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Comparative Analysis of Disc Brake Using Eco-Friendly Material

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Abstract

Brakes are crucial components for slowing or stopping the vehicle. Almost all vehicles use disc brakes. The working of a disc brake is simple; when the brake pedal is pressed, braking pads are forced mechanically against the rotor or disc on both surfaces. The friction generated between the rotor and brake pads slows down the vehicle. The design and materials of disc brakes play a significant role in their performance. Disc brake may fail due to various mechanical and thermal stresses. This problem can be overcome by choosing the right material and design. The primary aim of this research paper is to develop and examine the stresses on the disc brake by selecting environmentally friendly materials and design. Here, we have designed different models of disc brakes to reduce the weight of the disc and ensure good strength and stiffness. Gray cast iron is a conventional material used for making disc brakes. Though it has good thermal conductivity and strength, there are certain drawbacks, such as high weight and corrosion susceptibility. So, we have chosen Fly Ash & Aluminium as an alternative material for the disc brake. Three different models-Solid disc, Straight Vented, and Curved Vented were designed using Fusion 360 software. Structural and thermal analyses were performed on each design using ANSYS software. Total deformation, equivalent stress, and total heat flux were found in the analysis. After reviewing the outcomes, the optimal design and material for the disc brake have been selected. The findings suggest that disc brakes with Fly Ash Aluminium are the most viable and sustainable alternatives to gray cast iron.

Keywords: Disc brake, Gray Cast Iron, Fly Ash Aluminium Composites, Fusion 360, ANSYS

INTRODUCTION

Disc brakes are now used on nearly all modern vehicles because they are efficient, productive, and safe. The mechanical characteristics of efficiency, fatigue resistance, thermal conductivity, and wear resistance define the characteristics of disc brakes by the different properties of materials [1]. When the driver pushes down on the brake pedal, mechanical linkages or hydraulic fluid push the caliper and the brake pad clamps onto the rotor that creates friction that converts kinetic energy to heat that slows down or stops the vehicle entirely.

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The main elements of a disc brake system are the rotor, caliper, brake pads. When the driver pushes down on the brake pedal, hydraulic fluid or mechanical linkages transfer the force to the caliper, causing the brake pads to clamp the rotor, turning kinetic energy into heat thus slow down or stopping the vehicle.

The first patents and prototypes for disc brake technology were developed in the early 1900's, around 1902. However, it was not until the 1950's that they came into prominence in auto-related industries -specifically in high-performance vehicles and racing cars where having a superior braking system is critical. As disc brakes proved to be more user-friendly, they became a standard feature on modern vehicles owing to their ability to dissipate heat better, perform effectively when wet, experience significantly less brake fade than drum brakes. The best brake discs, in the case of this review paper, should be lightweight, crack resistant and be operationally effective at elevated temperatures [2].

WORKING OF THE DISC BRAKE

The operation of a disc brake relies on the science of friction, which is used to convert the kinetic energy of a wheel into some heat to slow or stop the vehicle. This occurs in a few steps.

- *Actuation:* The driver, by pushing downward on the brake pedal, directly actuates the master cylinder, which applies force, through mechanical means, to the brake fluid contained in the hydraulic lines.
- *Force Transmission:* The brake fluid will, under pressure, be pushed through the brake line to the piston in the disc brake caliper.
- *Pad Engagement:* The hydraulic system applies force to the piston that in turn moves the brake pads in the caliper outward against each of the rotating discs.
- *Friction Generation (and heat):* The pads and the disc begin to adhere to one another which generates friction and converts the kinetic energy in the wheel into heat.
- *Release:* The hydraulic pressure is lost, when the driver takes their foot off the brake pedal; therefore, the piston slightly retracts, and the brake pads are not pulled into the discs, allowing the wheels to spin again with minimal friction.

Braking effectively requires many components and variables to be fit for duty; quality of the friction materials, clamping force, disc material, disc design and others contribute to each braking application.

MATERIAL SELECTION

An ideal disc brake should be a combination of great mechanical strength, thermal characteristics, and long service life. It should have high tensile and compressive strengths and should resist large clamping forces without deformation or cracking. An ideal disc must have good thermal characteristics for effective thermal conductivity to dissipate heat generated in braking which may help prevent hot spots and brake fade. Good frictional characteristics with the brake pad should result in long service life and consistent performance as wear is high. When temperature meets or exceeds approximately 500 °C, and this is without dimensional stability a dis brake can begin to warp or crack. Lightweight materials such as aluminum perform well with disc brake because they are so rigid but very lightweight thus they reduce unsprung mass and rotational inertia to improve handling and efficiency which helps ensure that there is sufficient thermal mass to absorb and tolerate disc brake heat characteristics of the material. Good dampening characteristics help to control vibrations and brake noise which can lead to improved performance while using a heavier material having a improved mechanical and thermal performance. Ultimately, the most significant use characteristics are corrosion resistance which is the main driver for to providing the disc brake with extended resistance against moisture and other environmental factors created by salts and debris. These properties go a long way to help to maximize safety and durability in various driving conditions. In order for disc brakes to function appropriately the material must have a combination of good thermal conductivity, good thermal management capabilities and good wear resistance to allow proper long term performance and safety of the product.

