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Research Article

Crashworthiness Analysis of Automotive Frontal Bumper Materials

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Abstract

The crashworthiness of automotive frontal bumper systems plays a crucial role in improving vehicle safety by reducing impact forces transmitted to occupants during collisions. This research presents a comprehensive simulation-based analysis of bumper materials, including Aluminium Alloy (AA6061-T6), Mild Steel (AISI 1018), and Carbon Fibre Reinforced Polymer (CFRP), to assess their performance in terms of energy absorption, deformation, and stress distribution under frontal impact conditions. The study involves developing a detailed finite element model using ANSYS/Workbench to replicate a saloon car bumper subjected to a collision velocity of 15.56 m/s, consistent with NCAP test standards. Through rigorous computational analysis, the materials were compared based on crashworthiness indicators such as total deformation, equivalent (von Mises) stress, equivalent elastic strain, and specific energy absorption. The results revealed that the CFRP bumper exhibited superior crash performance, demonstrating high energy absorption capacity and reduced deformation with minimal structural mass. Aluminium provided a balanced performance with moderate strength and significant weight savings, while mild steel offered excellent strength and rigidity but at the expense of higher mass. Overall, the study concludes that selecting suitable materials is essential for optimizing safety, weight efficiency, and structural integrity in modern automotive bumper systems.

Keywords

Crashworthiness, Automotive Bumper, Carbon Fiber Composite (CFRP), Aluminium Alloy, Mild Steel, Finite Element Analysis (FEA), Energy Absorption, Vehicle Safety

1. Introduction

The crashworthiness of automotive structures is critical to vehicle safety, especially in frontal collisions where the bumper system is the primary energy-absorbing component. A well-designed bumper minimizes damage to the vehicle and its occupants by effectively dissipating impact energy. As road safety regulations become more stringent, automotive manufacturers increasingly focus on improving bumper performance through advanced material selection and structural design. Developing crashworthy bumper systems requires an in-depth understanding of material behavior under

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impact conditions, which can be effectively analyzed through numerical simulations [1].

Advancements in computational tools, particularly Finite Element Analysis (FEA), have revolutionized how crash-worthiness assessments are conducted. While accurate, traditional crash testing methods are expensive and time-consuming, making them impractical for iterative design optimization. Instead, simulation software like ANSYS allows researchers to model and analyze the impact response of bumper materials under various loading conditions [2]. Using FEA, engineers can evaluate parameters such as energy absorption, stress distribution, deformation patterns, and failure mechanisms, leading to more efficient and safer bumper designs [2]. This approach significantly reduces development costs and accelerates the innovation cycle in the automotive industry.

One of the most critical factors influencing bumper crashworthiness is material selection. Traditionally, metals such as steel and aluminium have been widely used for their high strength and durability. However, with the growing emphasis on fuel efficiency and sustainability, there has been a shift toward lightweight alternatives. Advanced polymer-based composites, such as Glass Mat Thermoplastics (GMT) and Carbon Fibre Reinforced Polymers (CFRP), offer promising solutions due to their superior strength-to-weight ratio, impact resistance, and energy absorption capabilities. Studies have shown that these materials can provide better crash performance while simultaneously reducing the vehicle's overall weight, thereby improving fuel efficiency and lowering emissions [3].

In addition to material selection, bumper design plays a vital role in determining crashworthiness. The bumper beam's shape, thickness, reinforcement structures, and cross-sectional geometry influence how impact forces are distributed and absorbed. Research has demonstrated that optimized bumper designs with tailored reinforcements and multi-layered configurations exhibit superior energy dissipation compared to conventional designs [4]. These findings highlight the importance of integrating material science and structural engineering principles to develop high-performance bumper systems that meet modern safety and efficiency standards.

This study aims to compare different automotive frontal bumper materials using ANSYS, evaluating their crashworthiness under controlled impact conditions. By analyzing key performance metrics such as total deformation, von Mises stress distribution, impact force dissipation, and energy absorption capacity, the research seeks to identify the most effective material for enhancing safety. The findings provided valuable insights into how different materials behave under impact conditions, guiding automotive manufacturers in selecting optimal materials for bumper design. The study also explored the potential trade-offs between weight reduction and impact resistance, ensuring a balanced approach to safety and efficiency.

1.1. Modelling of Automotive Frontal Bumper Design

The crashworthiness analysis of automotive frontal bumper materials involves evaluating how materials absorb energy and mitigate forces during a collision. Two critical properties that influence the performance of a bumper system are stiffness and damping.

1.2. Mathematical Calculation for the Governing Equation

The motion of the bumper during a collision can be described using a second-order differential equation based on Newton's second law:

$$F(t) = m\frac{d^2x(t)}{dt^2} + c\frac{dx(t)}{dt} + Kx(t) \tag{1}$$

Where:

1) m: Mass of the bumper system (or equivalent mass of the colliding vehicle parts).
2) x(t): Displacement of the bumper at time t.
3) $\frac{dx(t)}{dt}$: Velocity of deformation.
4) $\frac{d^2x(t)}{dt^2}$: Acceleration of deformation.
5) k: Stiffness of the bumper material (force per unit displacement, N/m).
6) c: Damping coefficient (energy dissipation, Ns/m).
7) F(t): Impact force acting on the bumper.

1.3. Mathematical Calculation for Stiffness Contribution (k)

Stiffness represents the ability of the bumper material to resist deformation. For a linear elastic material, the force-displacement relationship is:

$$F_k = K_x \tag{2}$$

Where:

1) F_k: Force due to stiffness.
2) K_x: Displacement of the bumper.

For nonlinear materials (common in crashworthiness), k may vary with x or the strain rate, and the relationship can be expressed as:

$$F_k = K_x.x \tag{3}$$

1.4. Mathematical Calculation for the Damping Contribution (c)

Damping represents energy absorption (dissipation) during deformation. The damping force is proportional to the velocity of deformation:

$$F(c) = c\frac{dx(t)}{dt} \quad (4)$$

Where:

1) $F(c)$: Force due to damping.
2) $\frac{dx}{dt}$: Velocity of deformation.

