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Research Paper

Structural Analysis of Brake Shoe with Aluminum Alloy, Cast Iron, Magnesium Alloy and Brake Linings with Different Carbon Variants under Static Load

Dony Eko Prasetyo, Hadi Sutanto, Arka Dwinanda Soewono

Department of Mechanical Engineering, Atma Jaya Catholic University of Indonesia, Jakarta 12930, Indonesia

arka.soewono@atmajaya.ac.id

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Abstract

The research is motivated by the issue faced by motorcycle users, namely the wear and tear of brake shoes, which can reduce braking effectiveness and increase the risk of accidents. The main objective of this study is to analyze the structural properties of motorcycle brake shoes with three different materials (aluminum alloy, cast iron, and magnesium alloy) and brake linings made of different carbon variants (alumina-carbon composite, carbon ceramics, and carbon fiber) under static pressures. Additional design aspects including weight and production cost are also evaluated during the material selection process for the motorcycle's brake shoe and brake lining. The 3D modeling of the brake shoe and lining was done in Solidworks using measurement data from a Coordinate Measuring Machine (CMM). The finite element analysis was performed using ABAQUS software. Considering the results from the finite element analysis, weight, and economic aspects, the study found that aluminum alloy (Al alloy) and carbon composite can be suitable materials for brake shoes and brake lining. The Al alloy brake shoe provides 62.7% weight saving while exhibiting good structural properties under static load and a moderate increase in production cost compared to cast iron. Similarly, brake lining with alumina-carbon composite showed the least deformation under static load while maintaining modest production costs compared to the other carbon variants.

Keywords: Brake shoe; Structural analysis; Finite element analysis; Solidworks; ABAQUS

1. Introduction

Brake shoes are components designed to press against the disc or inner wall of the drum brake, enabling the applied friction force to slow down and stop the rotation of the wheels on a vehicle and acting as a critical component for driver safety in a two-wheeler [1]. The drum brake systems are widely used by lightweight motorcycles with engine capacities up to 125cc due to their simple design, easy maintenance, and economic affordability [2]. Brake drums, however, also possess several disadvantages such as producing squealing noise and vibrations on the vehicle [3], [4]. Furthermore, the closed construction of the brake drum can lead to high temperatures during braking operation caused by excessive heat being trapped [5]. Some methods to improve the performance of the motorcycle brakes by adding a cooling system to drum brakes [6], [7]. Extensive operation of brake drums also can cause gradual development of faults and wear [8]. To address this issue, improvement in the design of the drum brake is essential.

Various research has discussed calculating geometry and designing braking systems while considering driver safety, ergonomics, performance, and manufacturing processes [9]–[11]. Other research papers have delved into the performance of a variety of commercially available brake discs and brake pads at different prices [12]. Further insights into the development and analysis of desired braking systems for high-performance racing cars are provided by Cravero and Marsano [13]. When designing a high-performance braking system, the need for brake disc cooling plays an important role in avoiding thermal failure in the brake disc material as outlined by Thuresson [14]. Moreover, previous studies highlight the importance of the geometry [15], the material variation and the addition of ventilation holes [16] to ensure quick heat as the primary feature of brake disc to prevent the vehicle brake system become overheating and reduce braking effectiveness [17].

Since the vehicle brake system utilizes the power of artificial frictional resistance to a moving vehicle to slow it down, the design of brake components must be durable. Several studies have conducted structural analysis of brake shoes to provide an understanding of how resistant the brake shoe design is to the loads and examine stress concentration, and structural deformation [18]–[23]. Furthermore, more advanced materials have been introduced in the manufacturing of automotive brake components in recent years. Several studies have suggested the use of composite materials for the component of the brake system due to their high-performance characteristics such as high strength and wear resistance [24], [25]. In general, Finite Element Analysis (FEA) has often been conducted to examine the influence of materials and design on the factor of safety and displacement for better selection of materials and design of automotive brake discs [26]. The challenge, however, lies in developing an accurate model for the brake system due to its intricate shape and the large number of associated components involved [1]. A more accurate three-dimensional (3D) image of the brake disc can be achieved by using a combination of Coordinate Measuring Machine (CMM) and Computer-Aided Design (CAD) software [27].

Considering the importance of the brake to ensure safety and a comfortable motorcycle ride, this research aims to investigate the use of alternative materials for motorcycle brake shoes and linings. In this study, a Coordinate Measuring Machine (CMM) is employed to generate an accurate 3D model of the brake shoe and brake lining from a commercial lightweight motorcycle. The finite element analysis is performed to provide in-depth insights into the structural response (stress, displacement, and deformation) of several brake shoes and brake lining made of different materials under static pressure. Additional design evaluation related to the weight and production cost concerning material selection of the brake shoe and brake lining is also presented. The analysis results in this study are expected to provide recommendations to the automotive industry to continuously improve the quality of disc brake components for motorcycles.

2. Method

2.1. *Research Steps*

The methodology used in this study is illustrated in **Figure 1**. The analytical process involves a literature study to gather relevant information about the mathematical and simulation model of the drum brake for two-wheelers, particularly for the brake shoe component. Once the necessary information is obtained, the braking force and pressure applied to the brake shoe can be calculated. The material selection process for the brake shoe and lining is achieved concurrently to obtain the required properties of materials for both components. The process of generating geometric models of the brake shoe involves measuring the dimensions of the brake shoe from a lightweight motorcycle using a Coordinate Measuring Machine (CMM) to accurately obtain their size and shape. Subsequently, a three-dimensional (3D) modeling process is carried out using Computer-Aided Design (CAD) methods based on the data obtained from the CMM. The data on the braking force and physical properties of the materials as well as the geometric model is then used in the Finite Element Analysis (FEA). The software used for the current research is namely Solidworks for generating 3D models and ABAQUS for finite element analysis applications. The ABAQUS, with its TOSCA optimization module, is chosen as the platform for the FEA analysis since it offers a comprehensive tool with various options for optimization algorithms, objective functions, optimization constraints, as well as complex load cases and boundary conditions [28]. The results from the finite element simulation and other design considerations such as weight and economic impact are then analyzed to find the most optimal material specifications for the brake shoe and brake lining of the motorcycle.