Conventional Material as Grey Cast Iron

It is primarily selected for disc brake rotors due to its impressive thermal conductivity, high compressive strength, and superior vibration-damping qualities. When braking occurs, a lot of heat is generated due to friction on the disc and pads. Grey cast iron is efficient in dissipating heat which significantly reduces vibrational warping which can lead to brake fade and quit reliable stopping performance. The microstructure of the material has a number of tiny flakes of graphite which helps to absorb vibrations, dissipate noise and provide a much smoother performance. The paper discusses the impact of the gray cast iron rotors content of graphite and ferrite on brake performance. It determines that ferrite is minimal, while more graphite improves friction and fade resistance, especially with nonsteel linings [3, 4]. In addition, the number of heavy loads that grey cast iron can handle due to its high compressive strength provides safety against sudden and repeated braking. A major component of making grey cast iron is due to it being relatively cheap and easy to use during manufacture. It is also abundant, inexpensive and displays excellent castability; thus allowing for complex rotor geometries to be made with minimal machining. Its wear resistance allows a greater lifespan for the brake disc, thus reducing the frequency with which it needs to be replaced. Gray cast iron is still favored because it is inexpensive and has good thermal conductivity and good mechanical properties [5]. Also grey cast iron has good frictional properties, which also ensures a stable and reliable braking performance.

Limitations of Gray Cast Iron

Selecting an alternative material instead of traditional Gray cast iron is driven by the desire to improve durability, efficiency, and performance. This study suggests that among all evaluated materials, Carbon-ceramics outperform others due to their lightweight, high strength, and long service life [6]. Grey cast iron presents certain drawbacks. While comparing Gray cast iron with aluminum metal matrix composites, the AMMC shows lower thermal conductivity variation, faster heat dissipation, and reduced weight. These are some reasons for selecting alternative materials [7].

- *Weight Reduction:* This is the most significant improvement. Using materials such as Aluminium metal matrix composites or carbon-carbon composites help reduce unsprung mass by over 90% which improves fuel economy significantly.
- *Thermal Performance:* The Gray cast iron is not able to disperse that heat as well as aluminium-based materials. It has a much higher change for brake fade when subjected to a prolonged period of braking.
- *Dimensional stability:* Higher energy braking creates more wear and dust particles than are created normally. Higher energy braking causes warping of the pad and disc, cracking of the disc, and variations in disc thickness.
- *Corrosion resistance:* Cast iron immediately rusts when subjected to humid and/or salty environments. Alloys such as composites resist corrosion in many environments; Alloy, composite brake pads and discs committee to improving durability and performance in a variety of conditions.

Composite Materials

Composite Disc brakes are the components that are made from Metal matrix composites instead of Conventional Gray cast iron. They combine a metal matrix like aluminium with ceramic reinforcements (SiC or Al2O3). The disc brakes made of composites act as a replacement for conventional materials by giving high strength, low weight, excellent thermal stability, and improved wear resistance. The Aluminum metal matrix composite 6061 disc brake is 74% lighter than a conventional disc brake, and it has a lower operating temperature at tested speeds [8]. The aluminium-based MMC disc brakes have better heat dissipation, lower weight, and better braking performance without compromising strength [9].

Eco-Friendly Material as Fly Ash + Aluminium Composites

The use of fly ash and aluminum as a combination of a MMC (metal matrix composite) is being noted to be more environmentally friendly and has superior performance compared to many disc brakes. Fly ash is a by-product of burning coal that is produced by thermal energy power plants, and contains a large percentage of alumina, silica and various oxides. The addition of fly ash into aluminum alloy matrix improves mechanical and thermal properties, and assists in sustainable engineering through the recycling of industrial waste. The study found that adding fly-ash increased porosity, micro-hardness, and ultimate tensile strength, with the highest values generally seen in the sample with 30% fly-ash (GAF-3) [10]. This composite features a lower density, significantly decreasing the weight of the disc brake in comparison to conventional grey cast iron, thereby enhancing fuel efficiency and overall vehicle performance.

