The variables needed for optimization analyses are sheet metal gauges and lightening holes. The optimization design space is limited to parts that are exclusive to the chassis. It has been demonstrated that conducting weight reduction analyses on frames, which are primarily designed to achieve durability (life), utilizing simplified stress objectives in optimization is an effective method. This procedure aids in a major weight loss of 5% or more.

In an investigation by Cinar, author explain about how the distribution of stresses in large truck chassis is affected by the loading rate[10]. This analysis uses the commercial finite element program Abaqus or Explicit and is entirely numerical. Crucial component stress values have been examined in relation to loading rate under the identical load magnitude. The findings demonstrate the significance of loading rate as an engineering parameter; employing larger loading rates causes greater changes in the expected stresses. Apart from the default bulk viscosity damping in the Abaqus solver, no specific damping parameter has been employed in the analysis. Physically, it is generally understood that stress results for the linear elastic response should converge to quasi-static values with suitable damping formulation.

A light agriculture truck was the vehicle considered in a study by Chuaymung *et al*. A mixture of experimental testing and computer simulations were set up with the aim to get accurate estimates of the stress that would be created in the frame under loads[11]. Investigations into the vehicle drove up one-wheel ramps and two-wheel ramps were conducted since the focal deformations were bending and torsion modes. Results for strains from simulations and experiments were examined. The extra cross member from the cargo component, that was not incorporated in the model, is what caused the disparity in the lateral stresses observed under torsional loading at either one of the rear wheels. Additionally, it was speculated that the limitations of the shell elements utilized by the model in this work were the cause of the disparity in longitudinal strain estimates under torsional stress. However, the

results from bending load scenarios, such as two-wheel ramps, remained ambiguous. The literature review indicates that there exists a body of literature that mostly focuses on stress analysis of chassis using finite element methods with the aid of different software packages. It can be also found that there are still many possibilities of using different materials and cross-sections for making ladder frame chassis for heavy vehicles. The upcoming section is intended to provide in-depth discussion about material selection.

2.0 Methodology

2.1 Material Selection

2.1.1 Requirement of Chassis Structure

Any automotive structure's essential requirement can be summed up as outlined below[12]:

i. The structure needs to be adequately stiff to resist both static loads-those mostly brought on by dead weight-and dynamic loads-those primarily brought on by handling maneuvers and driving through rough terrain.
ii. The structure needs to be strong enough to resist repeated cycles of the applied loading without experiencing material failure due to fatigue or other causes.
iii. When subjected to impact load conditions, the structure should deform in a way that minimizes the risk of injury to the passengers and other road users.

Unlike any other individual component of the automobile like braking system, suspension system, steering system *etc*., chassis is the only individual component to which all the structural requirements of full vehicle structure, as mentioned in above list, are applicable. As the first requirement from the above mentioned list holds paramount importance in evaluating the behavior of the automobile during normal and extreme maneuvers, it is duty of the structural designer to fulfill that requirement.

The overall requirements of the chassis can be summarized in the form of Figure 1.