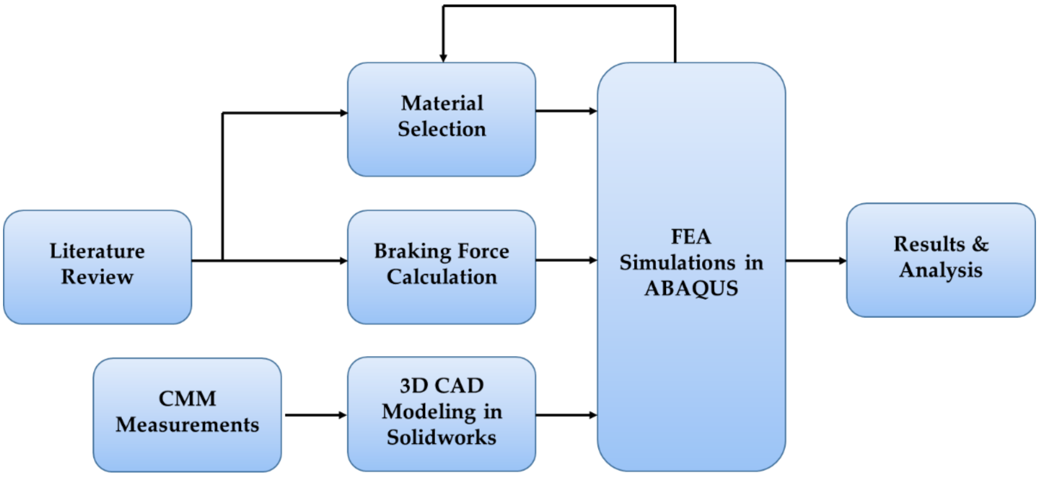

Figure 1. Research stages

2.2. *Braking Force Calculation*

The primary task of the automotive braking system is to decelerate the vehicle by applying frictional force. Newton's Laws of Motion provide formulas that can be used to calculate acceleration and the force required to stop a vehicle using Eq. (1).

$$v^2 = u^2 + 2 \times a \times s \tag{1}$$

where, a: Acceleration; v: Final velocity; u: Initial velocity; s: Braking distance

After calculating the acceleration, the braking force can be determined using the principle that 70% of the vehicle's weight acts on the front wheels during braking. Thus, the braking force can be estimated from the acceleration using Eq. (2).

$$F_b = 0.7 \times M \times a \tag{2}$$

where, F_b: Braking force; M: Mass of the vehicle; a: Acceleration

Finally, the pressure applied can be calculated from dividing the braking force by the brake shoe area as follow Eq. (3).

$$P_b = \frac{F_b}{A} \tag{3}$$

where, P_b: Brake shoe pressure; A: Brake pad area

The Eq. (1) to Eq. (3) are used to estimate the force needed to stop a motorcycle under an extreme braking condition from a speed of 80 km/h to a full stop. **Table 1** summarizes the parameters and the resulting braking force and pressure used as inputs for the finite element analysis.

2.3. *Material Selection*

Materials are a fundamental element in engineering, playing a crucial role in determining the reliability and performance of a product. A profound understanding of the mechanical characteristics of materials is essential in designing brake components that can function optimally under specific load conditions. The procedure used for selecting materials for brake shoes and lining follows the method of Ashby and Cebon [29], which is illustrated in **Figure 2**.

To properly assess the quality of brake shoes, it is pivotal to examine and compare the compositions of the raw materials of brake shoes [25].

Table 1. Specifications of brake shoes and parameters for braking force calculation

Parameter	Unit	Value
Radius of the brake shoes	mm	130
Thickness of lining	mm	4.5
Pad area	mm^2	5656
Weight of the vehicle	kg	90
Speed of the vehicle	km/h	80
Stopping distance	m	5
Acceleration	m/s^2	48.4
Braking Force	N	3049.2
Braking Pressure	Pa	540000

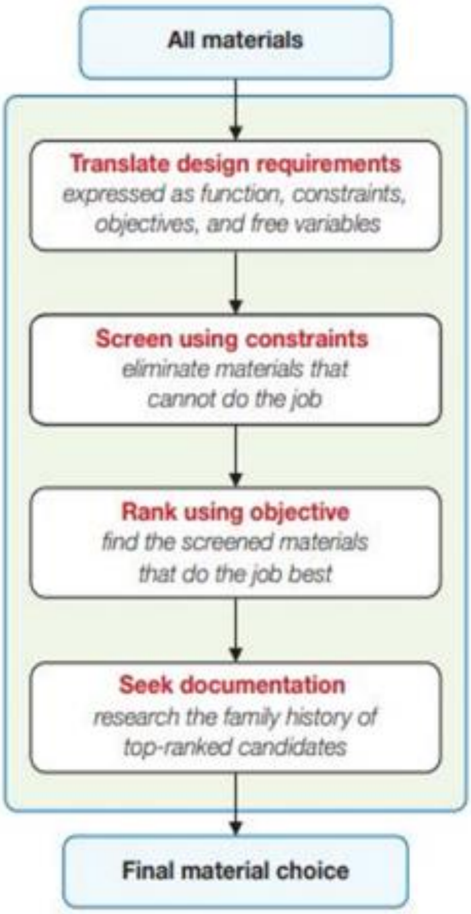

Figure 2. The procedure for selecting materials [29]

To properly assess the quality of brake shoes, it is pivotal to examine and compare the compositions of the raw materials of brake shoes [30]. The selection of appropriate materials for brake shoes is based on features like a high strength-to-mass ratio is normally applied to ensure structural safety. Other criteria used in the material selection process are material mass, cost, and availability. A common misconception in the automotive industry is that labor costs in manufacturing represent the largest expenditure. However, in reality, labor usually contributes to less than 35% of production costs, while the raw material price represents more than 65% of the total cost. In selecting material for motorcycle brake shoes, finding the balance between material strength, the need for component weight reduction, and cost is certainly a priority. **Figure 3** and **Figure 4** show the ratio between Young's modulus and density to price for a variety of materials, respectively. Based on this information, three materials are chosen for the brake shoe: aluminum alloy, cast iron, and magnesium alloy.

For the base material for the brake lining, some of the features required are high strength, as well as heat and wear resistance. Due to its nature as a consumable surface on brake systems, cost is also an important consideration for choosing the right brake lining material. **Figure 5** and **Figure 6** display the ratio of Young's modulus and density versus price for various prospective materials, respectively. Due to its availability and high durability, three different carbon variants are considered to be suitable materials for brake lining: alumina-carbon composite, carbon ceramics made of silicon carbide, and carbon fiber.

