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(Review Article)

Structural Integrity and Durability Assessment of Composite Brake Pads Using Finite Element Simulation

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Abstract

The demand for durable and environmentally sustainable brake pads has driven increasing interest in composite materials for automotive applications. This study presents a numerical assessment of the structural integrity and durability of a composite brake pad using finite element simulation techniques. Finite Element Analysis (FEA) was performed in ANSYS to evaluate key mechanical responses, including von Mises stress, principal stresses, and total deformation under representative braking loads. The composite formulation comprised phenolic resin as the binder, graphite as a solid lubricant, aluminum oxide as an abrasive, and agro-mineral fillers including coconut fiber, palm slag, and sawdust, selected for their functional performance and sustainability benefits. Simulation results revealed a maximum equivalent stress of 1.3981×10^7 Pa (13.98 MPa) and a minimum principal stress of -1.90×10^5 Pa (−0.19 MPa), with stress concentrations localized primarily within the frictional contact region. The total deformation ranged from 1.68 µm to 0.017 µm, indicating very low displacement and high stiffness under operational loading conditions. These findings confirm that the composite brake pad maintains structural stability and operates within safe stress limits, demonstrating suitability for repeated and prolonged braking scenarios. Overall, the study validates the effectiveness of simulation-based evaluation in predicting brake pad performance and highlights the potential of agro-based composite materials for reliable and sustainable automotive braking systems.

Keywords: Composite brake pad materials; Finite Element Analysis; Sustainable materials; Total deformation; Principal stress; Structural integrity; Automotive braking systems

1. Introduction

The third law of motion, formulated by Sir Isaac Newton, states that "for every action, there is an equal and opposite reaction. This fundamental principle governs the behavior of objects under the influence of external forces (Zagurskiy, 2024). In the context of vehicular movement and the braking systems, the third law of motion plays a critical role in the functioning of brake pads. Brake pads are vital components in automotive braking systems, directly contributing to vehicle safety, reliability, and performance (Sunil & Edwin, 2023). When a vehicle's brakes are applied, the brake pads exert a force on the rotating wheels, causing them to decelerate (Zagurskiy *et al*., 2024; Rao & Babji 2015). According to the third law of motion, the wheels exert an equal and opposite force on the brake pads, resulting in friction and heat generation (Hassan, 2021; Bahl, & Bagha 2021) The effectiveness of the brake pads in converting the kinetic energy of the vehicle into thermal energy, while withstanding the stresses and strain imposed by the braking process (via friction between the disc and the pad), is crucial for ensuring safe and reliable vehicle operation (Hassan 2021; Singaravelu,

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2019; Zagurskiy, 2024). Over the years, advancements in material science have revolutionized the design and functionality of brake pads, shifting focus from traditional asbestos-based materials to environmentally sustainable composite materials (Lamidi *et al*., 2025a; Lamidi *et al*., 2025b). The ban on asbestos due to its adverse health effects has further accelerated this transition, leading to extensive research on alternative materials with superior mechanical and thermal properties (Parker *et al.*, 2020; Lamidi *et al*., 2025a; Chen *et al*., 2020). Composite brake pads are engineered using a combination of binders, abrasives, lubricants, and fillers to meet the high demands of modern braking systems (Borawski *et al.*, 2023; Yevtushenko *et al*., 2022). These waste-derived fillers are attractive for a waste-to-wealth approach and for reducing material costs while achieving desirable tribological and mechanical performance (Kazeem et al., 2023; Bello et al., 2020; Risti, 2023; Paula & Nogueira 2023). Binders are essential components in composite brake pads, providing structural integrity by holding the various ingredients together (Lamidi *et al*., 2025b; Sathyamoorthy *et al*., 2022). Phenolic resin, a type of thermosetting polymer, is frequently used as a binder due to its ability to accommodate all materials and its thermal resilience (Ammar, 2023; Andreea-Catalina 2023). The material properties of each constituent significantly influence the overall performance, including wear resistance, thermal stability, and frictional behavior (Arman, 2018; Aulin, 2024; Bilvatej, 2023). Phenolic resin, for instance, is commonly used as a binder due to its thermal resilience, while graphite serves as a lubricant to reduce frictional wear. Abrasives like aluminum oxide enhance the braking efficiency by increasing friction, and eco-friendly fillers such as coconut fiber, palm slag, and sawdust offer a sustainable alternative while reducing the environmental footprint of production (Nwankwo *et al*., 2025; Chiejine *et al.*, 2025).