Fly ash particles improve wear resistance, hardness, and thermal stability of the aluminum matrix. Not only does the resultant composite have better heat dissipation characteristics crucial for brake applications, but it also can withstand high temperatures resulted from friction with little thermal deformation. The study suggests that fly ash reinforcement improves stiffness and wear resistance by reducing the costs and recycling industrial wastes [11]. In addition to the inherent corrosion resistance in aluminum, the thermal properties of fly ash further extend service life in harsh environments. The material also reduces brake dust and emission in some carbon footprint-friendly manufacturing. The paper also talks about manufacturing processes, challenges such as cost and machinability, and the possibility of using environmentally sustainable composites such as Aluminium–Fly Ash for more sustainability without sacrificing performance [12].

In this research paper, we have taken the Fly ash aluminium composite at 10:90 % Weight of the composition.

Table 1 gives the information about the properties of Gray cast iron and Fly ash aluminium composite at a 10:90 ratio. From Table 1, we understood that the Fly ash aluminium is significantly lighter and stronger, and offers improved Tensile strength and Compressive strength.

Table 1. Properties of Materials.

Property	**Gray Cast Iron**	**Fly Ash + Aluminum Composites (10:90)**
Density(g/cm3)	7.2	2.65
Youngs Modulus (GPa)	130	74
Poisson ratio	0.28	0.317
Tensile Strength (MPa)	240	280
Compressive Yield Strength (MPa)	240	270

Overall, aluminum-fly ash composites a sustainable, lightweight and strong material should be a good choice for automotive disc brake applications, especially as we see industries shifting toward more sustainable and efficient means of transportation.

DESIGN OF DISC BRAKE

The designs for a disc brake severely influences performance of a braking system. A well-designed disc brake will provide an optimal balance of good heat balance, friction performance, and weight to deliver solid, safe brake performance while managing a percentage of daily braking. To minimize the aerodynamic losses, the combined designs of radial and tangential were the best [13]. The Key factors for effective disc brake designs include Geometry (Drilled, slots, or grooves), Ventilation, Surface Topology, Thickness, Material, and mass distribution.

Generally, regarding their cooling method, disc brakes are classified as either solid disc brakes or Vented disc brakes. The solid disc brake is a single-piece rotor, which is simpler and cheaper but has less cooling efficiency. But while coming to Vented disc brakes, it is the two friction surfaces are separated by internal cooling vanes. The brakes with fins and strategically placed holes give the best cooling, braking performance, and with reduced weight [14]. Especially in demanding applications, disc brakes must dissipate heat quickly to prevent performance issues. This can be done by the development of ventilated disc brakes [15]. The brake, having the ventilated discs, effectively dissipates heat, reduces brake fade, and maintains structural integrity under high loads, making them superior to discs for performance and durability [16].

MODELING AND ANALYSIS

Modelling in FUSION 360

For designing of disc brake, we have chosen Fusion 360 software. Table 2 gives the specifications of the disc brake that we have designed. These dimensions were taken from the Suzuki Ertiga model with some modifications. Three different designs were designed. The first design has no drilled holes. The second design contains straight vented holes of 8mm, and the third design contains curved vented holes.

Table 2. Specifications of Disc Brake Rotor.

S.N.	Description	Dimension Value (mm)
1	Outer diameter of rotor	240
2	Inner diameter of rotor	150
3	Hub diameter	120
4	Thickness of rotor	16
5	Hole diameter	8

The Figures are the designs of disc brakes. Figure 1 is a solid disc (Design 1) whereas Figure 2 is disc with straight vented holes (Design 2) and Figure 3 with Curved vented holes (Design 3).

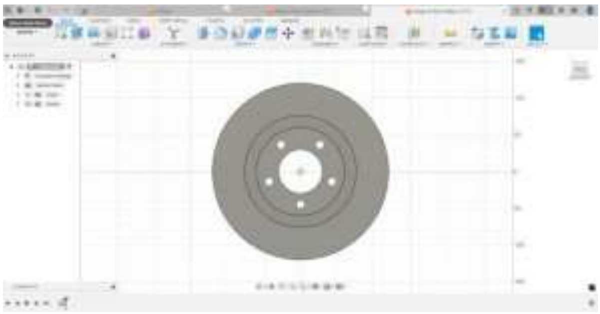

Figure 1. Solid Disc (Design 1).

Figure 2. Disc with Straight Vented Holes (Design 2).

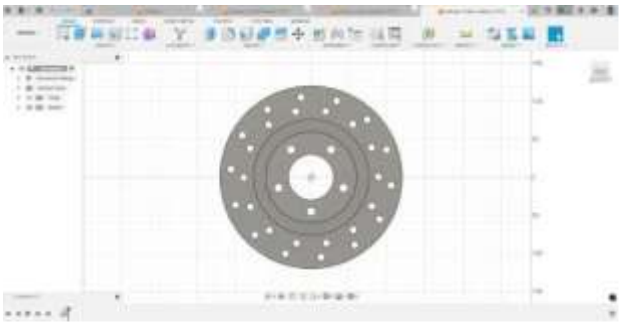

Figure 3. Curved Vented Holes (Design 3).