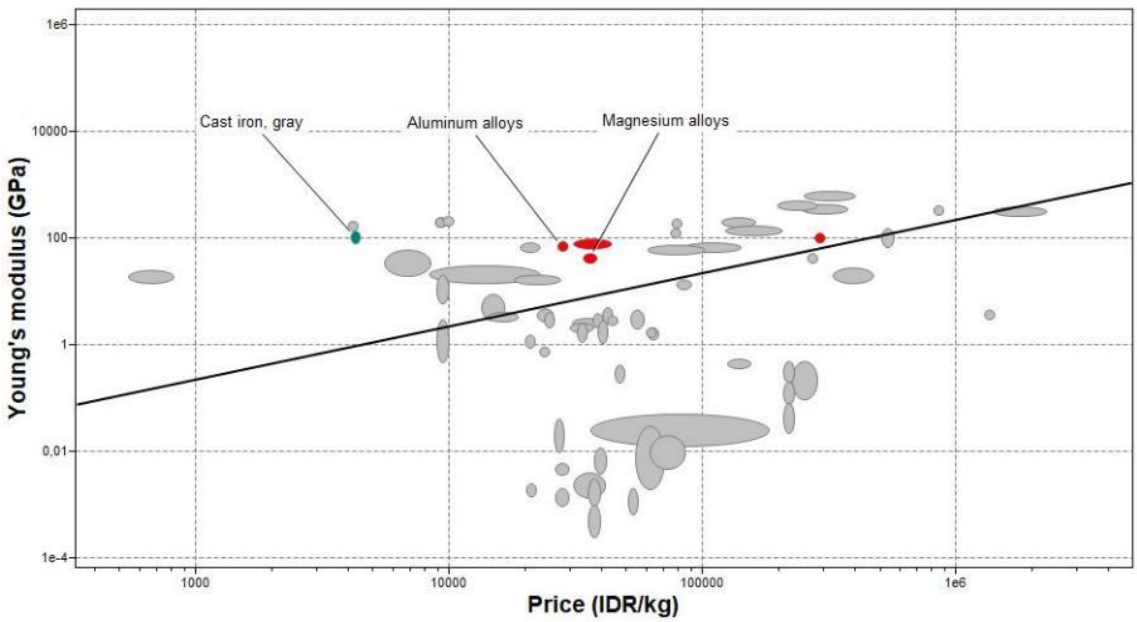

Figure 3. Brake shoe material young's modulus vs price

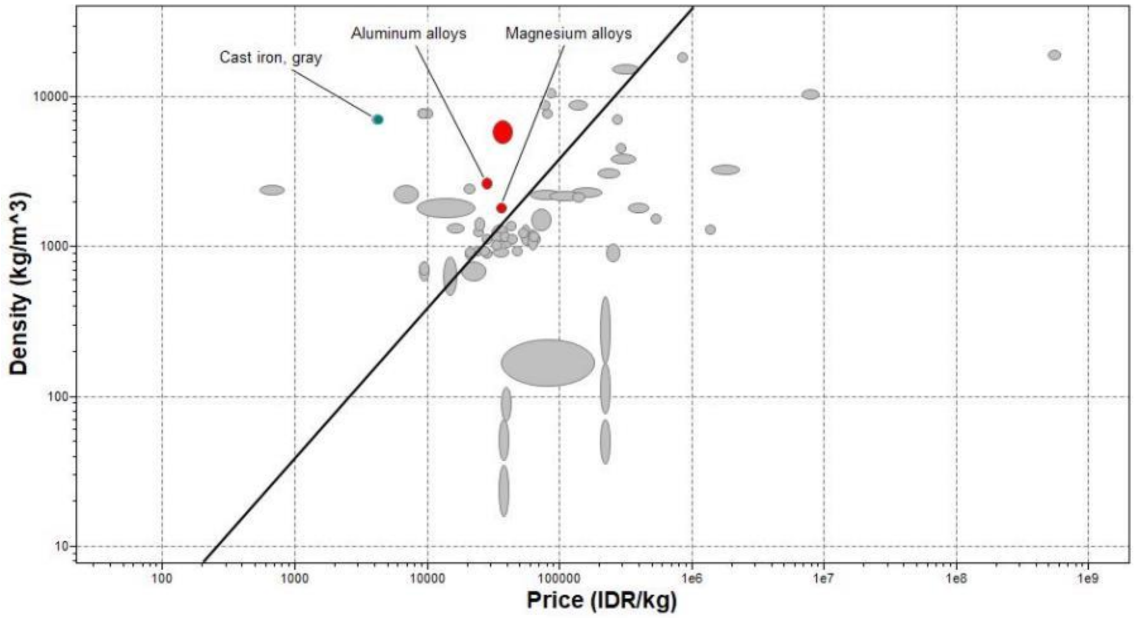

Figure 4. Brake shoe material density vs price

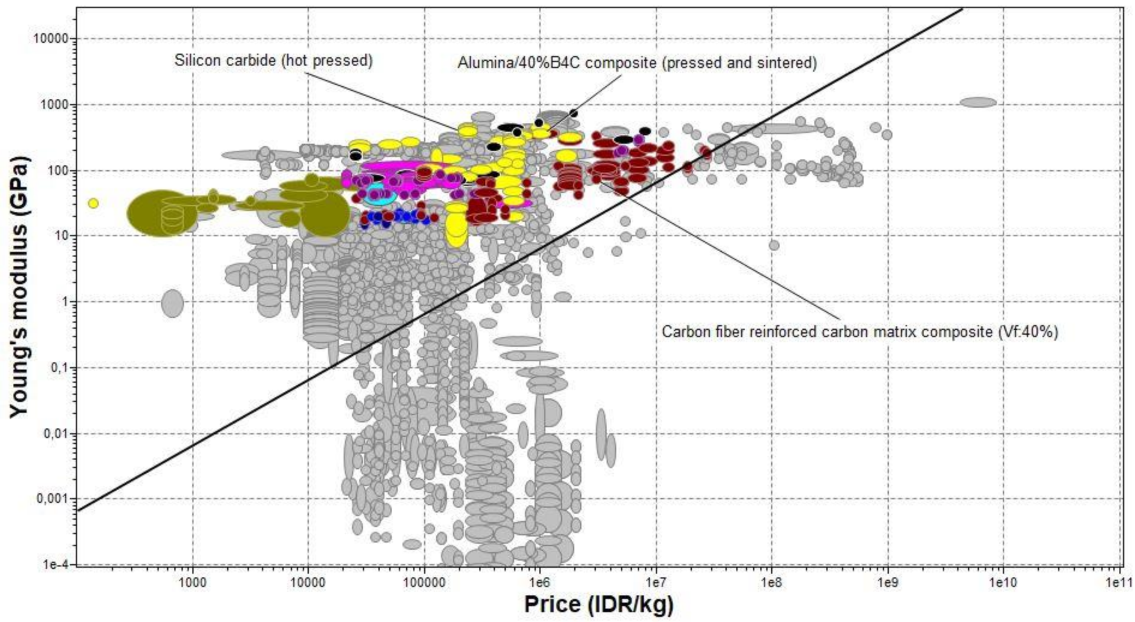

Figure 5. Brake pad material young's modulus vs price

The mechanical and thermal material properties of aluminum alloy (Al alloy), cast iron, and magnesium alloy (Mg alloy) used for the brake shoes are taken from the previous study [30] and shown in **Table 2**. Similarly, the material properties of carbon composite, carbon ceramics made of silicon carbide, and carbon fiber for the brake lining can be seen in **Table 3**. These material specifications are used as input for the ABAQUS simulations.

2.4. 3D Modelling and Finite Element Analysis

The brake shoe and brake lining modeling is a crucial step in this research since the models are used for Finite Element Analysis (FEA). The geometry and dimensions of the drum brake system of a lightweight motorcycle are accurately obtained (less than 1% error) from the Coordinate Measuring Machine (CMM) and subsequently converted into a three-dimensional drawing using Solidworks, as seen in **Figure 7**.