Finite Element Analysis (FEA) has emerged as a powerful tool for evaluating the mechanical behavior and durability of brake pad materials under operational conditions. It provides a comprehensive analysis of stress distribution, deformation, and failure mechanisms, allowing researchers to optimize material composition and design. ANSYS simulation software, widely used in engineering applications, offers accurate modeling of brake pad performance under simulated loads, speeds, and thermal conditions. Studies have shown that FEA not only predicts material behavior but also reduces the cost and time associated with physical prototyping and testing (Samsudin *et al*., 2025; Risti, 2023). In this study, a composite brake pad material was developed with ANSYS for the Toyota Camry 2010 model, popularly used as a taxi in Nigeria. Using a combination of phenolic resin, graphite, aluminum oxide, and natural fillers. The objective was to assess its structural integrity and durability through FEA. Key performance parameters such as total deformation, von Mises stress, and principal stresses were analyzed to understand the material's response to operational loads. The findings aim to validate the material's suitability for automotive applications and provide insights into optimizing composite brake pads for enhanced performance, durability, and sustainability.

2. Materials and Methodology

2.1. Methodology for ANSYS Modelling and Simulation of Composite Brake Pad

The process involved in designing and simulating the composite brake pad using simulation techniques is presented in this section. Phenolic resin was used as a binder, graphite as a lubricant, aluminum oxide as an abrasive, and coconut fiber, palm slag, and sawdust were the filler materials used. Five different sample formulations were used to produce the brake pads using the rule of mixture, and a weight percent of 40% filler, 20% binder, 20% reinforcement materials, 10% lubricant, and 10% abrasive were employed for the production. The simulation models the frictional behavior, wear resistance, hardness, and thermal conductivity of the composite material under various braking conditions. The methodology of this research involves into key phases which are material selection, material property definition, creation of ANSYS material library for the composites, finite element modeling, boundary condition setup, simulation, and result analysis.

2.2. Material Selection and Properties

The constituent materials for the composite brake pad were carefully selected based on their individual and synergistic contributions to the mechanical, thermal, and tribological performance required for automotive braking applications. The formulation was designed to achieve a balance between structural integrity, durability, thermal stability, and cost effectiveness. Phenolic resin was employed as the primary binder due to its excellent adhesive characteristics, mechanical strength, and thermal resistance, which are critical for maintaining structural cohesion under braking loads and elevated temperatures. Graphite was incorporated as a solid lubricant to stabilize the friction coefficient, reduce wear, and minimize noise and vibration during braking. Aluminum oxide served as the abrasive component, enhancing frictional performance and improving wear resistance under repeated braking cycles. Agro-based and mineral fillers, namely coconut fiber, palm slag, and sawdust, were introduced to improve stiffness, rigidity, and thermal stability while also reducing material cost and supporting sustainable material utilization. These fillers contribute to load transfer within the composite and help maintain mechanical integrity under service conditions. For the numerical analysis, material properties including Young's modulus, Poisson's ratio, density, thermal conductivity, and specific heat capacity for each constituent were obtained from established literature sources. These properties were implemented in ANSYS by developing a custom material database, which enabled accurate representation of the composite constituents in the simulation framework used to assess the structural integrity and durability of the brake pad system.

2.3. Composite Material Composition and Formulation Strategy

The composite brake pad was formulated by combining the selected constituents in carefully controlled proportions informed by established research findings and preliminary material design considerations. The formulation strategy was aimed at achieving a balanced combination of mechanical strength, thermal stability, frictional performance, and wear resistance suitable for automotive braking applications. Phenolic resin which is the binding matrix constituted 20 wt.% of the composite, ensuring effective load transfer and structural cohesion among the reinforcement and filler phases. Graphite was incorporated at 10 wt.% to stabilize the coefficient of friction and reduce wear during repeated braking cycles. Aluminum oxide, also fixed at 10 wt.%, to enhance frictional effectiveness and improve the durability of the brake pad under high contact stresses. Coconut fiber was added at 20 wt.% as a reinforcement filler to improve stiffness, toughness, and thermal stability, while also contributing to the sustainability of the composite. The combined content of palm slag and sawdust was varied between 0 and 40 wt.% to investigate their influence on the composite's mechanical and thermal behavior. This variation enabled systematic evaluation of the role of agro-mineral fillers in optimizing performance while reducing material cost. The selected compositional ranges ensured that the total formulation remained balanced, allowing for effective bonding, controlled frictional behavior, and adequate thermal resistance. This composition design provided a robust basis for subsequent simulation-based structural integrity and durability assessments of the composite brake pad.