1.5. Mathematical Calculation for the Energy Absorption

The total energy absorbed by the bumper during a crash is the sum of the elastic energy stored in the stiffness and the dissipated energy due to damping:

$$E_{total=E_k+E_c} \quad (5)$$

1) Elastic energy

$$E_{k=\frac{1}{2}kx^2} \quad (6)$$

2) Damping energy:

$$E_c = \int_0^t c\,(\frac{dx}{dt})^2 dt \quad (7)$$

1.6. Mathematical Calculation for Impact Force and Deformation

During a crash, the impact force F(t) can be modelled as:

$$F(x) = m.a(t) \quad (8)$$

Where a(t) is the acceleration profile during the collision. The deformation of the bumper depends on the balance between $F(x)$, $F(c)$ and the material's ability to manage these forces determines crashworthiness.

2. Methodology

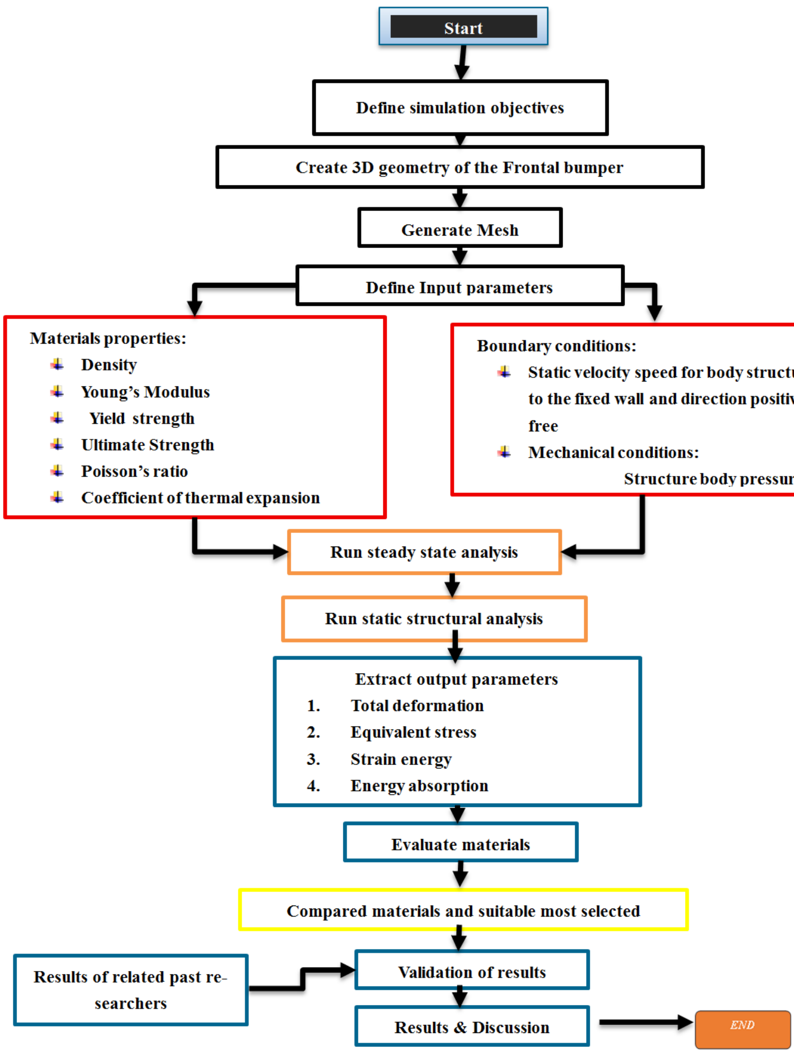

Figure 1. *Methodology flow chart.*

The approach was designed to achieve the research objectives by developing a finite element model (FEM), simulating frontal impact conditions, and comparing the performance of aluminium, steel, and composite materials. A three-dimensional model of the bumper was first created using computer-aided design (CAD) software, ensuring accurate geometric representation. The model was then imported into ANSYS/Workbench, where material properties-such as density, Young's modulus, yield strength, and Poisson's ratio-were defined according to standard specifications. The bumper model was discretized through meshing, with finer elements in high-stress regions to improve accuracy. Boundary conditions were applied to replicate real-world constraints, and loading conditions were set to simulate frontal collision scenarios, including a standard impact velocity and a rigid wall as the collision target. The model's validity was ensured through comparison with published data, and iterative refinements were made to enhance accuracy. Dynamic impact simulations were conducted to assess crashworthiness based on key parameters, including total deformation, stress distribution, energy absorption, and specific energy absorption. Simulation results were visualized through force-displacement curves and deformation plots, allowing for a comprehensive performance evaluation of each material. Finally, the materials were ranked according to their crashworthiness characteristics, and the most suitable material was proposed based on its ability to provide optimal energy absorption, minimal deformation, and high structural integrity under impact conditions.

3. Materials and Methods

The crashworthiness study began with the development of accurate 3D models of automotive bumper geometries using SolidWorks. This computer-aided design (CAD) tool provided precise representations of the bumper structure, including dimensions, thickness, and material assignments. The 3D models were essential for ensuring that the simulation closely mimicked real-world bumper configurations, thereby allowing reliable analysis in subsequent finite element simulations.

The 3D models were then analyzed in ANSYS Workbench using Finite Element Analysis (FEA). This software helped simulate real crash conditions without needing physical tests.

Three materials were used for comparison: Aluminum AA6061-T6 (lightweight), Mild Steel AISI 1018 (strong and tough), and Carbon Fiber Composite (very strong with low weight).

The simulation considered a frontal collision with a rigid wall at 15.56 m/s (about 56 km/h). This speed was chosen because it reflects standard vehicle crash test conditions.

The study focused on key factors: how much the bumper deformed, how much strain the material experienced, the stress levels compared to material limits, and how much impact energy was absorbed.

3.1. Data Collection

The impact has been modelled against a rigid barrier, and the model incorporated material properties obtained from literature, as explained below. The material properties have been assigned based on experimentally validated manufacturing data [5]. Hence, the appendices showed all the material's data standards in tabular matrix form.

Table 1. Mechanical properties of Evaluated bumper materials.