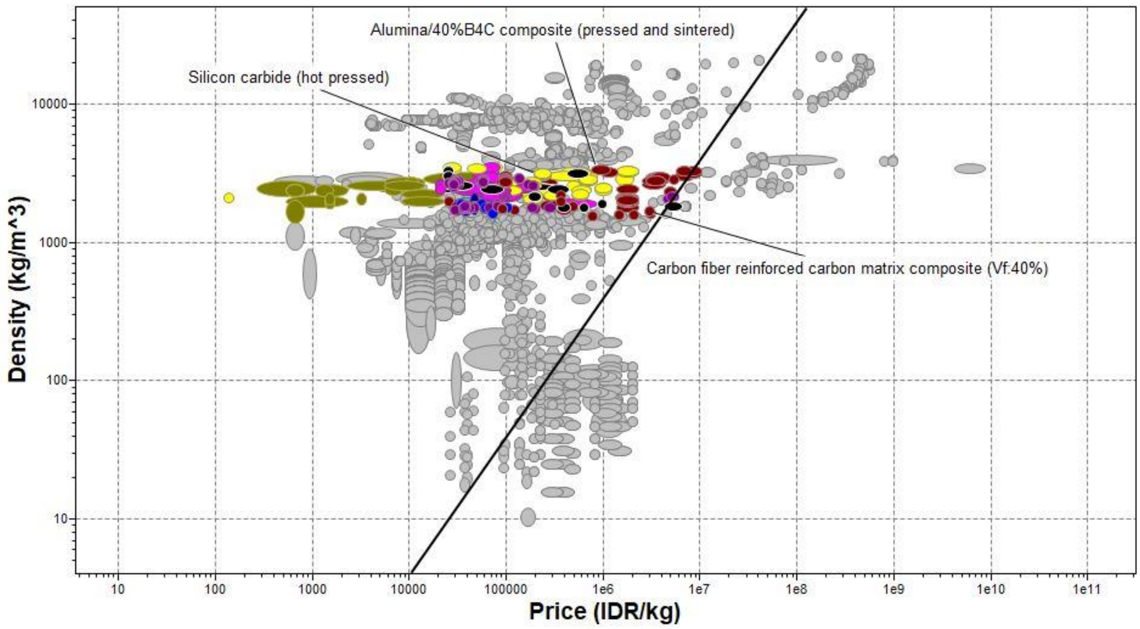

Figure 6. Brake pad material density vs price

Table 2. Material properties of brake shoe [30]

Property	Units	Al Alloy	Cast Iron	Mg Alloy
Density	kg/m^3	2700	7200	1800
Young Modulus	Pa	7 x 10^{10}	1.1 x 10^{11}	4.5 x 10^{10}
Poisson's Ratio	-	0.3	0.28	0.35
Yield Strength	Pa	2.8 x 10^8	3 x 10^8	1.93 x 10^8
Max. Temperature	°C	350	500	300
Thermal Conductivity	W/mK	171	52	156
Specific Heat	J/gK	875	447	1024

Table 3. Material properties of brake lining [30]

Property	Units	Carbon Composite	Carbon Ceramics	Carbon Fiber
Density	kg/m^3	1600	2500	1700
Young Modulus	Pa	8 x 10^{10}	2 x 10^{10}	3 x 10^{10}
Poisson's Ratio	-	0.25	0.3	0.2
Yield Strength	Pa	1.9 x 10^8	3 x 10^8	2 x 10^8
Max.Temperature	°C	290	1000	500
Thermal Conductivity	W/mK	6	10	5
Specific Heat	J/gK	1.1	1.1	0.7

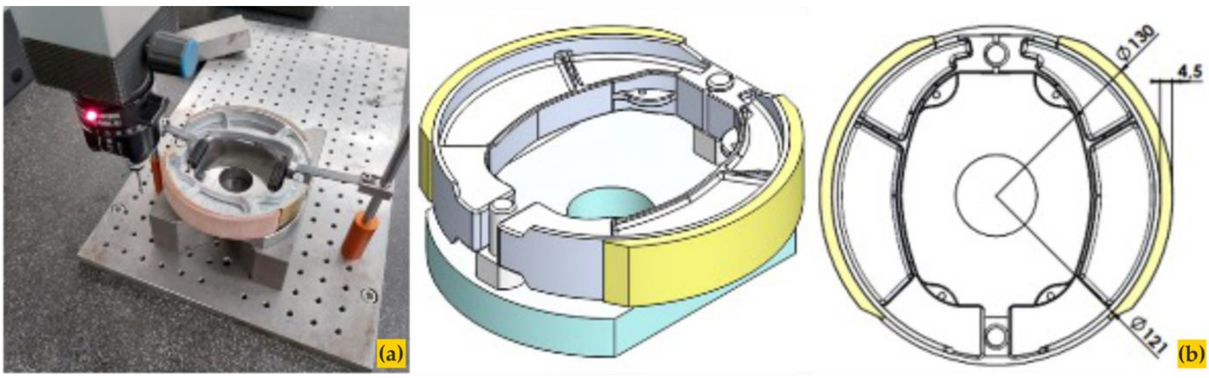

Figure 7. (a) The modeling process of the brake shoe component using a Coordinate Measuring Machine; (b) Followed by generating a technical drawing in Solidworks

The structural responses in the form of stresses, displacements, and deformations of the brake shoe and lining under static load are investigated using the finite element analysis software ABAQUS. The input parameters for the finite element simulations include the geometric model of the brake shoes and lining, material properties, and predefined boundary conditions. Before running the simulations, the finite element model of the brake shoes and lining are generated automatically in ABAQUS where the geometric model is discretized into discrete tetrahedral meshes, as illustrated in **Figure 8** and **Figure 9**, respectively. Once the meshing process is complete, the next step involves assigning boundary conditions. Fixed support conditions are applied at specific points on the brake shoe as shown in **Figure 8** and **Figure 9**. A pressure load of 540,000 Pascal is applied to the relevant surface of the brake shoe using pressure load elements in ABAQUS. After all the preparations are completed, the finite element simulations are executed to predict the structural response of the brake shoe to the applied forces and pressures. ABAQUS will automatically solve the mathematical equations arising from the finite element models, taking into account boundary conditions, loads, and material properties. The finite element analysis provides information about the distribution of von Mises stresses, displacements, and deformations in the brake shoe and lining.

Meshing plays a crucial role in finite element analysis where finer meshing tends to offer more accurate results as it decides numerical convergence to the solution. To ensure a continuous geometrical representation in the brake shoes and lining, the mesh element thickness is set to 4 mm. The detailed information for the mesh can be found in **Table 4** and **Table 5**.