2.4. Numerical Modeling Framework in ANSYS

The brake pad model is developed using the following steps:

2.4.1. Brake Pad Geometry Development

The brake pad geometry was developed as a simplified three-dimensional model using AutoCAD Inventor and subsequently imported into ANSYS for numerical simulations. The geometric model was designed to closely represent the actual brake pad profile, with particular attention given to critical contact regions where frictional interaction and stress concentration are most significant

2.4.2. Material Property Definition and Assignment

Table 1 Mechanical Properties of Composite Materials Used

S/N	MATERIALS	TENSILE STRENGTH (MPa)	YOUNG'S MODULUS (GPa)	DENSITY (g/cm^3)	HARDNESS (vickers)	POISSON'S RATIO
1	Coconut Fibre	175	2	1.0	28	0.2
2	Saw dust	30	1.4	0.5	19	0.2
3.	Palm Slag	45	11	1.5	120	0.2
4	Phenolic resin	42	1.7	1.30	30	0.30
5	Aluminum oxide	470	350	3.80	1750	0.22
6	Graphite	30	10	2.0	55	0.15

The material properties of the composite constituents phenolic resin, graphite, aluminum oxide, coconut fiber, palm slag, and sawdust were defined in ANSYS based on data presented in Tables 1 and 2. Table 1 summarizes the mechanical properties of the brake pad compositions, while Table 2 presents the corresponding thermal properties. Temperature-dependent behavior was incorporated, particularly for thermal simulations, to reflect realistic operating conditions. The composite brake pad was modeled as a homogeneous material, and effective mechanical and thermal properties, including Young's modulus, Poisson's ratio, specific heat capacity, and thermal conductivity, were estimated using the rule of mixtures, as illustrated in figure 1 below.