FEA Analysis

Three designs were analysed using ANSYS Workbench. On each design, using two materials, Gray cast iron and Fly ash Aluminum at (10:90%), structural and transient thermal analyses were performed. Table 3 below shows the applied boundary conditions for the static structural analysis of the disc brake rotor. From the structural analysis, we have found the Deformation, Equivalent stress, and strains. Now, from the Transient thermal analysis, we have found the Total Heat flux.The inputs for the Thermal analysis are at a temperature of 100ºC.

Table 3. Inputs for Structural analysis.

S.N.	**Static Structural**
1	Meshing (5)
2	Fixed Support
3	Pressure(4MPa)
4	Rotational Velocity (60 rad/s)

RESULTS AND DISCUSSION

From the ANSYS software, the results of the structural & thermal analysis using both materials, Gray cast iron and Fly ash aluminium, are presented below.

Results of Gray Cast Iron

Design 1

The Figure 4–7 give the results of Total deformation, Equivalent Stress, Equivalent strains, and Total Heat flux of Design 1.

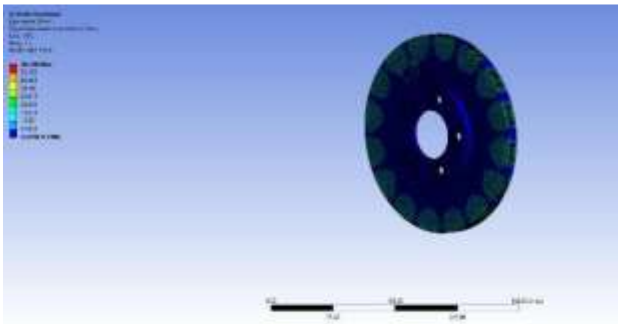

Figure 4. Deformation of Design 1.

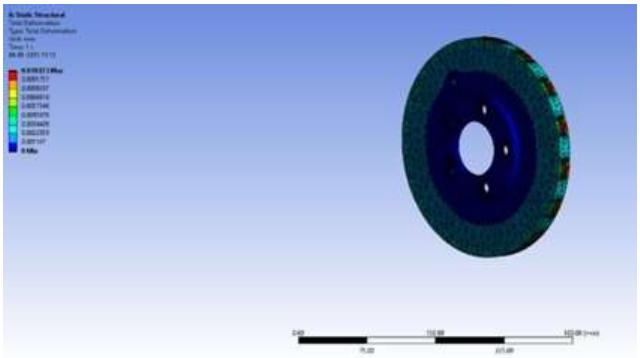

Figure 5. Equivalent Stress of Design 1.

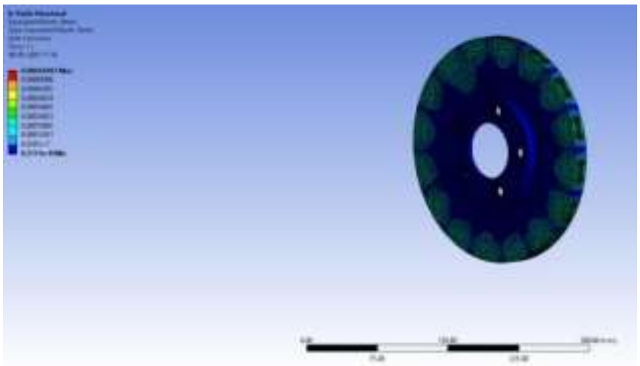

Figure 6. Equivalent Strain of Design 1.

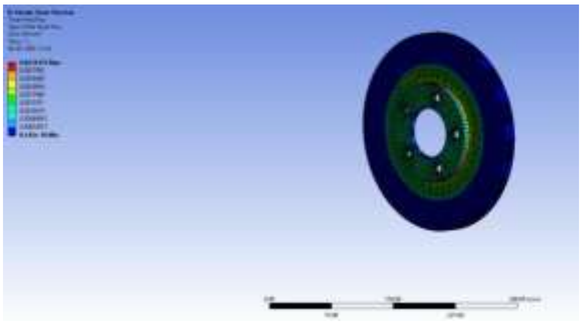

Figure 7. Total Heat Flux of Design 1.

Design 2

The Figure 8–11 give the results of Total deformation, Equivalent Stress, Equivalent strains, and Total Heat flux of Design 2.