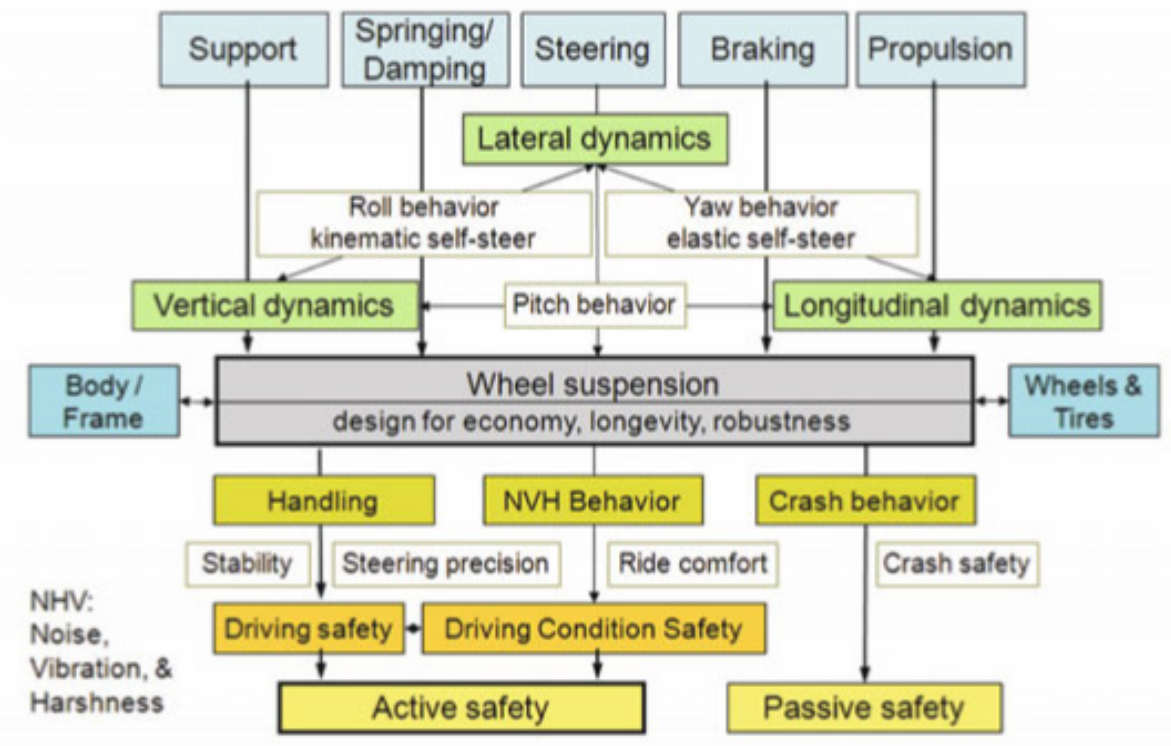


Figure 1. Summary of chassis requirements.

2.1.2 Loads Experienced by Chassis

The three main types of dynamic loading that tend to cause the vehicle structure to deform around the mounting locations of suspension system are as follows:

i. Torsional loads, which are transmitted through the vehicle structure when a wheel strikes a bump in the road and an extra suspension load is applied to that corner of the automobile.
ii. Bending loads, such as when two wheels on an axle collide with a kerb or a bump at the same time.
iii. Longitudinal or lateral pressures brought on by inertia effects during circumstances of traction, braking, and cornering, especially the consequences of minor accidents and impacts that occur in-plane.

Perhaps the most crucial factor to take into account in the early stages of a chassis design is the structure's torsional stiffness. Although a high torsional stiffness is preferred, stiffening a vehicle's structure typically comes with an expense of weight. The torsional stiffness per unit weight is thus a desirable parameter to be addressed during the design stage. Additionally, a very high stiffness may cause NVH issues, including issues at the support locations of the more flexible body elements and little absorption of suspension load changes brought on by driving on gravel roads. In general, a vehicle's structure will be appropriate for bending if it is sufficiently rigid in torsion. Additionally, there won't be much stress on individual structural parts under normal driving circumstances.

2.1.3 Necessity of Weight Reduction

The imposition of obligatory regulations on vehicle manufacturers to decrease the average emissions of Carbon dioxide (CO_2) from their fleets has prompted advancements in powertrain technologies, including downsized Internal Combustion (IC) engines and hybrid or electric propulsion systems. Additionally, there has been a significant impetus to minimise the weight of vehicles. The reduction in vehicle mass has been found to have a positive impact on fuel efficiency, as well as improving acceleration, deceleration, and handling ability. Furthermore, the implementation of this technology has the potential to mitigate the detrimental effects on road surfaces, while concurrently improving overall road safety by decreasing the amount of kinetic energy exerted by vehicles. The implementation of light weight chassis structure in commercial vehicles can yield advantages, as it enables hauliers to augment the payload within a designated Gross Vehicle Weight (GVW) limit[12].

2.1.4 Desirable Properties of Prospective Material of Chassis

Considering the structural requirements and load experienced by the structure of chassis, a suitable material for the chassis needs to be selected. A number of composite materials provide an appropriate strength and modulus superior to any traditional metallic metals, even if steel remains the material of choice for manufacturers due to its inexpensive cost, significant relative strength, and ductility.

Numerous emerging materials have been formulated that exhibit equivalent load-bearing capabilities to conventional materials, while concurrently exhibiting substantially reduced weight in comparison to their present counterparts. Composite materials possess a unique combination of high stiffness and low Coefficient of Thermal Expansion (CTE), making them highly desirable for the development of lightweight and durable constructions. Significant progress has been made in recent years in the development of light metal matrix composites, with the aim of integrating them into major applications. These materials exhibit several notable features, such as a high Young's modulus, exceptional compression and tensile strength, mechanical compatibility, and economic efficiency. The combined range of characteristics exhibited by composite materials holds significant value within the automobile industry, particularly in relation to quality assurance and production processes. This is due to the major worries surrounding vibration, toughness, and the escalating costs of fuel, among several other technological prerequisites[7].