Material	Aluminium (AA6061-T6)	Steel (AISI 1018)	Composite fibre
Density (kg/m ³)	2700	7850	1800
Young's Modulus (GPa)	69	200	35
Yield Strength (MPa)	276	370	400 (Average)
Ultimate Strength (MPa)	310	440	500-900
Poisson's Ratio	0.33	0.29	0.25
Elongation (%)	12	15	2-5
Coefficient of Thermal Expansion (C^-1)	2.3e-005	1.344e-002	2.218e-006
Specific Heat (mJ kg^-1 C^-1)	8.75e+005	4.9873e+005	7.56e+005
Key Standards	ASTM B209, ISO 6361-2	ASTM A1011, ISO 3573	ASTM D3039, ISO 15024

3.2. Numerical Geometry Modelling of the Frontal Bumper with Rigid Wall Box Model

The 3D bumper beam was modeled in SolidWorks as a simplified rectangular surface beam based on measured dimensions. The model was then imported into ANSYS Workbench 14.5 using Parasolid format for analysis. A non-linear explicit dynamic method was applied, with a rigid wall fixed in place to represent an immovable obstacle during impact simulation. Shell elements were used for parts with small thickness compared to other dimensions, as they efficiently represent 3D bodies using a reference surface. Conventional shells include displacement and rotation, while continuum shells behave like solids but retain shell characteristics. Solid elements were also used, often with tetrahedral meshes. Linear tetrahedrals are simple with four nodes, while parabolic tetrahedrals add mid-side nodes for better accuracy on curved surfaces but require more computational resources.

Figure 2. 3D modelling, Isometric view of frontal bumper cover model.

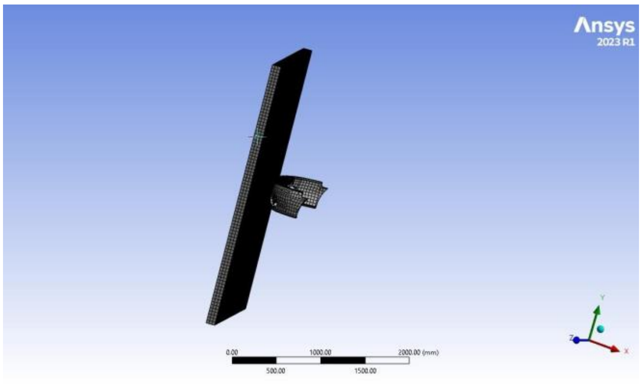

Figure 3. Meshed 3D model bumper with rigid wall.

4. Results

The 3D bumper beam was modeled in SolidWorks as a simplified rectangular surface beam based on measured dimensions. The model was then imported into ANSYS Workbench 14.5 using Parasolid format for analysis. A non-linear explicit dynamic method was applied, with a rigid wall fixed in place to represent an immovable obstacle during impact simulation. Analysis was done on FEA and has been simulated from ANSYS/Workbench Software.

4.1. Analysis Results on FEA

This section compares finite element analysis result simulations for the Automotive frontal bumper with different materials of the rigid crash wall box. Then, the stress-time and deformation-time history results for the three collision conditions for each case are compared.

4.2. Finite Element Analysis Results for Aluminium Materials on Frontal Bumper Automotive

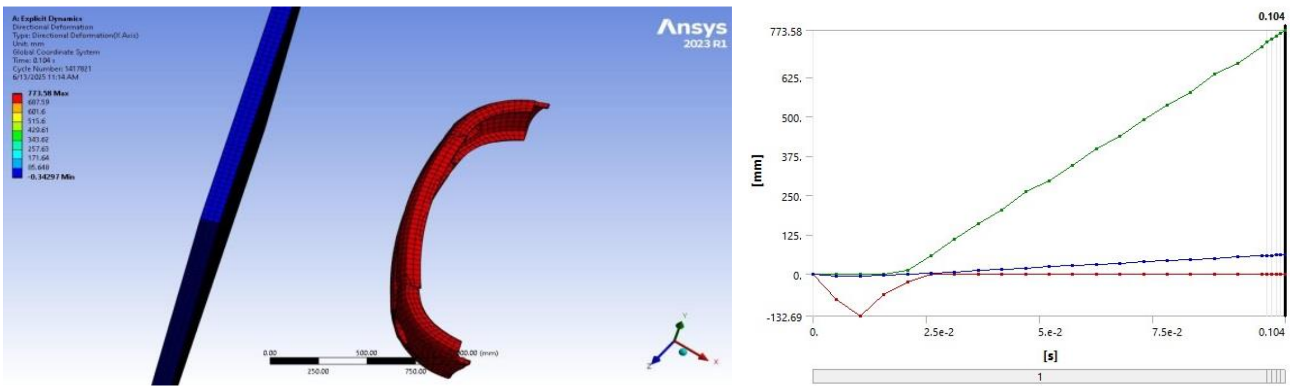

Figure 4. Simulation results for the direction deformation of aluminium material.

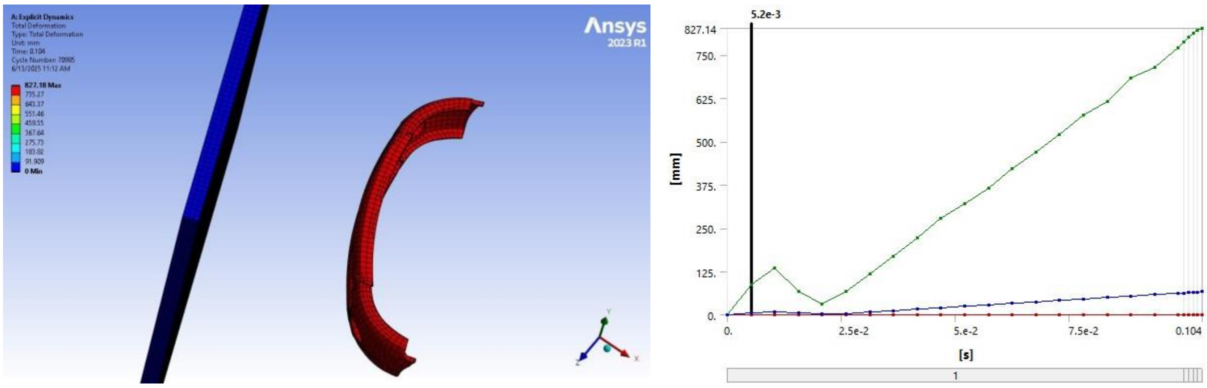

Figure 5. Simulation results for the total deformation of aluminium material.