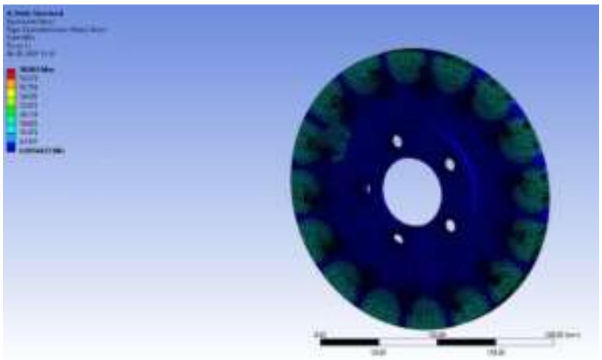

Figure 8. Deformation of Design 2.

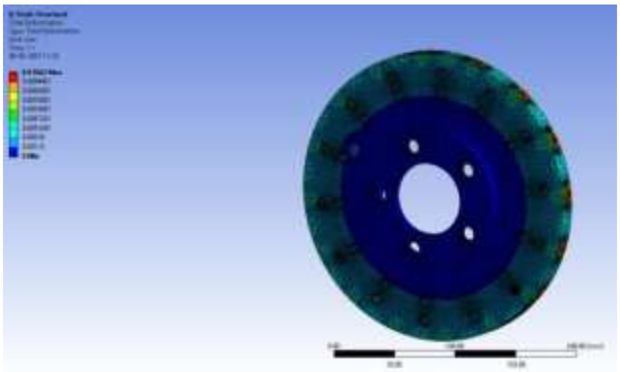

Figure 9. Equivalent Stress of Design 2.

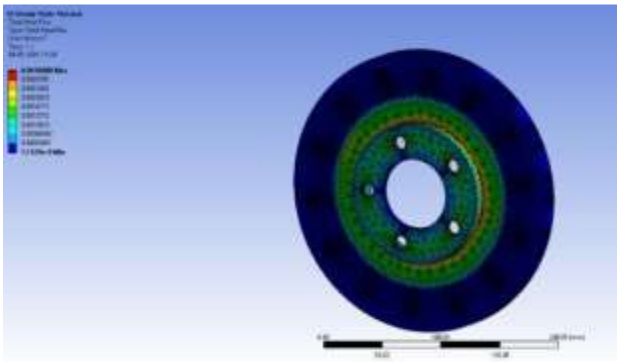

Figure 10. Equivalent Strain of Design 2

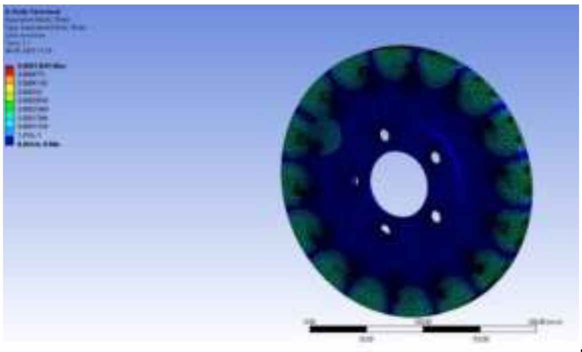
Figure 11. Total Heat Flux of Design 2.

Design 3

The Figure 12–15 give the results of Total deformation, Equivalent Stress, Equivalent strains, and Total Heat flux of Design 3.

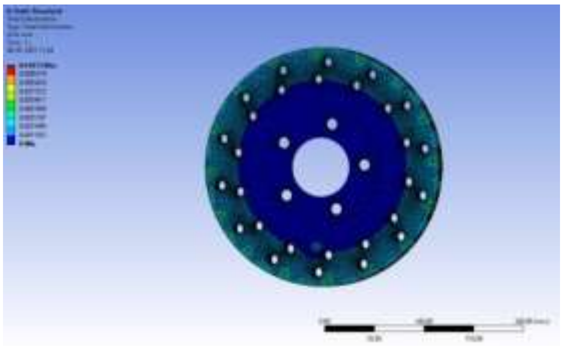
Figure 12. Deformation of Design 3.

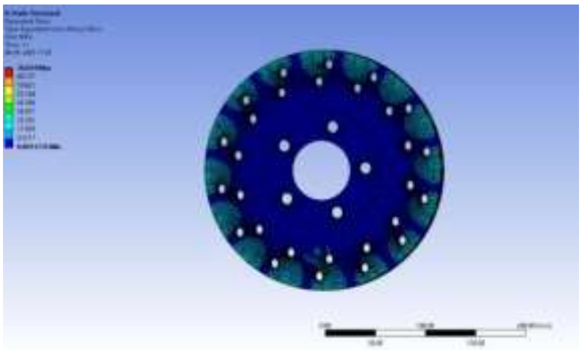
Figure 13. Equivalent Stress of Design 3.