2.1.5 Summary of Material Selection

So, after considering the numerous points considered in the aforementioned discussion, the current study considers three different materials, including a steel alloy, an aluminum alloy and an aluminum Metal Matrix Composite (MMC), for its suitability for the application of chassis. The materials considered for the study are

ASTM A148 Gr 80–50, P100/6061 Al, and Graphite Al GA 7–230 MMC and properties of these materials are evaluated using mechanical testing methodologies.

2.2 Stir Casting

Due to its affordability, suitability for mass production, simplicity, nearly net shaping, and ease of composite structure control, stir casting is a sort of casting method that is appropriate for the manufacturing of metal matrix composites. A furnace, reinforcement feeder, and mechanical stirrer combine to create a stir casting apparatus. The ingredients are heated and melted in the furnace. In order to create the vortex that facilitates the blending of the reinforcement materials added to the melt, a mechanical stirrer is employed. This stirrer is linked to motors with various speeds, and the regulator associated with the motor regulates the stirrer's rotational speed. The feeder is also connected to the furnace and is used to feed the reinforcing powder into the melting metal.

At most, a few important stirring process variables have an impact on how reinforcement is distributed. These variables include the impeller blade angle, size, position, and speed as well as the time spent stirring and the rate at which reinforcements are fed. The dispersion of the reinforcing particles within the matrix material is significantly impacted by the stirring speed. Reduced stirring time may cause clustering of the reinforcing particles and produce a non-homogeneous dispersion of the particles. In contrast, longer stirring times may cause the stirrer impeller blade to distort at extremely elevated working temperatures. The right impeller blade angle must be chosen in order to get a good amount of axial flow and shearing action. The reinforcement particles remain suspended at the crucible's edge if the impeller is insufficiently small, which prevents suspension of particles in the core. The reinforcement particles, however, would cluster in the middle of the crucible bottom if the impeller size were excessively large. To prevent agglomeration of reinforcement particles at the bottom of the crucible, the impeller's position should not be greater than 30% of the height of the fluid from the base of the crucible. Lower feed rate values are hard to obtain as a result of the production of lumps of small solid particles and high feed rate which causes particles accumulation in the composite.

2.3 Mechanical Testing

2.3.1 Tensile Test

Tensile testing is a method of destructive evaluation that is utilised to acquire knowledge about the mechanical

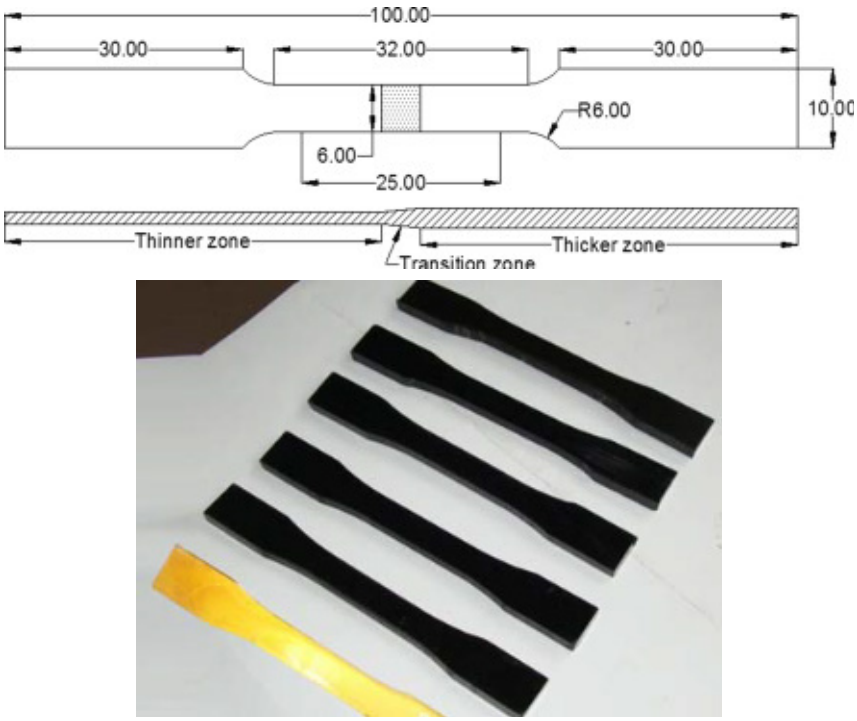


Figure 2. Specimens used for the mechanical testings.