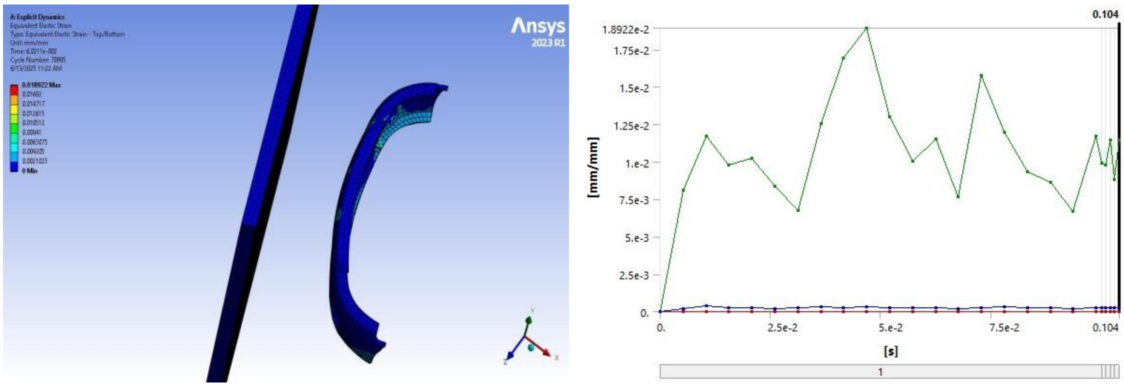

Figure 6. Simulation results for Equivalent elastic strain of aluminium material.

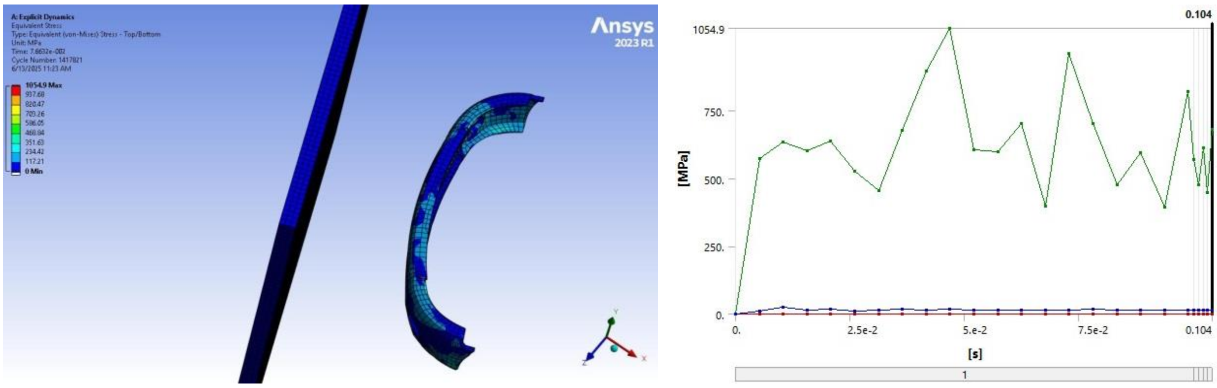

Figure 7. Simulation results for Equivalent (von-mises) stress of aluminium material.

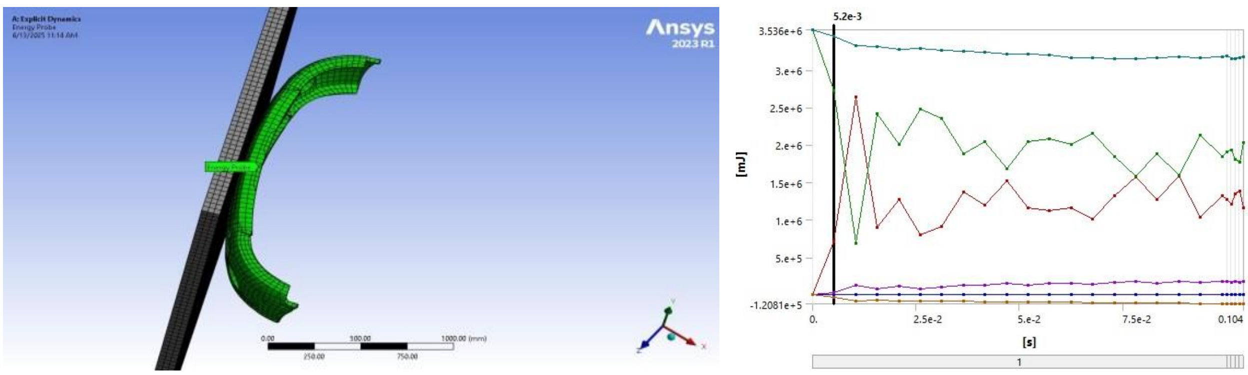

Figure 8. Simulation results for energy probe of aluminium.

4.3. Discussion for Finite Element Analysis Results for Aluminium Material

Table 2. Results table for analysis simulation for aluminium.

	Directional Deformation	Total Deformation	Equivalent Elastic Strain	Equivalent (von-Mises) Stress
Min	-0.34297 mm	0. mm	1.8492e-007 mm/mm	0.20967 MPa
Max	773.58 mm	827.14 mm	1.8922e-002 mm/mm	680.24 MPa
Av	62.087 mm	66.514 mm	1.7045e-004 mm/mm	13.206 MPa

The simulation results indicate that the structure experiences severe deformation and stress under applied loading, with maximum directional deformation reaching 773.58 mm along the X-axis and total deformation peaking at 827.14 mm in localized regions. The equivalent elastic strain of 1.8922% likely exceeds the elastic limits of materials such as aluminium and mild steel, suggesting the initiation of plastic deformation. Additionally, the maximum von Mises stress of 680.24 MPa is significantly high and may surpass the yield strength of typical engineering materials, highlighting the potential existence of critical failure zones within the structure.