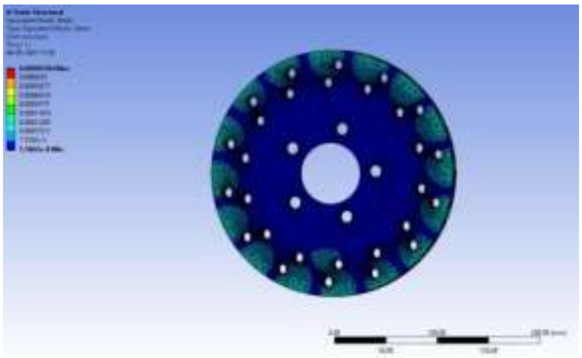
Figure 14. Equivalent Strain of Design 3.

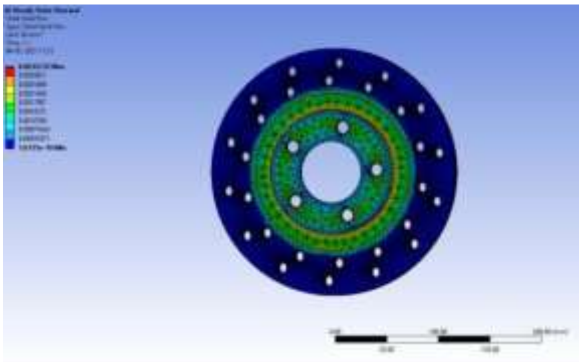

Figure 15. Total Heat Flux of Design 3.

Results of Fly Ash Aluminium Composite

Design 1

The Figure 16–19 give the results of Total deformation, Equivalent Stress, Equivalent strains, and Total Heat flux of Design 1.

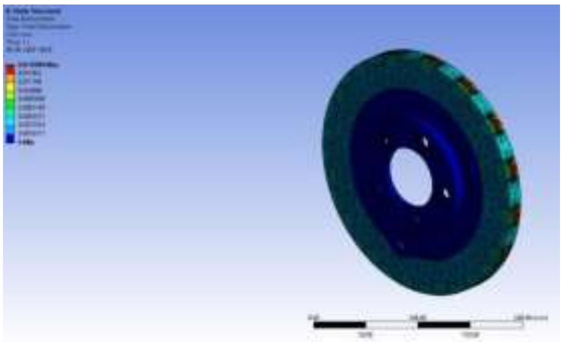

Figure 16. Deformation of Design1.

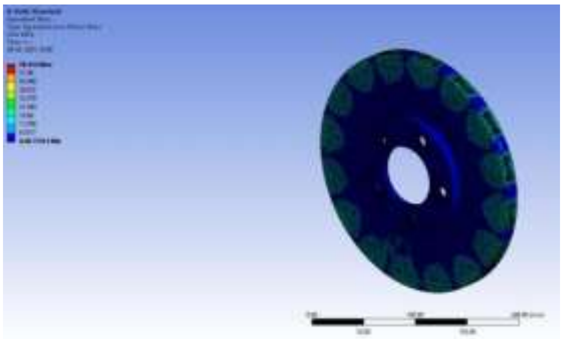

Figure 17. Equivalent Stress of Design1.

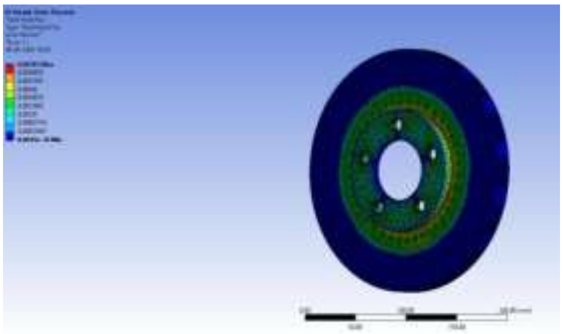

Figure 18. Equivalent Strain of Design 1

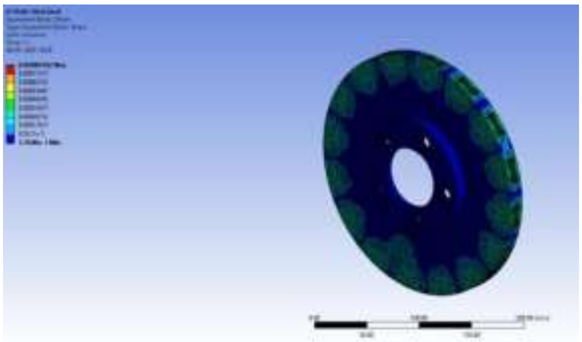
Figure 19. Total Heat Flux of Design 1.

Design 2

The Figure 20–23 give the results of Total deformation, Equivalent Stress, Equivalent strains, and Total Heat flux of Design 2.