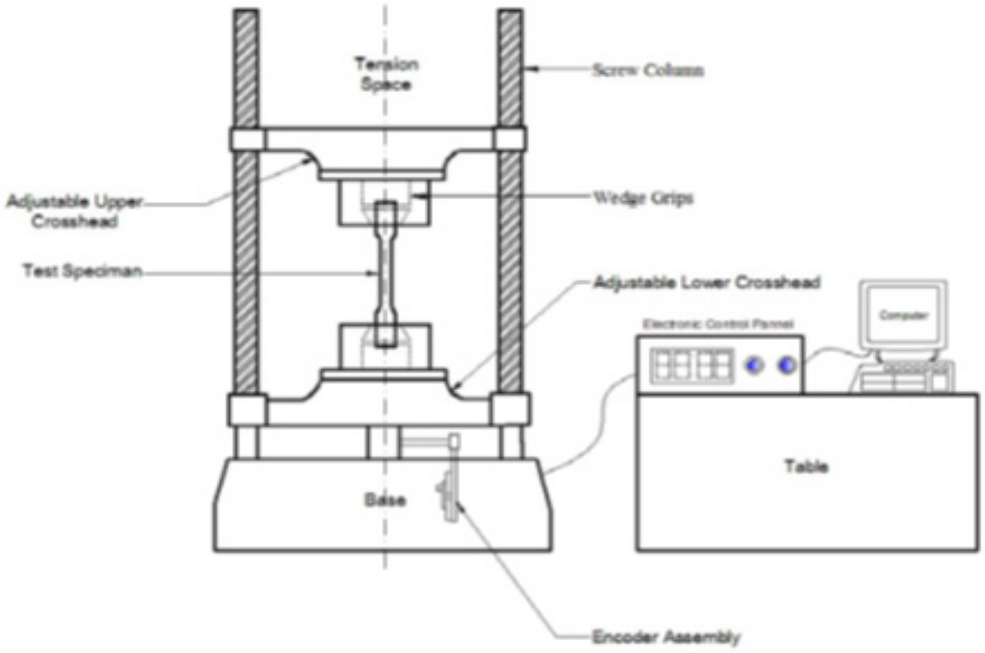


Figure 3. Schematic of universal testing machine.

properties of metallic materials. This methodology reveals essential data pertaining to the tensile strength, yield strength, and ductility of a given material. The primary purpose of this measurement is to determine the level of deformation or elongation that a metallic or composite specimen can sustain prior to experiencing failure. The universal testing machine is commonly utilised for the execution of this particular test.

The testing apparatus consists of two crossheads, namely the upper and lower crossheads. The lower crosshead remains fixed, while the upper crosshead can be adjusted within the tension area. The upper crosshead is supported by a screw column that is attached to the base. In order to ensure the stability of the test specimen, a wedge grip is employed to secure it between the two crossheads. The process of recording data involves the utilisation of a data logger system, comprising an electronic control panel and a computer. The complete configuration is depicted in the diagram.

The test specimens are prepared following established standards, including ASTM D638 for conducting tensile tests and ASTM D790 for performing flexural tests. Tensile testing evaluates the capacity of a specimen to withstand permanent deformation, whereas flexural testing gauges its resistance to deformation caused by bending stress. In the context of tensile testing, a load cell with a capacity of 5 kN is utilised, along with a crosshead speed of 50 mm/min. In the context of flexural testing, the yielding flexural strength is determined by employing a load cell with a capacity of 0.5 kN. In order to accommodate for potential discrepancies in experimental results, each trial is carried out in triplicate. As a result, three sets of specimens for tensile strength and flexural strength are subjected to testing.

2.3.2 Flexural Test

Flexural testing evaluates the amount of force needed to bend a metallic beam and formulates a material's stiffness or resistance to flexing. Flexural modulus is a measure of how far a material can bend without permanently changing its shape. According to standards like ISO 7438, ASTM E855, ASTM E290, *etc.*, basic bending testing is the most common type of flexural testing for metallic composites. Tensile modulus can be calculated using the stress-strain graphs created by these tests. For the flexural test, two-point and three-point bending fixtures are frequently employed. Flexural strength was determined from three point bending test. Specimen size for flexural testing was 120 mm × 19 mm with span to thickness ratio of 16:1. Strain rate was kept at 1 mm/min. Average of five

sample values were recorded for determining the flexural strength of the composites.