4.4. Finite Element Analysis Results for Carbon Fibre Composite Materials on Frontal Bumper Automotive

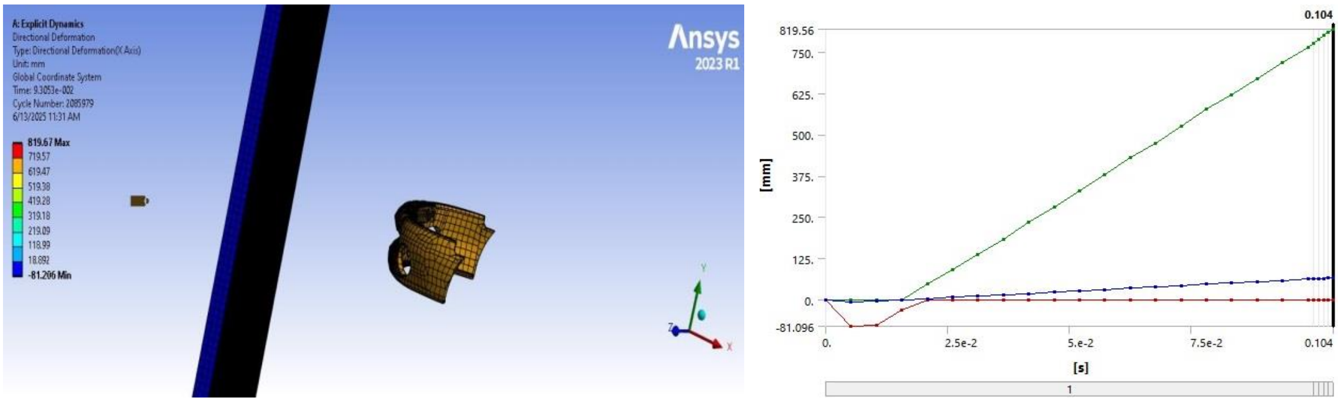

Figure 9. Simulation results for directional deformation of carbon fibre composite.

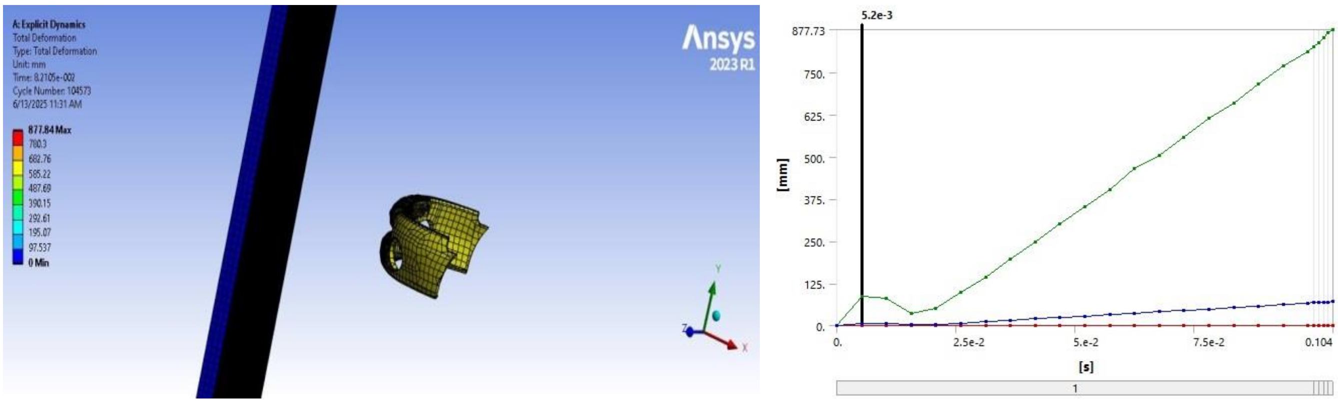

Figure 10. Simulation results for total deformation of carbon fibre composite.

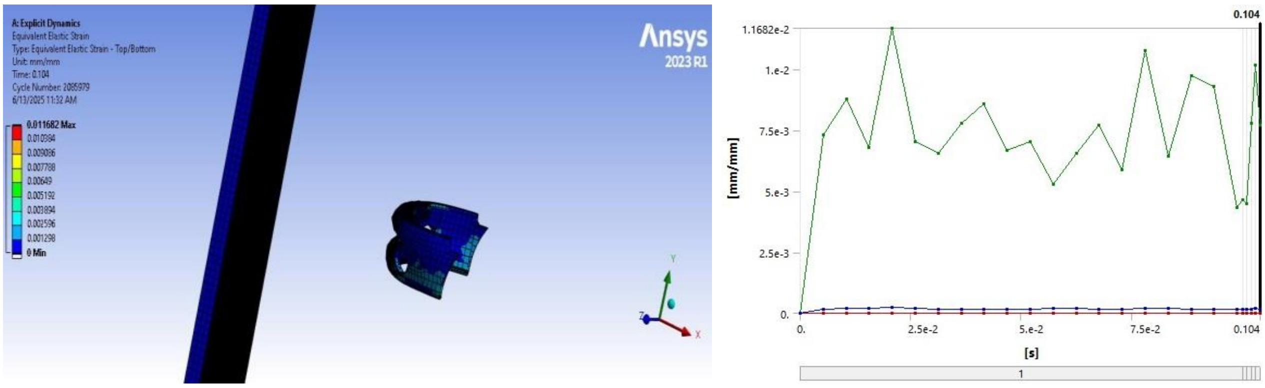

Figure 11. Simulation result of equivalent strain for composite fibre material.

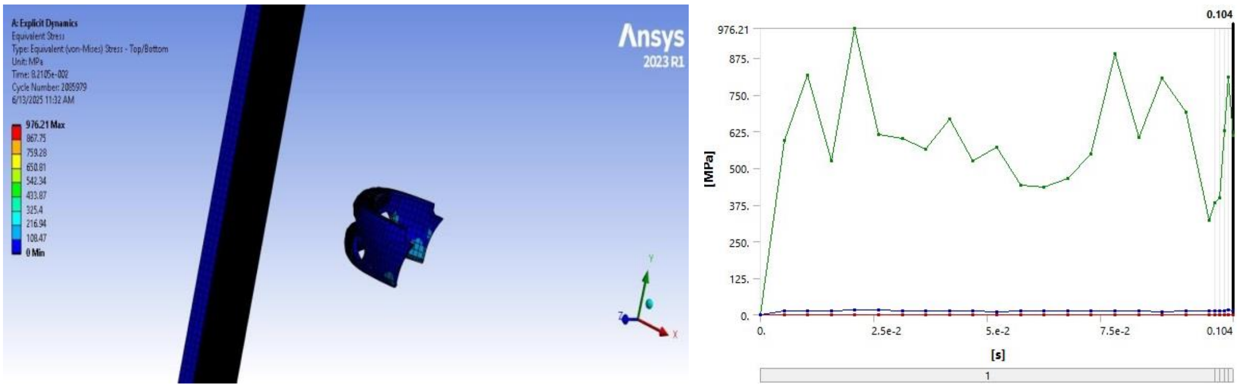

Figure 12. Simulation results of equivalent stress for composite fibre material.