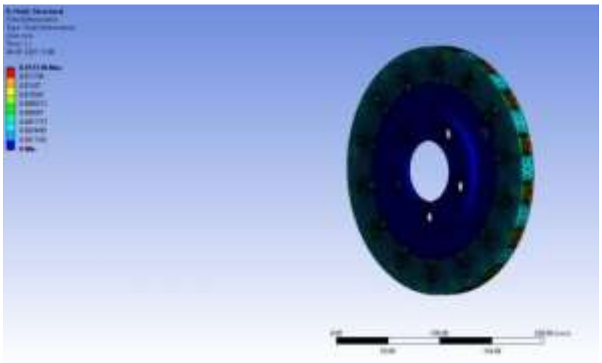
Figure 20. Deformation of Design 2.

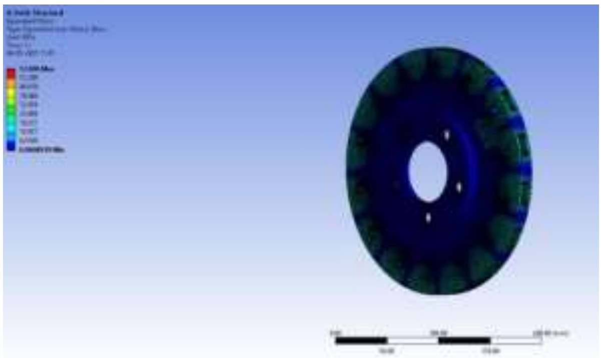
Figure 21. Equivalent Stress of Design 2.

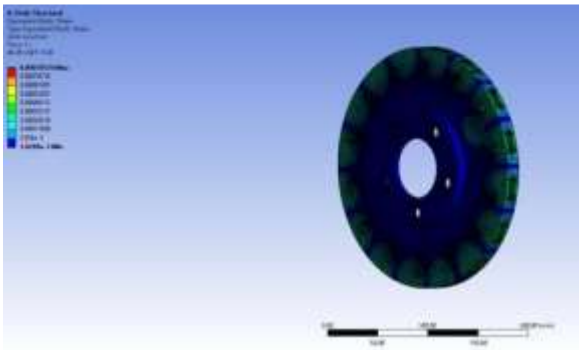
Figure 22. Equivalent Strain of Design 2.

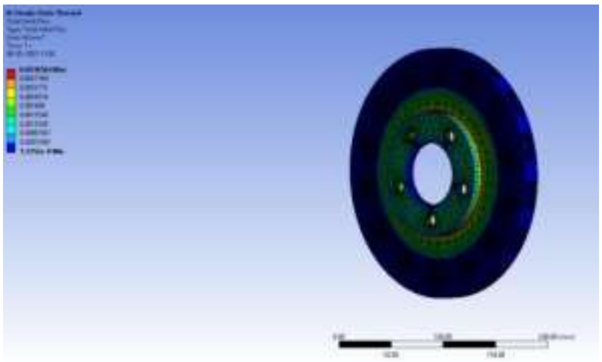

Figure 23. Total Heat Flux of Design 2.

Design 3

The Figure 24–27 give the results of Total deformation, Equivalent Stress, Equivalent strains, and Total Heat flux of Design 3.

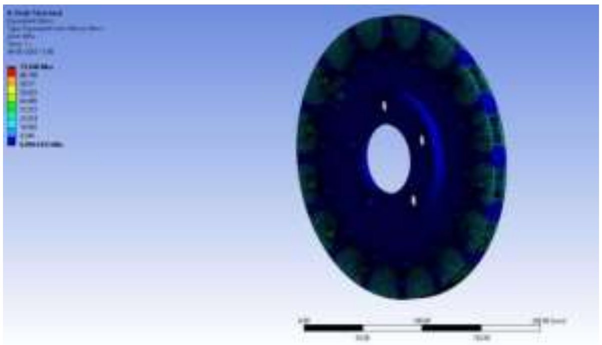

Figure 24. Deformation of Design 3.

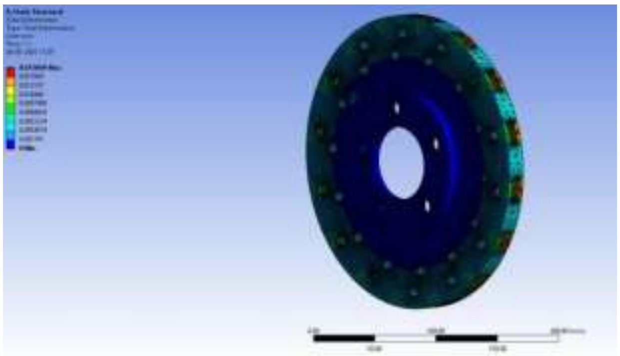

Figure 25. Equivalent Stress of Design 3.