Table 4. Mesh details of the brake shoe

Material	Meshing (mm)	Total elements	Total nodes
Al Alloy	4	14803	24536
Cast Iron	4	15209	25188
Mg Alloy	4	60068	99576

Table 5. Mesh details of the brake lining

Material	Meshing (mm)	Total elements	Total nodes
Carbon Composite	4	2066	3734
Carbon Ceramics	4	2066	3734
Carbon Fiber	4	2066	3734

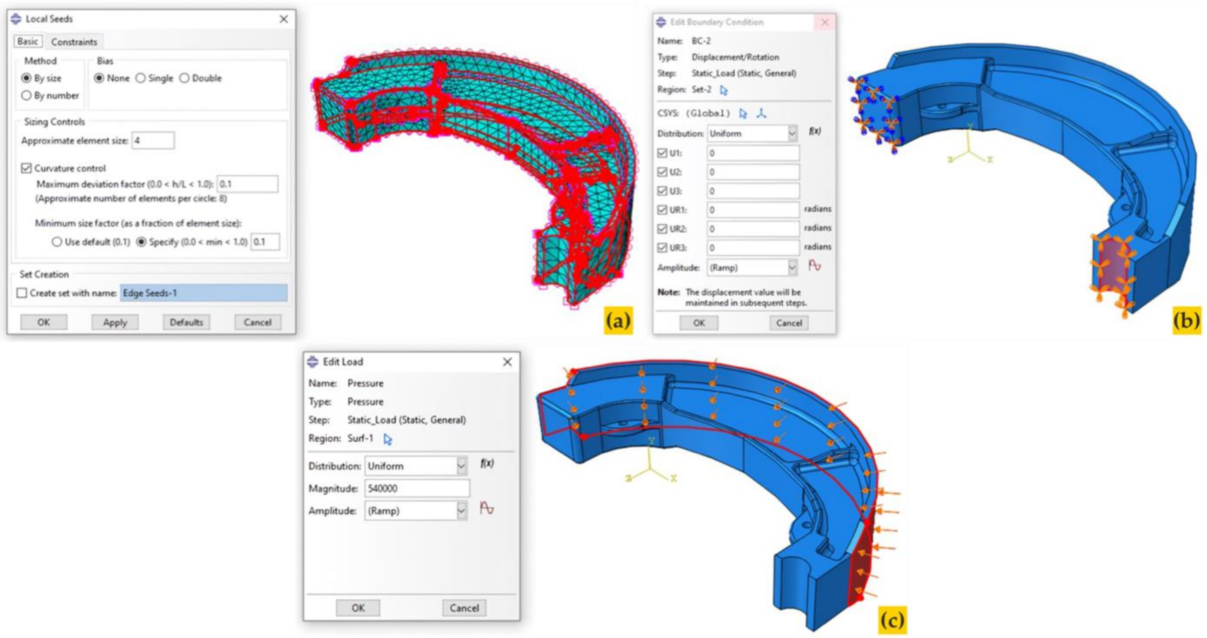

Figure 8. System constraints and boundary conditions for the brake shoe: (a) Meshing; (b) Fixed supports; (c) Pressure load

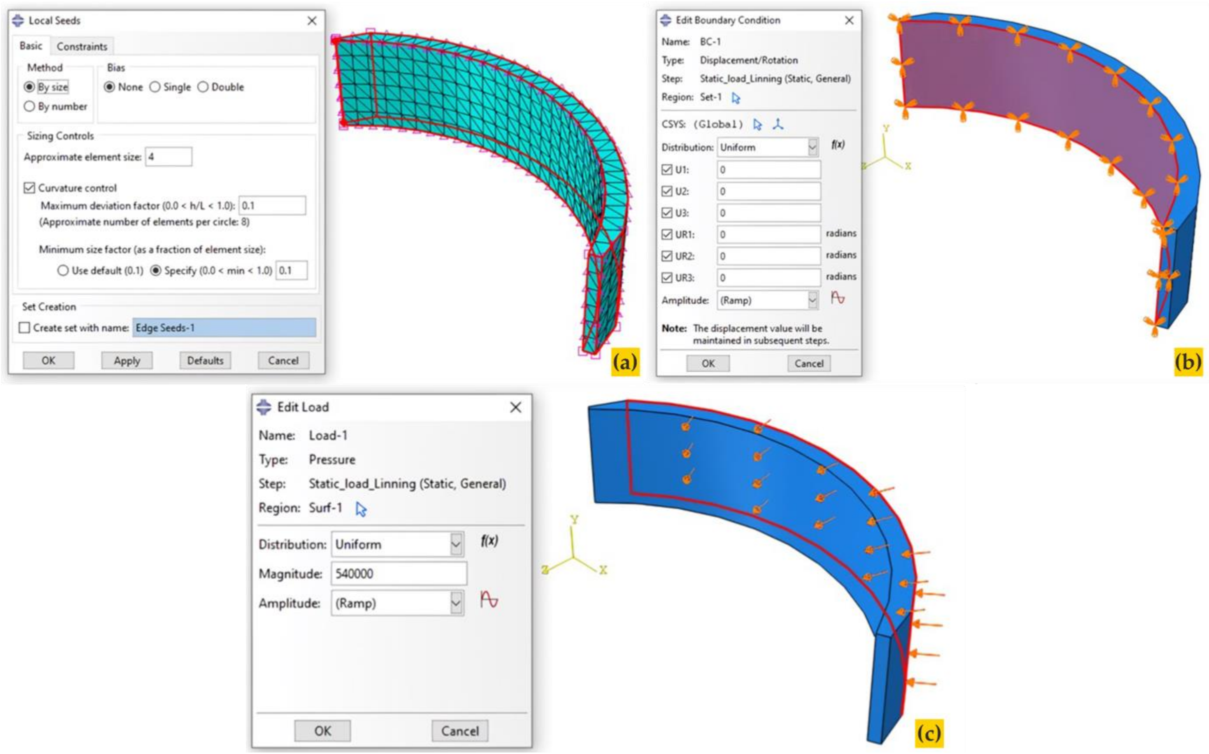

Figure 9. System constraints and boundary condition for the lining: (a) Meshing; (b) Fixed supports; (c) Pressure load

3. Result and Discussion

3.1. Structural Analysis on the Brake Shoe

The von Mises stress distributions induced in the brake shoes under static load have been determined using finite element analysis and can be observed in **Figure 10**. Applying a static braking pressure of 540,000 Pa yields a maximum stress of 1.664 x 107 Pa for aluminum alloy (Al alloy) brake shoe, 1.716 x 107Pa for cast iron brake shoe, and 2.487 x 107 Pa for magnesium alloy (Mg alloy) brake shoe. It can be observed that the stress distribution in the Al alloy brake shoe is almost identical to the cast iron brake shoe, while the Mg alloy brake shoe exhibits greater stress distribution. As expected, the maximum stress concentration occurs at the contact surface between the brake shoe and shoe lining.

The corresponding displacements in the brake shoes due to static brake pressure obtained from the finite element analysis are shown in **Figure 11**. The cast iron brake shoe braking force displays the best maximum displacement of 5.566 x 10^{-3} mm under the static pressure of 540,000 Pa, followed closely by the Al alloy brake shoe with a maximum displacement of 8.699 x 10^{-3} mm. The Mg alloy brake shoe produces a significantly worse maximum displacement of 1.331 x 10^{-2} mm under the same load condition.