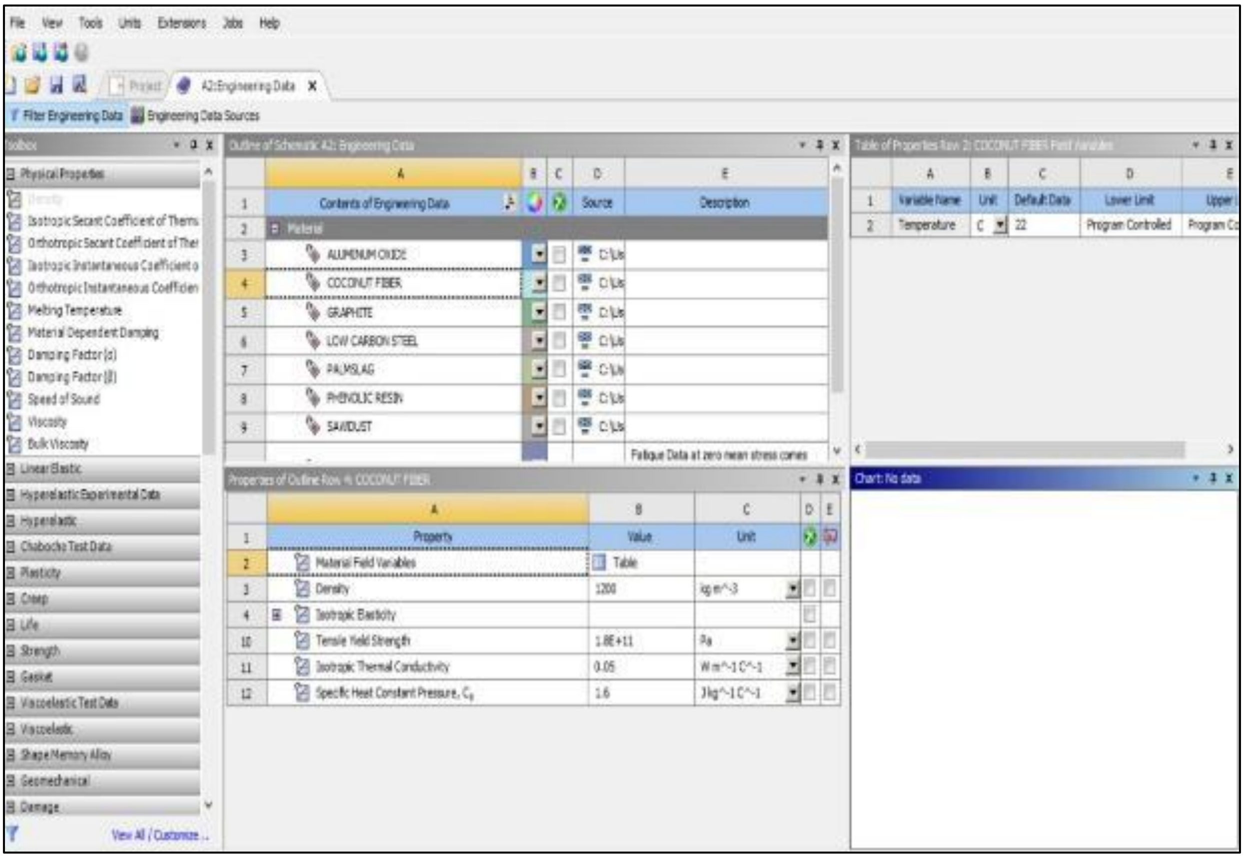

Figure 1 Customization of composite materials and their property

Table 2 Thermal Properties of Brake Pad Composite Materials

S/n	Composite materials	Thermal conductivity (w/m-k)	Specific heat capacity (j/g-k)	Temperature (^{o}c)
1	Coconut Fibre	0.05	1.6	230
2	Saw dust	0.07	1.5	250
3	Palm Slag	0.2	1.0	350
4	Phenolic resin	0.3	1.3	400
5	Aluminum oxide	25	0.85	N/A
6	Graphite	110	0.85	N/A

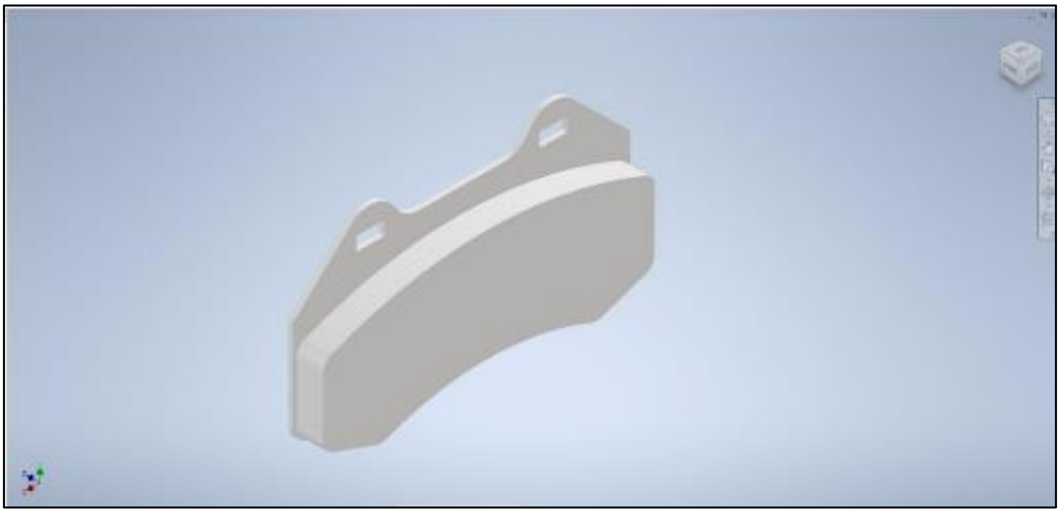

Figure 2 3D model of the brake pad

2.5. Design Parameters, Boundary Conditions and Loading of the Brake Pad Samples

For this design and design date, the following design parameters or vehicle specifications were used for the simulation of the brake pad samples;

- Curb Weight: Approximately 1,375Kg (3,031 lbs).
- Brake System: Front disc brakes and rear drum.
- Tire Radius: Approximately 0.3m (standard 15-inch wheels).