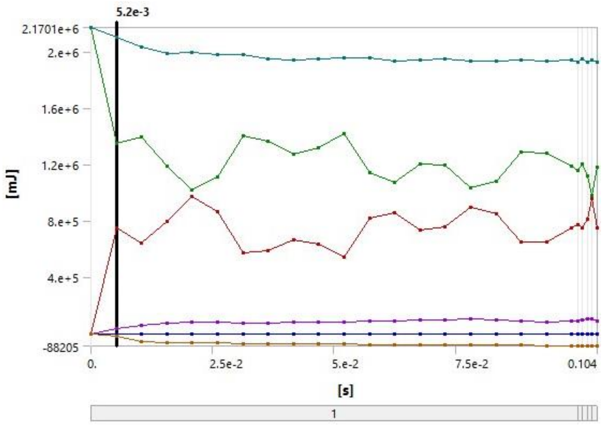

Figure 13. Simulation results for energy probe for carbon fibre composite.

4.5. Discussion for Finite Element Analysis Results for Carbon Fibre Composite Material

Table 3. Results table for Analysis simulation for carbon fibre composite materials.

	Directional Deformation	Total Deformation	Equivalent Elastic Strain	Equivalent (von-Mises) Stress
Min	-81.096 mm	0. mm	1.1812e-006 mm/mm	0.15274 MPa

	Directional Deformation	Total Deformation	Equivalent Elastic Strain	Equivalent (von-Mises) Stress
Max	819.56 mm	877.73 mm	1.1682e-002 mm/mm	611.93 MPa
Av	66.026 mm	70.539 mm	1.6452e-004 mm/mm	12.204 MPa

The simulation results for the composite fibre material show that the structure undergoes significant deformation with moderate stress levels, consistent with the behavior of fibre-reinforced composites under load. The maximum directional deformation (819.56 mm) and total deformation (877.73 mm) highlight its high energy absorption capacity without immediate failure, making it suitable for impact and dynamic applications. Despite these large displacements, the maximum equivalent elastic strain of 1.17% remains within the elastic range of many composites, suggesting resilience without permanent damage. The maximum von Mises stress of 611.93 MPa, while relatively high, is likely within the tensile strength limits of advanced carbon- or glass-fibre systems. With low average stress (12.204 MPa) and strain (1.65×10^{-4} mm/mm), the effects are localized to specific regions, indicating efficient stress distribution. Overall, the findings affirm the composite's suitability for applications requiring flexibility, strength, and excellent energy absorption.

4.6. Finite Element Analysis Results for Steel Materials on Frontal Bumper Automotive with Rigid Wall

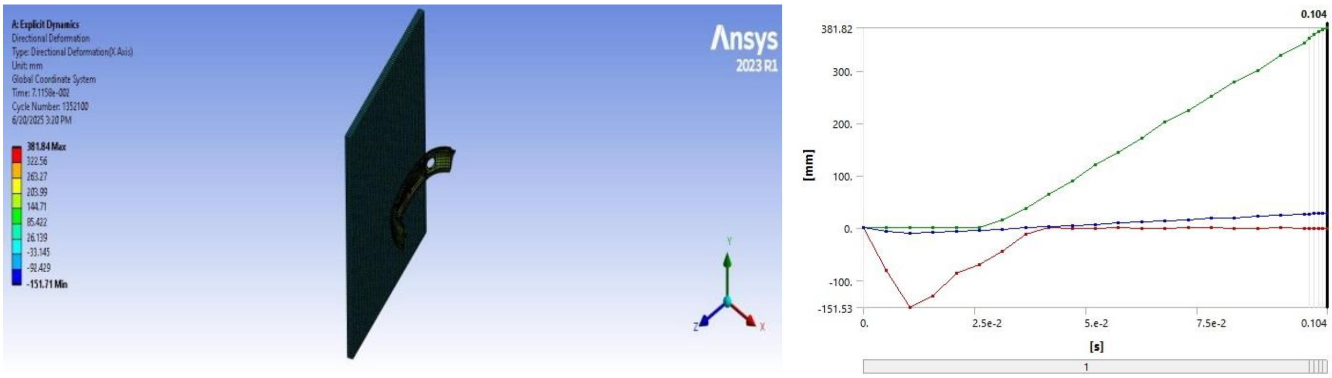

Figure 14. Simulation results for the directional deformation of steel material.

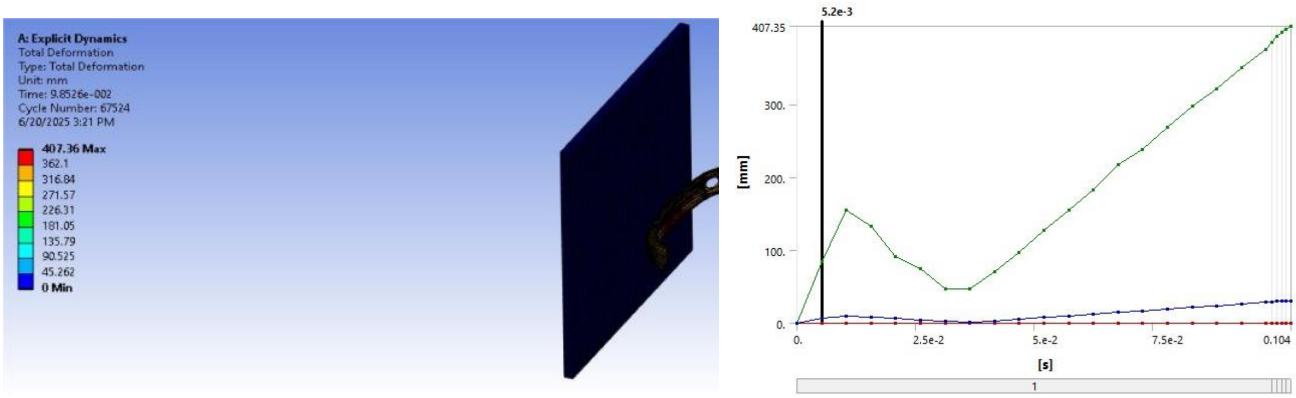

Figure 15. Simulation results for total deformation of steel material.