Table 6 summarizes the maximum stresses, displacements, and deformations of brake shoes made of Al alloy, cast iron, and Mg alloy under static load. The finite element analysis indicates that the Mg alloy brake shoe has the worst performance since it exhibits the highest maximum von Mises stress, displacement, and deformation. As expected, cast iron brake shoe produces the best structural performance under static load which explains why cast iron is predominantly used for automotive brake components [31], [32]. The stresses in the Al alloy brake shoe are almost identical to the cast iron brake shoe, which implies that the design factor of safety is maintained in both brake shoes and supports the previous verdict that the aluminum alloy can be a viable technical solution for critical brake components [33]. Even though the maximum stress is slightly lower, the maximum deformation in the Al alloy brake shoe is noticeably higher than the cast iron which is consistent with the finding from the previous study [11]. It should be noted, however, that the increase in the deformation is still within the tolerance limit set by automotive manufacturers.

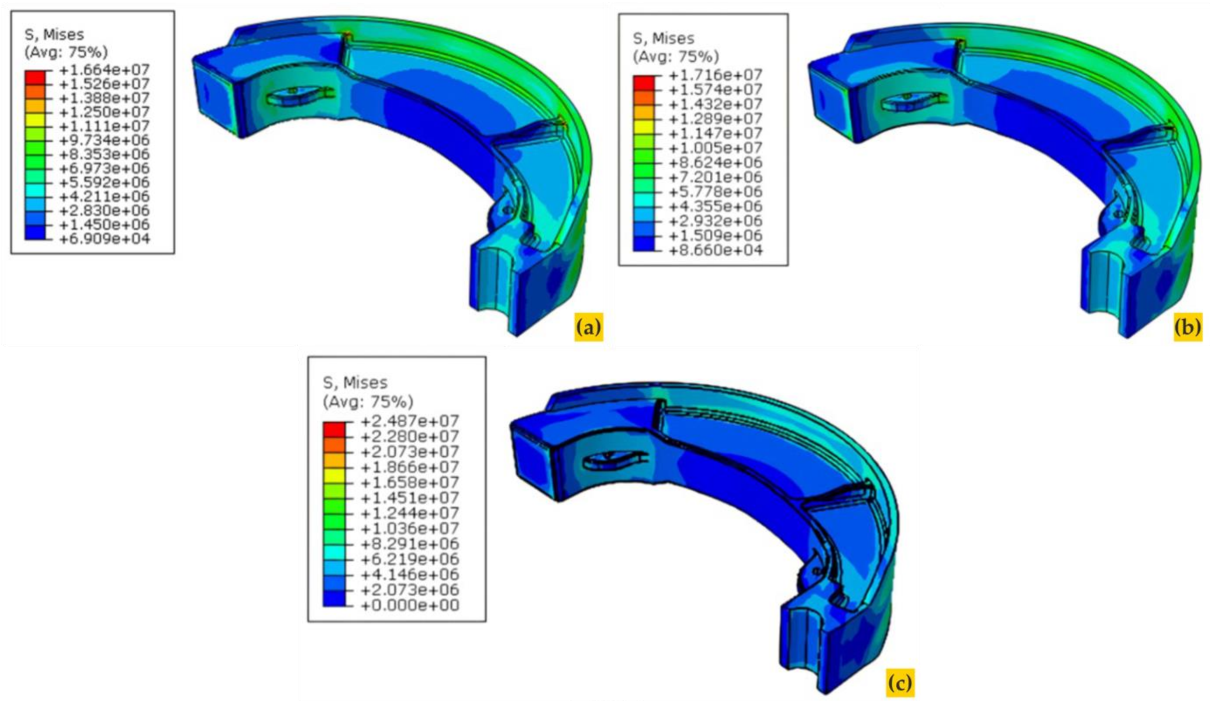

Figure 10. The FEA results in ABAQUS for brake shoe: (a) von Mises stress for Al alloy; (b) von Mises stress for cast iron; (c) von Mises stress for Mg alloy

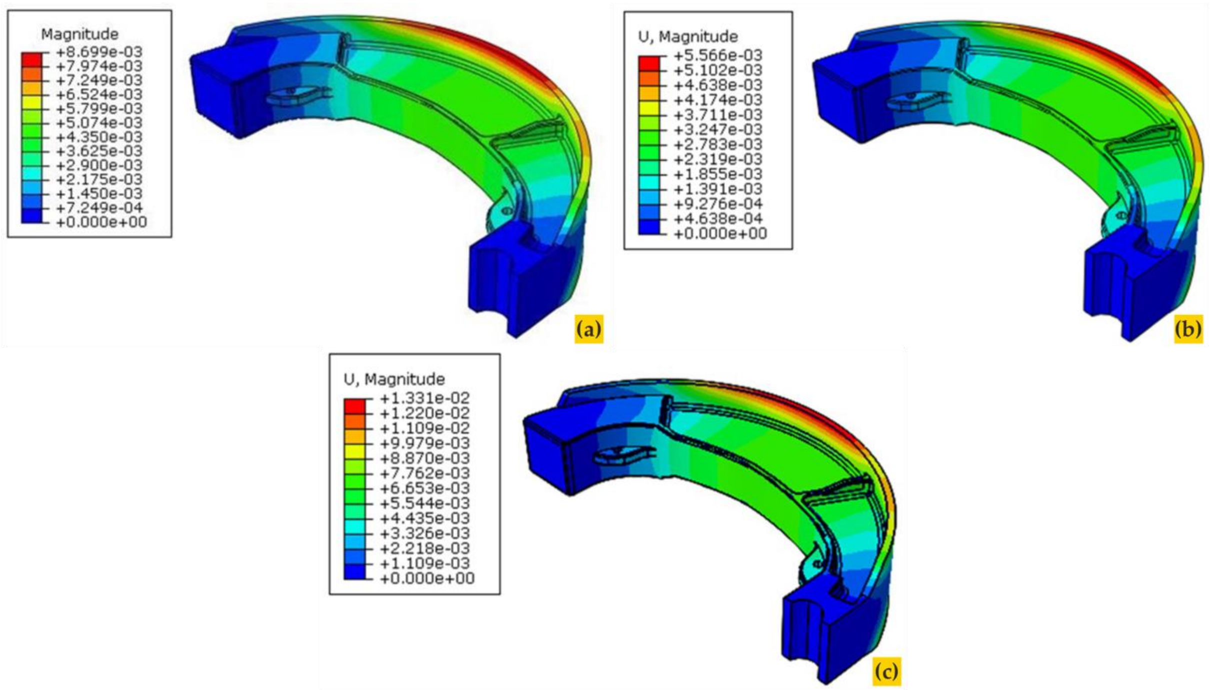

Figure 11. The FEA results in ABAQUS for brake shoe: (a) Displacement for Al alloy; (b) Displacement for cast iron; (c) Displacement for Mg alloy