3.0 Results and Discussion

In the automotive industry, the quest for materials capable of withstanding extreme forces, ensuring vehicle safety, and enhancing overall performance has never been more crucial. This section undertakes a comprehensive examination of mechanical test results for three distinct materials: ASTM A148 Gr 80–50, P100/6061 Al, and Graphite Al GA 7–230 MMC, with a specific focus on their applicability to automotive chassis construction. These materials represent a spectrum of mechanical properties, each offering unique advantages and considerations.

3.1 Tensile Testing

ASTM A148 Gr 80–50, with its impressive tensile strength of 390 MPa, stands out as a prime candidate for automotive chassis applications. Its remarkable strength, combined with a 22% elongation and 35% reduction in area, suggests a material capable of enduring dynamic loads while accommodating deformation, making it particularly suitable for critical chassis components. P100/6061 Al, a composite material featuring an aluminum component, reveals a tensile strength of 320 MPa, showcasing its strength-to-weight ratio. With a 30% elongation and a 41% reduction in area, this material strikes a balance between strength and ductility. For applications where weight reduction is paramount, P100/6061 Al presents

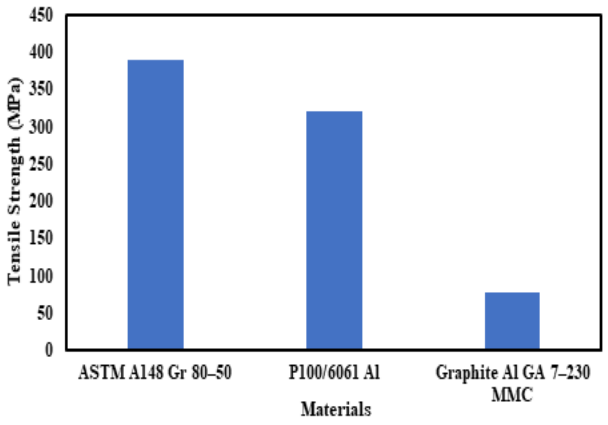


Figure 4. Comparison of tensile strength for different materials.

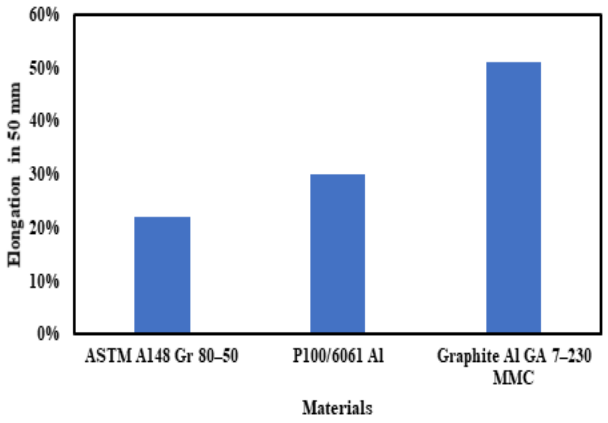


Figure 5. Comparison of % elongation for different materials.

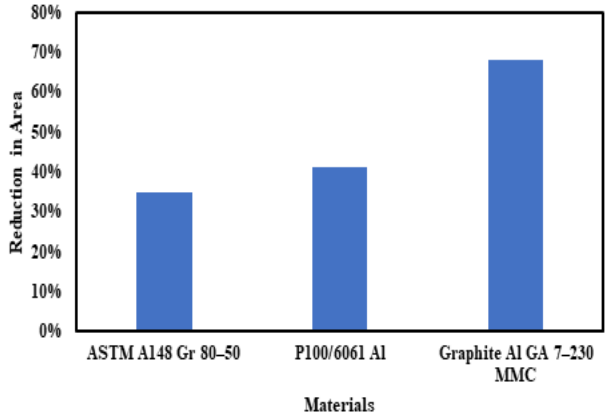


Figure 6. Comparison of reduction in area for different materials.

an attractive option in chassis design, contributing to enhanced fuel efficiency without compromising on structural integrity. In contrast, Graphite Al GA 7–230 MMC, though displaying the lowest tensile strength at 76.9 MPa, unveils an unparalleled degree of ductility. Its impressive 51% elongation and 68% reduction in area position it as a material capable of absorbing energy during deformation. In scenarios where impact resistance and energy absorption are critical, such as automotive crumple zones, Graphite Al GA 7–230 MMC may provide a distinct advantage.