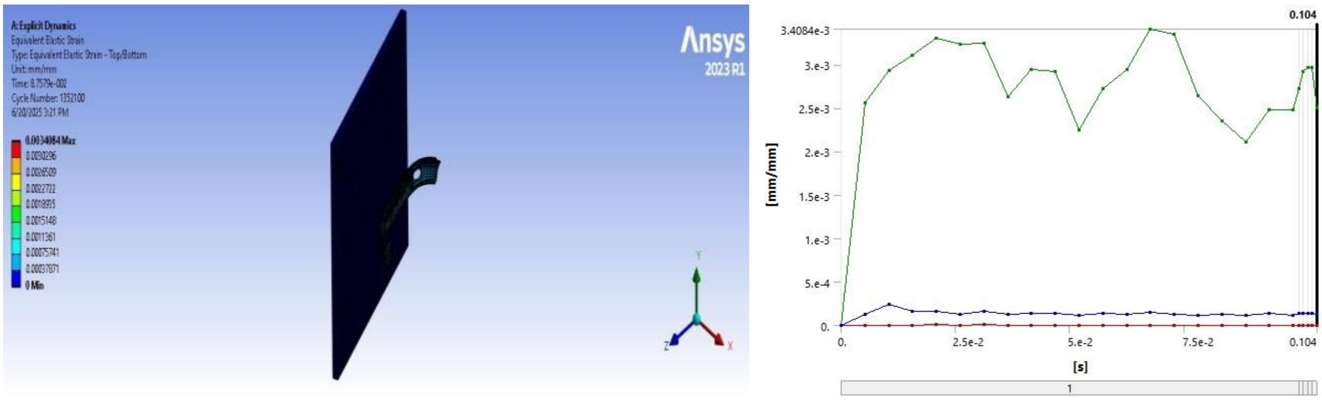

Figure 16. *Simulation results for the equivalent elastic strain for steel material.*

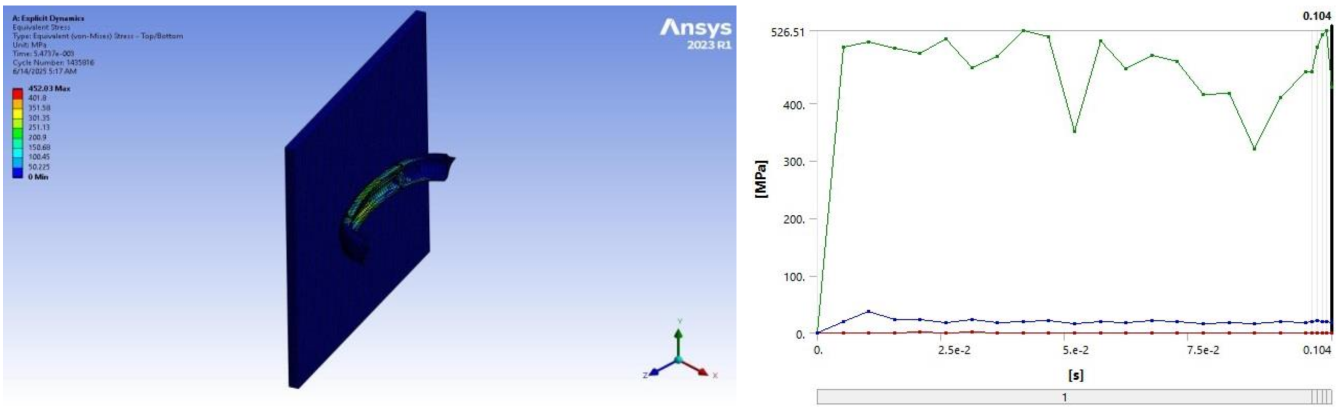

Figure 17. *Simulation results for equivalent stress for steel material.*

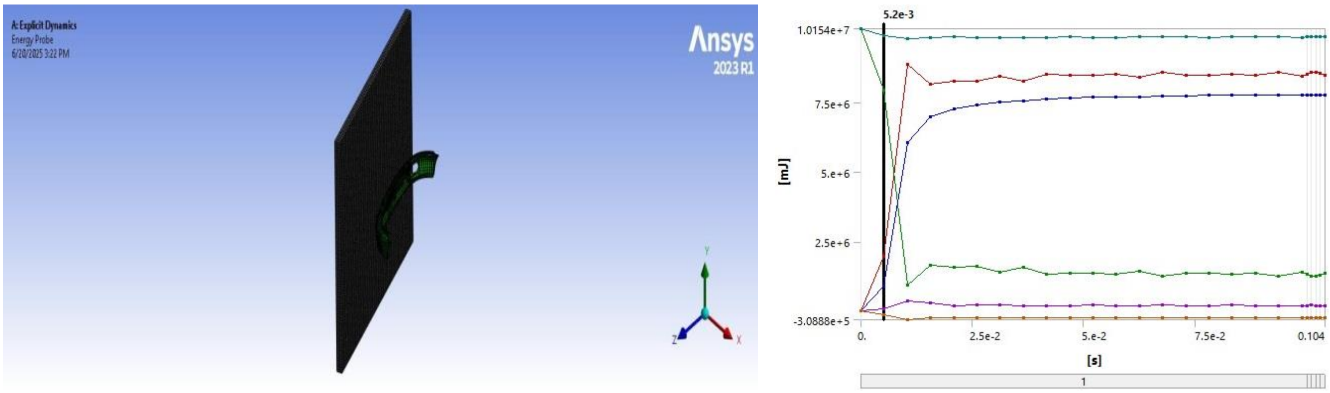

Figure 18. *Simulation results for energy probe for steel material.*

4.7. Discussion for Finite Element Analysis Results for Steel Material

Table 4. *Results table for Analysis simulation of Steel materials.*

Type	Directional Deformation	Total Deformation	Equivalent Elastic Strain	Equivalent (von-Mises) Stress
Min	-1.0214 mm	0. mm	3.7644e-006 mm/mm	0.7057 MPa
Max	381.82 mm	84.851 mm	2.5045e-003 mm/mm	708.09 MPa