Table 6. Structural analysis results for the brake shoe under static load

Material	Max. Stress (Pa)	Max. Displacement (mm)	Max. Deformation (mm)
Al alloy	1.664×10^{7}	8.699×10^{-3}	0.0077
Cast iron	1.716×10^{7}	5.566×10^{-3}	0.0049
Mg alloy	2.487×10^{7}	1.331×10^{-2}	0.012

3.2. *Structural Analysis on the Brake Lining*

The results from the stress analysis of the brake lining under a static load of 540,000 Pascal are depicted in **Figure 12**. The results show maximum von Mises stresses in the brake lining are 5.949 x 10^5 Pa for carbon composite, 6.054 x 10^5 Pa for carbon ceramics, and 5.932 x 10^5 Pa for carbon fiber, respectively. The maximum stresses induced in all shoe linings are almost the same with the lining made of carbon fiber having a trivial advantage. This finding supports the conclusion from the preceding research that carbon fiber linings were suitable for use in automotive brake [34]. Furthermore, compared to the other two carbon variants, the finite element analysis predicted a slightly higher stress distribution on the inner surface of the carbon fiber brake lining, which represents a contact surface with the brake shoe.

The resultant displacements in the brake lining made of three different carbon variants from the finite element analysis are displayed in **Figure 13**. It can be observed that the carbon composite lining has significantly lower maximum displacement compared to both carbon ceramics and carbon fiber, implying a higher stiffness. Considering that the brake lining is purposed as a friction material placed on the brake shoes to control the kinetic energy through friction when rubbed against the drum, the superior stiffness of carbon composites is expected to result in relatively stable wear [35]. Moreover, recent studies have identified carbon composites as ideal friction materials for automotive applications due to their high strength, superior thermal conductivity, high-temperature stability, and wear resistance [36], [37].

The summary of the structural responses of brake lining with differentcarbon variants is shown in **Table 7**. In terms of maximum stress, there is practically no difference between all carbon variants. The shoe lining with carbon composite, however, exhibits significantly lower maximum displacement and subsequently, smaller deformation compared to other carbon variants. This finding reinforces the results of the previous study that advocate the use of carbon composite for automotive brake application [38].

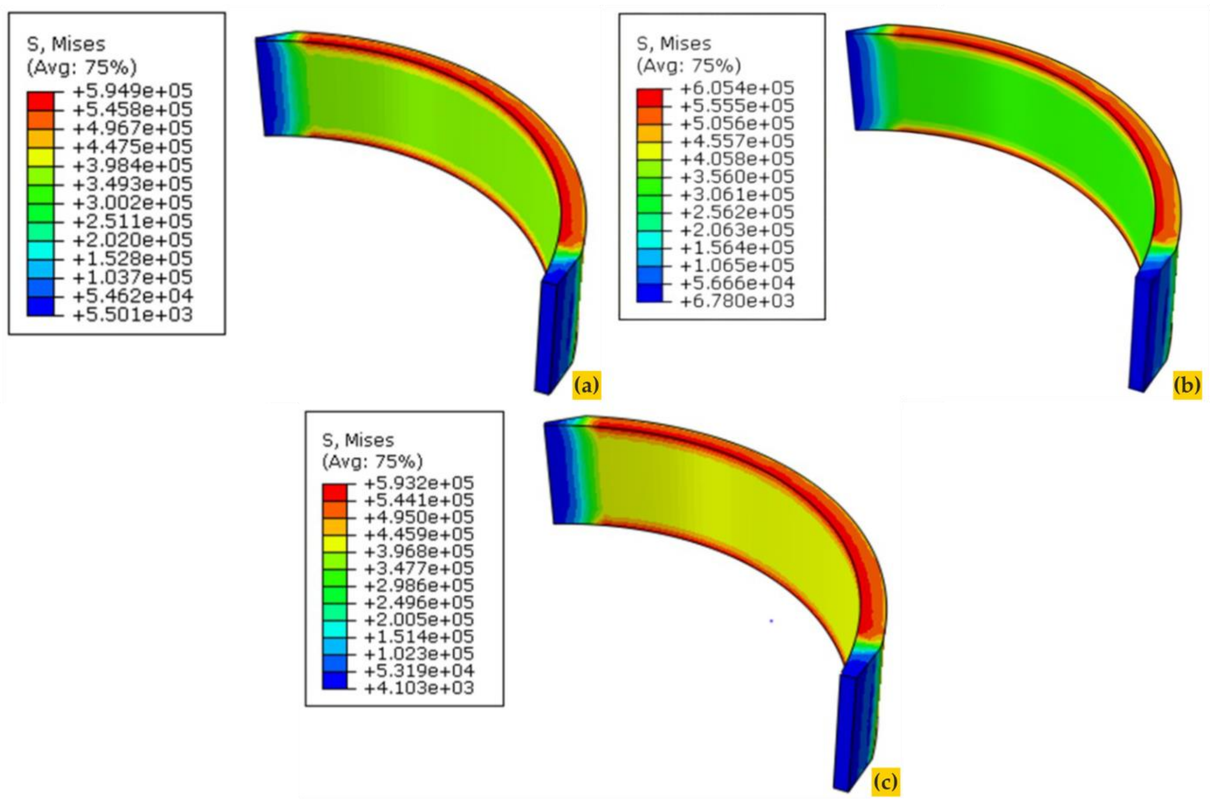

Figure 12. The FEA results in ABAQUS for brake lining: (a) von Mises stress for carbon composite; (b) von Mises stress for carbon ceramics; (c) von Mises stress for carbon fiber