2.5.1. Estimated Pressure (P):

Assuming a braking force applied at the front brake which handles majority of the braking force:

- **Braking Force (F):** assuming an emergency braking scenario, the force can be estimated using the formula:

F = Weight × g × Deceleration factor ………………(1)

Where;

Weight = 1,375kg × 9.81 m/s^2 ………………(2)

= 13,488.75N

Deceleration factor = 0.8 (typical factor for emergency braking)

Thus, the braking force;

F = 13,488.75 × 0.8 = 10,791N ………………..(3)

- Contact Area (A): Approximately the contact area for the front brake pads to be around 0.0125m^2

$$P = \frac{F}{A} = \frac{10{,}791N}{0.0125m2}$$ ………………..(4)

P = 863,280 Pa

- Velocity (V): Considering a traveling velocity at 100 km/h (27.78m/s):

For angular velocity (ω)

$$\omega = \frac{v}{r} = \frac{27.78\ m/s}{0.3m} \quad \text{………………..(5)}$$

$= 92.6$ rad/s

- Velocity at the brake pad contact (v):

$$V = \omega \times r = 92.6 \text{ rad/s} \times 0.3 \text{ m} \quad \text{………………(6)}$$

$= 27.78$ m/s

- Acceleration (a):

The acceleration (negative acceleration) during braking can be calculated as;

Assume the stopping time (t) to be 5 seconds from 100km/h:

$$a = \frac{v}{t} \quad \text{……………(7)}$$

$$= \frac{27.78\ m/s}{5s} \quad \text{…………..(8)}$$

$= 5.56$m/s

2.6. Brake pad modelling in ANSYS

For Toyota Camry 2010 generation with applied pressure load of 0.863MPa which is applied at the surface where the brake pad contacts the rotor, simulating braking force. The brake pad is constrained to prevent rigid body motion. During the process we can estimate the effects of the load on the brake pad as follows; Von Mises stress is a scalar value that predicts yielding in ductile materials, based on the distortion energy theory. It is crucial in brake pads to determine if the material can withstand stress without permanent deformation (M. Sunil Kumar Hemanth & J.Edwing Raja Dhas 2023). Principal stresses, the largest tensile and compressive stresses, are also important in brake pads. Maximum principal stress highlights potential tensile failure, while minimum principal stress identifies areas under compression that could lead to delamination or matrix cracking. Total deformation, the magnitude of displacement experienced by a material under applied loads, measures how much the brake pad deforms during braking. High von Mises stress regions often correlate with large deformations, especially near stress concentrators. Total deformation depends on material stiffness and boundary conditions. Total deformation is the cumulative effect of stress distribution and the composite material's mechanical properties, validating stress predictions (R.Hinrichs & M.R Soares 2001).

2.7. Thermal Loading

A heat flux is applied to the brake pad’s friction surface, simulating the heat generated during braking. Convective heat transfer is considered for the brake pad's surfaces exposed to the air, with appropriate heat transfer coefficients assigned.

2.8. Simulation Setup

2.8.1. Static Structural Analysis

A static structural analysis is conducted to study the stress distribution within the brake pad under applied pressure. The focus is on determining the areas of maximum stress to ensure the structural integrity of the brake pad under operational loads. Equivalent stress is a useful metric for comparing the stress levels in the brake pad due to different stress distribution patterns, whereas maximum principal stress is more useful for pointing out critical locations where the brake pad is most likely to fail.

2.8.2. Thermal Analysis

A steady-state thermal analysis is conducted to simulate the temperature distribution across the brake pad during braking. The thermal analysis ensures that the brake pad can withstand high temperatures without failure.