3.2 Flexural Testing

For automotive chassis components exposed to torsional forces and dynamic loads, high flexural strength is

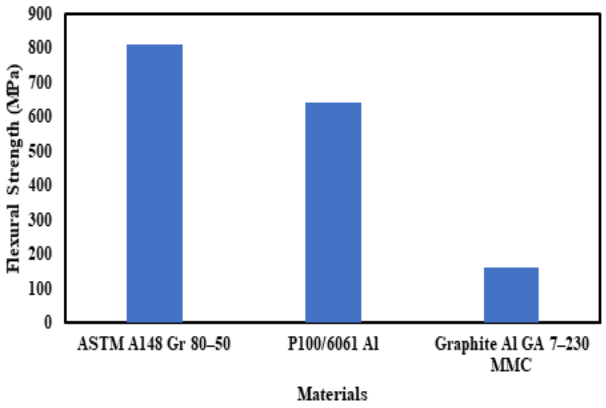


Figure 6. Comparison of reduction in area for different materials.

essential. ASTM A148 Gr 80–50 excels in this regard, exhibiting a flexural strength of 810 MPa. Its ability to resist bending ensures the structural integrity of vital chassis elements, making it an excellent choice for demanding applications. P100/6061 Al, with a flexural strength of 640 MPa, emerges as an appealing alternative in scenarios where a balance between tensile and flexural strength is sought. Its relatively high flexural strength, coupled with its lightweight properties, positions it favorably for various chassis components, including suspension parts and structural members. Graphite Al GA 7–230 MMC, despite its lower flexural strength at 159 MPa, compensates with remarkable ductility. In specific automotive chassis applications where components are designed to deform and absorb energy during a collision, such as in modern vehicle safety systems, this material's unique properties may offer distinct advantages.

The choice of material for automotive chassis applications encompasses a multifaceted evaluation, including factors such as strength, ductility, weight, and specific performance requirements. ASTM A148 Gr 80–50 stands as a robust choice for applications demanding high strength and reliability. P100/6061 Al holds promise in scenarios prioritizing weight reduction without compromising on strength, contributing to enhanced vehicle efficiency. Meanwhile, Graphite Al GA 7–230 MMC's exceptional ductility positions it as a contender in applications where impact resistance and energy absorption are paramount. The ultimate material selection hinges on the precise requirements of automotive chassis design, including adherence to safety standards, weight considerations, and performance expectations.

4.0 Conclusion

As the automotive landscape evolves, continued research into the optimization of composite materials and innovative manufacturing techniques will play a pivotal role in harnessing the strengths of these materials while mitigating their weaknesses. This study explored the mechanical properties of three materials-ASTM A148 Gr 80-50, P100/6061 Al, and Graphite Al GA 7–230 MMC-with a primary focus on their suitability for automotive chassis applications. Our analysis of these materials mechanical properties, conducted through rigorous testing methodologies, yielded valuable quantitative insights. ASTM A148 Gr 80-50, with its tensile strength of 390 MPa and flexural strength of 810 MPa, emerged as a robust candidate, boasting impressive load-bearing capabilities. Additionally, its 22% elongation and 35% reduction in area demonstrated commendable ductility, contributing to its appeal for critical chassis components. P100/6061 Al, a composite material featuring an aluminum alloy, showcased an appealing balance between strength and weight. With a tensile strength of 320 MPa and a flexural strength of 640 MPa, this material offers significant structural integrity. Its 30% elongation and 41% reduction in area provide a favorable ductility profile, enhancing its potential in weight-sensitive applications. Graphite Al GA 7–230 MMC, while displaying lower tensile and flexural strengths at 76.9 MPa and 159 MPa, respectively, made a strong case for itself through its exceptional ductility. With a 51% elongation and a 68% reduction in area, this composite material excels in energy absorption during deformation, particularly in applications demanding impact resistance. The choice of material ultimately hinges on the specific demands of automotive chassis design, encompassing factors like safety standards, weight considerations, and performance expectations. Based on the findings, subsequent study will concentrate on key areas to enhance the structural design and performance of vehicle chassis systems.

- **Deeper Exploration of Materials**: Focus on nano-composites, bio-composites, and hybrid materials.
- **Emphasis on Manufacturing**: Integration of 3D printing and topology optimization.

- **Inclusion of EV Systems**: Align material research with the needs of electric vehicles.
- **Structural Monitoring**: Suggest IoT-based health monitoring systems.
- **Lifecycle Assessment**: Highlight the need for a circular economy and cost analysis.
- **Dynamic Testing**: Include testing for impact loads, vibrations, and other real-world conditions.

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