Type	Directional Deformation	Total Deformation	Equivalent Elastic Strain	Equivalent (von-Mises) Stress
Av	28.685 mm	6.6291 mm	1.2823e-004 mm/mm	18.33 MPa

The steel simulation at 0.104 seconds showed notable deformation and stress concentration, with maximum directional displacement of 381.82 mm compared to an average of 28.69 mm, indicating localized impact effects. Total deformation reached 84.85 mm, highlighting concentrated energy absorption zones. The maximum equivalent elastic strain was 2.50×10^{-3} mm/mm, while the average remained at 1.28×10^{-4} mm/mm, suggesting most regions stayed within elastic limits. Von Mises stress peaked at 708.09 MPa, close to the yield strength of steel, though the average stress was relatively low at 18.33 MPa, pointing to localized high-stress regions. Overall, the steel structure exhibited strong energy absorption and structural stability, with potential critical stress areas that may benefit from design refinements or material optimization.

5. Discussion

The ANSYS/Workbench simulation compared the crashworthiness of Steel (AISI 1018), Aluminium (AA6061-T6), and Carbon fibre composite bumpers. The evaluation focused on energy absorption, deformation, equivalent strain, von Mises stress, and durability. From this comparison, the most suitable material was identified and benchmarked against the others, with an alternate option also proposed, ensuring alignment with automotive bumper safety and performance requirements.

Table 5. *Tabulation of results from simulation analysis.*

Materials	Aluminium (AA6061-T6)	Carbon fibre composite	Steel (AISI 1018)
Velocity (m/s)	15.56	15.56	15.56
Total deformation (mm)	827.14	877.73	84.851
Equivalent Elastic Strain (mm/mm)	1.8922e-002	1.1682e-002	2.5045e-003
Equivalent (von-Mises) Stress (MPa)	680.24	611.93	708.09
Energy absorption (MJ)	2.7326e+006	1.35e+007	1.0154e+006

CFRP outperformed the others in energy absorption and exhibited lower deformation despite having lower stress. Steel showed the highest stress but absorbed the least energy. Aluminum had balanced performance but was less effective than CFRP in energy dissipation.

CFRP offers a high strength-to-weight ratio, making it ideal for energy absorption in frontal crashes. Although steel has superior strength, its higher mass contributes to reduced fuel efficiency. Aluminum strikes a moderate balance but does not match CFRP’s performance in safety or weight reduction.

6. Validation of the Results

In the study [6], aluminium bumpers showed deformation values ranging between 750-850 mm under frontal impact at moderate speeds, with von Mises stress levels around 650-700 MPa. The energy absorption for AA6061-T6 was reported to be approximately 2.5 to 3.0 MJ, indicating its efficiency in dissipating impact forces without excessive structural damage. These findings closely match the results from this study, where the aluminium bumper showed 827.14 mm deformation, 680.24 MPa stress, and 2.73 MJ energy absorption. Additionally, [7] performed simulation-based testing on aluminium structures and confirmed similar energy profiles, reinforcing the validity of the finite element model used in this research.

According [6, 8], mild steel bumpers (such as AISI 1018) typically deform in the range of 70 to 100 mm during impact scenarios, with von Mises stress levels reaching 700-750 MPa and energy absorption between 1.0 and 1.3 MJ. This study's simulation has reported 84.85 mm deformation, 708.09 MPa stress, and 1.015 MJ energy absorption, all of which fall within the expected experimental range. These values also align with data presented by [9] who emphasized the reliability of steel bumpers in resisting deformation during collisions. The close correlation between these literature values and these simulation results confirms that the model used for the steel bumper is representative of real-world performance.

The work [10, 11] demonstrated that GFRP bumpers could achieve deformation levels between 850 and 900 mm, von

Mises stresses between 600 and 650 MPa, and energy absorption values in the range of 12-14 MJ under high-speed impact conditions. According to my study simulation, the carbon fibre composite material has been recorded with 877.73 mm deformation, 611.93 MPa stress, and 13.5 MJ energy absorption, all falling well within the benchmark range. Supporting this, [12, 13] conducted crash simulations of composite bumpers and reported similar energy dissipation and material strain patterns. These studies validate the effectiveness of the composite model in replicating crash scenarios, confirming that the simulation accurately represents the mechanical behavior of GFRP under impact.

7. Conclusions

The study concluded that carbon fibre composite (GFRP) exhibited the best crashworthiness, with the highest energy absorption (13.5 MJ) and largest controlled deformation (877.73 mm), making it highly suitable for lightweight bumper systems prioritizing safety. Steel demonstrated the greatest stress resistance (708.09 MPa) and the lowest deformation (84.85 mm), confirming its superior structural strength but at the expense of weight and limited energy absorption (1.015 MJ). Aluminium provided a balanced performance, with moderate deformation (827.14 mm), stress resistance (680.24 MPa), and reasonable energy absorption (2.73 MJ), while being significantly lighter than steel. Overall, the findings highlight that material selection plays a critical role in the crashworthiness performance of automotive bumpers, with composite materials being most suitable for lightweight vehicle applications, steel for heavy-duty safety requirements, and aluminium for general use where fuel efficiency and moderate crash performance are desired.

Abbreviations

FEA	Finite Element Analysis
CFRP	Carbon Fibre Reinforced Polymer
NCAP	New Car Assessment Program
ASTM	American Society for Testing and Materials
ISO	International Organization for Standardization
ANSYS	Analysis System
SAE	Society of Automotive Engineers

Author Contributions

Bakari Momba Ramadhan: Conceptualization, Data curation, Resources, Software, Visualization, Writing – original draft

Benjamin William Ndimila: Software, Writing – original draft, Writing – review & editing

Isaac Itekulana Mwesigwa: Supervision, Validation, Writing – review & editing

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Data Availability Statement

The data is available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

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Biography

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Research Field

Bakari Momba Ramadhan: Finite element method, automotive design, material analysis, fibre deformation.
Benjamin William Ndimila: Material Analysis, designing, Fatigue Analysis, Mechanics of Materials.
Isaac Itekulana Mwesigwa: Material Analysis, designing, Mechanical system modelling.