3. Results of Simulation

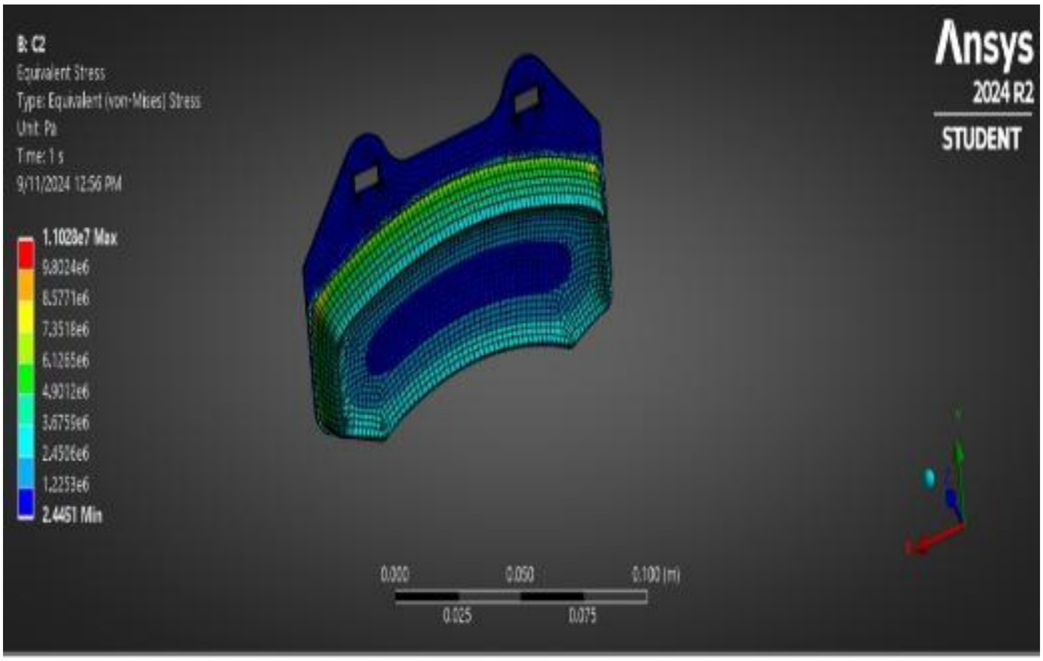

Figure 3 Brake Pad Sample 2: Equivalent Stress

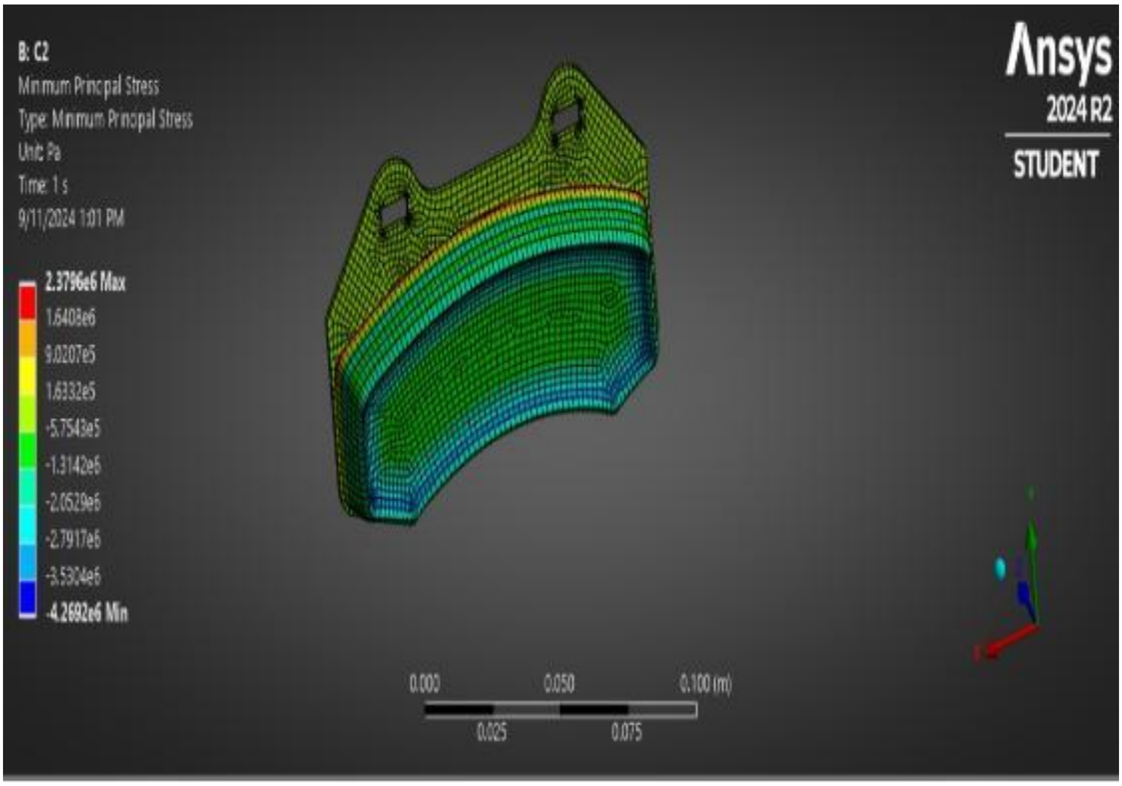

Figure 4 Brake Pad Sample 2: Minimum Principal Stress

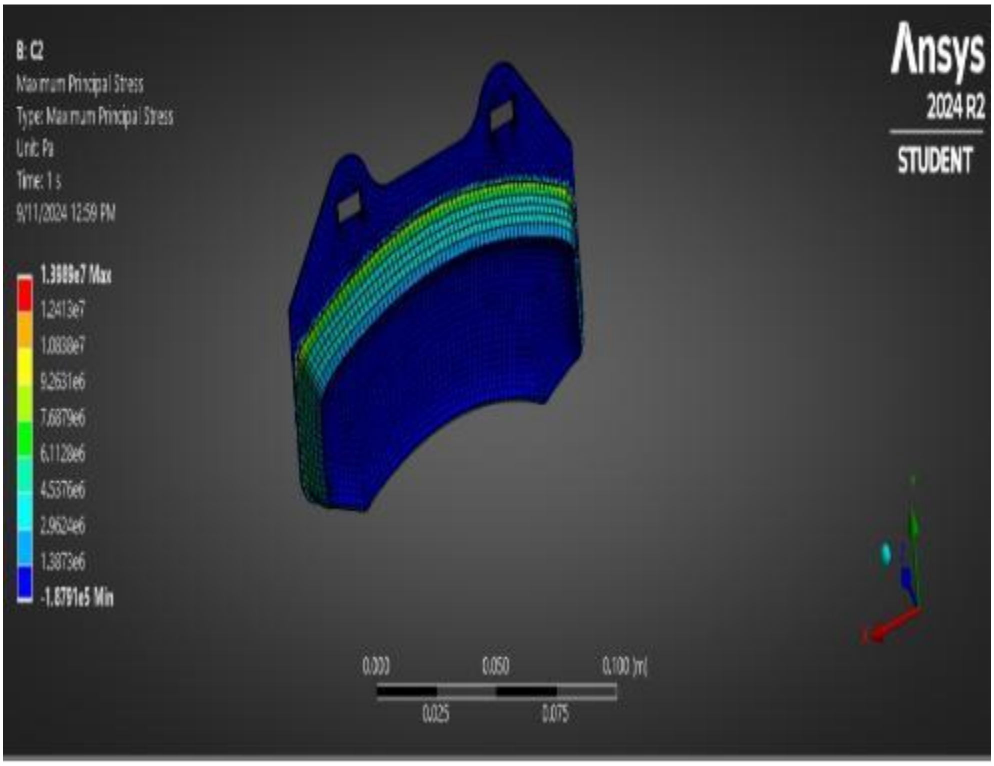

Figure 5 Brake pad Sample 2: Maximum Principal Stress

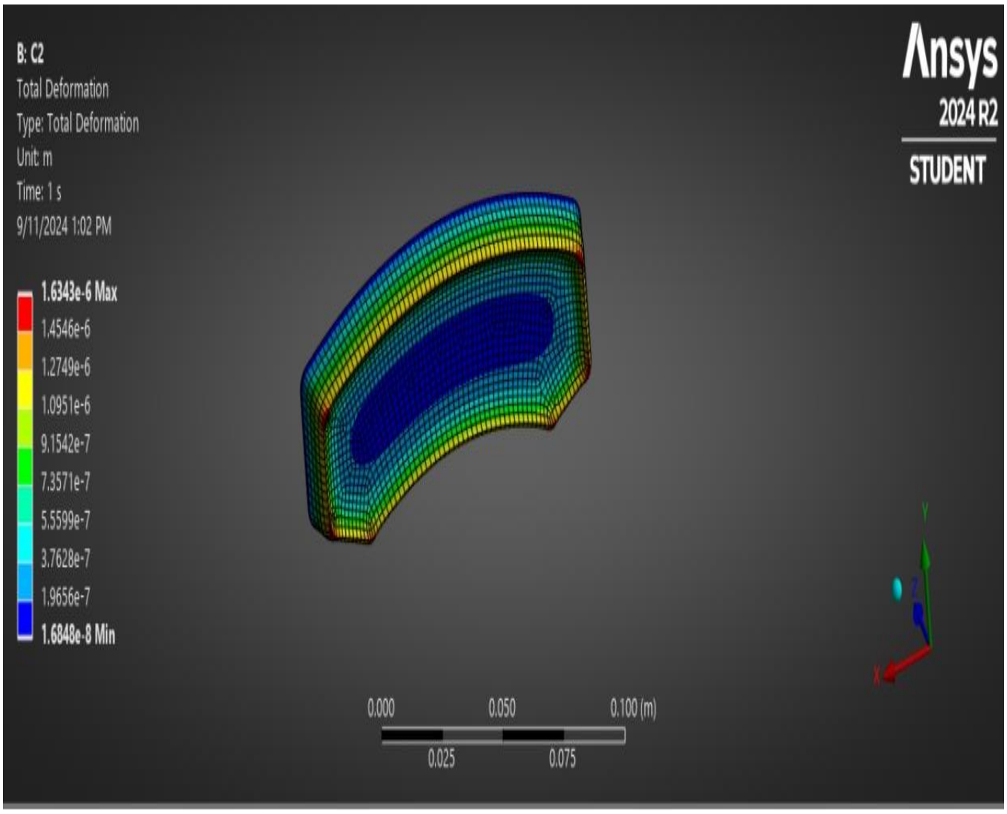

Figure 6 Brake Pad Sample 2: Total Deformation

4. Discussion of Simulation Results

4.1. Equivalent Stress (von mises stress)

The finite element simulation results provide critical insights into the structural integrity and mechanical response of the composite brake pad under applied braking loads. The equivalent (von Mises) stress distribution Figure 3 indicates that the maximum stresses are predominantly concentrated along the frictional contact surface and at the inner curved regions of the pad. These regions are known to experience the highest contact pressure during braking, confirming that the numerical model realistically captures the operational stress state of the brake pad. Importantly, the peak von Mises stress values remain within acceptable limits relative to the expected strength of the composite material, suggesting a low likelihood of yielding or catastrophic failure under the simulated conditions.

4.2. Maximum and Minimum Principal Stress

According to Figure 5, the maximum principal stress contours further highlight tensile stress development near the outer friction layer and localized edge regions. These tensile zones are critical, as they often govern crack initiation in brake pad materials. However, the relatively moderate magnitude and smooth stress gradients observed imply that the composite