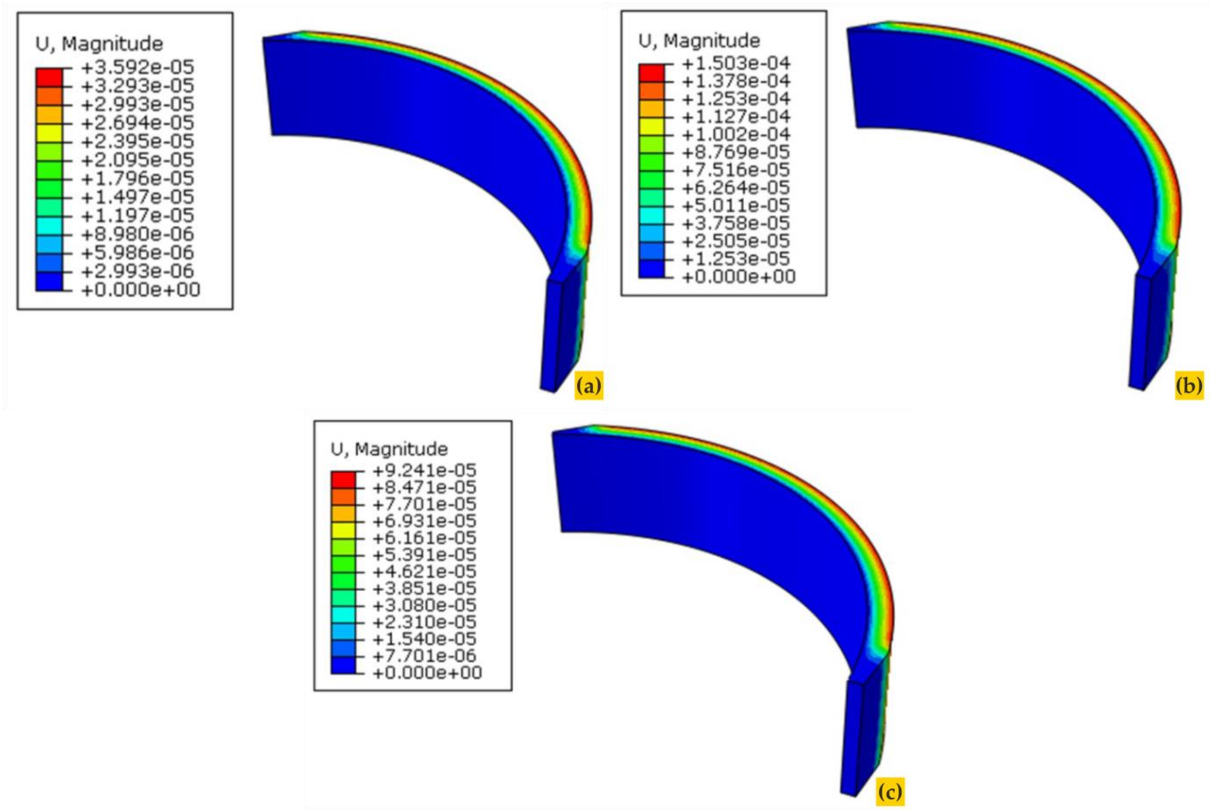

Figure 13. The FEA results in ABAQUS for brake lining: (a) Displacement for carbon composite; (b) Displacement for carbon ceramics; (c) Displacement for carbon fiber

Table 7. Structural analysis results for the brake lining under static load

Material	Max. Stress (Pa)	Max. Displacement (mm)	Max. Deformation (mm)
Carbon composite	5.949×10^5	3.592×10^{-5}	0.0067
Carbon ceramics	6.054×10^5	1.503×10^{-4}	0.027
Carbon fiber	5.932×10^5	9.241×10^{-5}	0.018

3.3. *Design Considerations Based on Component Weight and Economic Impact*

To select the best material for the brake main components, other design criteria such as weight and cost must be considered. By incorporating the calculation of production cost for each material into this study, we can generate a more comprehensive understanding of the impact of different material choices on brake components from both cost and economic sustainability perspectives. The raw material prices are provided by the local suppliers and the production costs are estimated based on the interviews with the plant managers in the automotive manufacturing industry.

Table 8 compares the total weight and production cost for each brake shoe, providing in-depth insights into the economic impact of material selection.. As mentioned before, cast iron is the most common material utilized in the manufacturing of automotive brake parts due to its excellent mechanical properties such as high yield strength and good wear resistance, durability, and cost-effectiveness. However, cast iron brake shoes are heavy while the current trend in the automotive industry requires brake systems to also meet the requirement of light weight. Hence, researchers have recently proposed aluminum alloy or aluminum metal matrix composite as a viable replacement for cast iron for vehicle brake components [39]–[42]. As shown in Table 8, the aluminum alloy and magnesium alloy brake shoes are around 62.7% and 76.3% lighter compared to the cast iron, respectively. Furthermore, there is negligible variation in the stress and deformation in the aluminum alloy and cast iron brake shoes during the application of static load. In terms of production costs, the material and manufacturing costs of Al alloy are higher compared to cast iron. However, the economic implications of replacing cast iron with Al alloy are deemed modest. Considering both the opportunity for weight saving and economic impacts, the use of aluminum alloy as a material for motorcycle brake shoe applications should be favored by the automotive sector.

The weight and production cost of brake lining made of three different carbon variants are summarized in Table 9. Although the literature on brake lining is scarce compared to brake shoes, several researchers have pioneered the use of carbon fibers or carbon composite for brake lining [32], [34]. The alumina carbon composite and carbon fiber yield equal mass, while carbon ceramics brake lining is found to be slightly heavier in this study. In terms of mechanical stress and deformation under static braking force, the finite element analysis predicted that the carbon composite brake lining displays more advantageous characteristics compared to carbon fiber and carbon ceramics. In the context of economic impacts, carbon fiber brake lining has the highest while carbon composite and carbon ceramics have lower material and manufacturing costs. Based on the mechanical strength and economic reasons, carbon composites seems to be the best candidate material for the brake lining applications of motorcycles.

4. Conclusion

The finite element analysis of the brake shoe and lining of the motorcycle has been performed using ABAQUS software. The analysis is conducted for Al alloy, cast iron, and Mg alloy brake shoes and carbon composite, carbon ceramics, and carbon fiber brake linings. The results indicate that the stress induced by the static load in the Al alloy and cast iron brake shoes are almost the same while the deformation of cast iron is marginally better compared to the Al alloy. The Al alloy brake shoe, however, has significantly less weight than the cast iron brake shoe. After thorough consideration based on the structural strength, weight, and cost-effectiveness, it is decided that the Al alloy is a viable material to replace cast iron for brake shoe application. For the brake lining, the finite element analysis found that the stress distributions for all shoe linings made of three different carbon variants are almost similar. The carbon composite lining, however, demonstrates significantly lower deformation compared to carbon ceramics and carbon fiber. Since its material and manufacturing costs are moderate, the carbon composite is considered to be the most suitable material for the brake lining.

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Table 8. The impact of structural strength on production costs of brake shoe

Cost Factors	Al Alloy	Cast Iron	Mg Alloy
Brake Pad Mass (g)	107	287	68
Max. Stress (Pa)	1.664×10^7	1.716×10^7	2.487×10^7
Max. Displacement (mm)	8.699×10^{-3}	5.566×10^{-3}	1.664×10^{-2}
Max. Deformation (mm)	0.0077	0.0049	0.012
Raw Material Cost (IDR)	16000	10500	36800
Manufacturing Cost (IDR)	24000	15900	55200
Production Cost Impact	Moderate	Low	High

Table 9. The impact of structural strength on production costs of brake lining

Cost Factors	Carbon Composite	Carbon Ceramics	Carbon Fiber
Brake Lining Mass (g)	25	27	25
Max. Stress (Pa)	5.949×10^5	6.054×10^5	5.932×10^5
Max. Displacement (mm)	3.592×10^5	1.503×10^5	9.241×10^5
Max. Deformation (mm)	0.0067	0.027	0.018
Raw Material Cost (IDR)	8000	5300	18400
Manufacturing Cost (IDR)	12000	8000	27600
Production Cost Impact	Moderate	Low	High

Author's Declaration

Authors' contributions and responsibilities

The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors read and approved the final manuscript.

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Availability of data and materials

All data are available from the authors.

Competing interests

The authors declare no competing interest.

Additional information

No additional information from the authors.

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