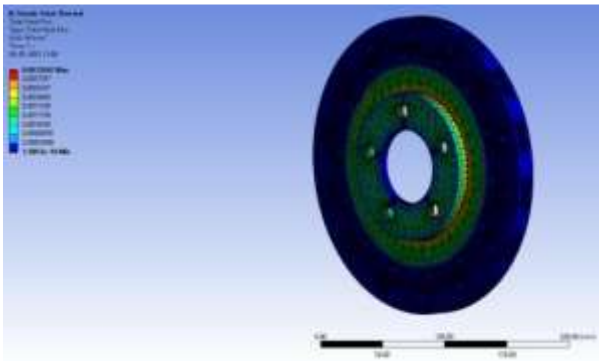

Figure 26. Equivalent Strain of Design 3.

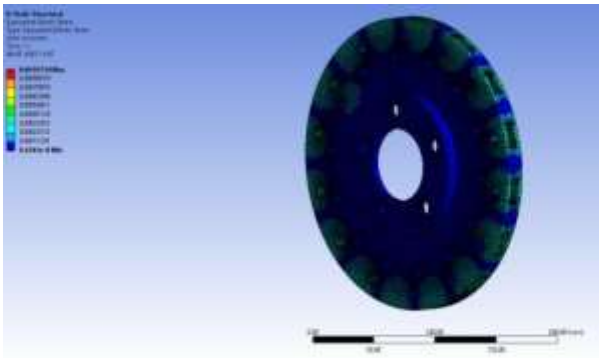

Figure 27. Total Heat Flux of Design 3.

RESULTS TABLE

Structural analysis results

Table 4 below gives information about deformation, Equivalent strain, and Equivalent stress of both materials.

Table 4. Results of Structural Analysis.

Design	Deformation(mm)		Equivalent Elastic Strain		Equivalent Stress (MPa)	
	Gray Cast Iron	*Fly Ash Aluminum*	*Gray Cast Iron*	*Fly Ash Aluminum*	*Gray Cast Iron*	*Fly Ash Aluminum*
Design 1	0.010323	0.015099	0.00054107	0.00080162	58.708	58.454
Design 2	0.01062	0.015518	0.00053695	0.00079574	58.805	57.696
Design 3	0.01073	0.015669	0.00069784	0.0010154	76.654	75.046

Thermal Analysis Results

The Table 5 below gives the total heat flux of Gray Cast Iron and Fly Ash Aluminium Composites.

Table 5. Results of Thermal Analysis.

Design	Total Heat Flux(W/mm2)	
	Gray Cast Iron	*Fly Fly Ash Aluminum Composite*
Design 1	0.0031435	0.00303
Design 2	0.0030088	0.0030564
Design 3	0.0032232	0.0031047

RESULTS SUMMARY

Analysis of deformation, strain, stress, and heat flux in three disc brake designs utilizing Gray Cast Iron and Fly Ash–Aluminium Composite reveals the following insights.

- *Deformation:* The levels are consistently greater in Fly Ash Aluminium compared to Grey Cast Iron across all three designs.
- *Elastic Strain:* It exhibits a similar pattern, with Fly Ash Aluminium demonstrating increased strain in each design, suggesting enhanced flexibility.
- *Equivalent Stress:* Marginally lower in Fly Ash Aluminium, with the peak stress recorded in Design 3 for both materials—76.654 MPa for Grey Cast Iron and 75.046 MPa for Fly Ash Aluminium.
- *Thermal Performance:* Design 3 exhibits the highest heat flux for both materials, with Fly Ash Aluminium demonstrating superior performance (0.0031047 W/mm² compared to 0.0032232 W/mm² for GCI).
- *Overall Braking Efficiency:* Eco-friendly composite shows a better braking efficiency compared to conventional Gray Cast Iron with an added advantage significant weight reduction and environmental benefit.

- *Wear Mechanisms:* From the above responses, different wear mechanisms are dominant in Eco-friendly composites compared to conventional cast iron. In Fly Ash Aluminium, Abrasive and Oxidative wear are expected to be the primary mechanisms due to hard ceramic phases. Whereas, adhesive wear is more in cast iron systems.

CONCLUSIONS

Design 3 produced the highest heat flux for the two materials, and Fly Ash Aluminium shows better thermal performance with higher heat flux values, which means that it's dissipating more heat than Grey Cast Iron. Iron shows slightly more deformation and strain; however, with the same resistance to stress means that it remains structurally sound. Design 3 appeared to achieve the highest values across all areas, which represents the hardest design issue. In conclusion, Fly Ash Aluminium Composite is a viable, appropriate, sustainable alternative to Grey Cast Iron, with the benefit of weight loss and thermal performance while having enough structural integrity to perform as a disc brake. The use of Fly Ash aluminium has various advantages, like weight reduction, improved fuel efficiency, and sustainable reuse of industrial waste. While this study is simulation-based, Future work should focus on experimental testing to validate these findings and tribological testing to confirm wear mechanisms such as abrasive and oxidative wear.

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