formulation is capable of redistributing applied loads effectively, thereby reducing the risk of localized damage. Conversely, the minimum principal stress results, Figure 4, show dominant compressive stresses across the bulk of the pad, which is desirable for braking applications since brake pads are primarily designed to operate under compressive loading.

4.3. Total Deformation

Figure 6 presents the total deformation results which reveal minimal overall displacement of the brake pad, with maximum deformation occurring at the friction surface and free edges. The magnitude of deformation is very small, indicating high stiffness and dimensional stability of the composite under load. This behavior is essential for maintaining consistent contact with the brake disc, minimizing uneven wear, vibration, and brake judder during service. The smooth deformation pattern also suggests good bonding and mechanical compatibility among the composite constituents, validating the assumption of homogeneous material behavior used in the simulation. Collectively, the stress and deformation responses demonstrate that the agro-mineral-based composite brake pad exhibits favorable load-bearing capacity, structural stability, and resistance to excessive deformation. The results also suggest that the inclusion of reinforcing fillers and abrasives contributes positively to stress distribution and stiffness without inducing critical stress concentrations.

5. Conclusion

The finite element simulation results obtained from the stress and deformation contours demonstrate that the composite brake pad exhibits a mechanically stable response under the applied braking loads. The equivalent (von Mises) stress distribution shows a maximum value of approximately 11.03 MPa, primarily concentrated along the frictional contact region, indicating effective load transfer without excessive stress localization. The maximum principal stress reaches about 13.99 MPa, while the minimum principal stress attains a compressive value of approximately –4.27 MPa, confirming that the brake pad operates predominantly under compressive stress, which is desirable for braking applications. The total deformation response further supports the structural adequacy of the composite material. The deformation ranges from a maximum of about 1.63 µm to a minimum of approximately 0.017 µm, reflecting very low displacement under service loads. Such minimal deformation indicates high stiffness and dimensional stability, ensuring consistent contact between the brake pad and disc during braking operations. Overall, the combined stress and deformation results suggest that the developed composite brake pad possesses high structural integrity and resistance to mechanical failure under operational conditions. The stress levels remain well within the material's expected load-bearing capacity, while the low deformation values indicate suitability for repeated and prolonged braking cycles. These characteristics align with the performance demands of Toyota Camry 2010 model, a vehicles commonly used by mid-level Nigerian subjected to frequent braking, supporting the composite brake pad's potential for reliable and durable service in demanding operating environments.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest exist among the others.

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