

Comparing and Contrasting the Performance of Mechanical, Material and Thermal Properties of Carbon-Carbon, Carbon-Ceramic and Metal Iron Brake Discs

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ABSTRACT

This research investigates the thermal and material properties of three types of brake discs: traditional cast iron, carbon-ceramic, and carbon-carbon. Utilizing Finite Element Analysis (FEA), the study simulates the behaviour of these materials under extreme conditions to evaluate their performance and suitability for high-stress motorsport applications. The findings indicate that carbon composite materials, owing to their superior thermal resistance and lower density, significantly enhance braking performance by reducing brake fade and improving heat dissipation. Carbon-ceramic and carbon-carbon brake discs demonstrate improved wear resistance and frictional performance, leading to safer and more efficient braking systems. This research aims to inform future material selection and engineering design processes, encouraging the exploration of innovative composite materials and manufacturing techniques. By addressing current gaps in comparative performance analysis and long-term durability studies, this study contributes to the advancement of brake disc technology, with potential implications for broader automotive safety standards. The outcomes of this research are expected to foster innovation in the motorsport industry, ultimately leading to the development of more reliable and high-performance braking systems.

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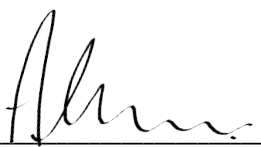
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Table of Contents

ABSTRACT.....	2
Acknowledgements	3
List of Figures & Tables	6
Nomenclature & Abbreviations	8
1.0 Introduction.....	9
1.1 Context and Motivation.....	9
1.2 Background & Literature Review.....	9
1.2.1 Thermal capacity of brake rotors	10
1.2.2 Theoretical Proof	13
1.3 Problem statement.....	14
1.4 Objective	14
1.5 Delimitation.....	15
1.6 Methodology	17
1.6.1 Brake Thermal Analysis Using Computational Methods.....	17
1.6.2 Failure criteria Prediction using analytical methods.....	17
1.6.3 Single Stop Temperature Rise (SSTR) and Thermal Analysis	19
1.7 Design of Experiment	22
1.7.1 Evaluation of ANSYS Mechanical FEA approach	22
1.7.2 Calculation of Rotational velocity from specified RPM	24
1.7.3 Brake Rotor modelling	25
1.7.4 Brake Pad modelling	26
1.7.5 Brake system design (components)	27
2.0 Validation of ANSYS Thermal Simulation	28
3.0 Results	31
3.1 Preliminary Results	31
3.1.1 Thermal Performance Simulations	31
3.1.2 Heat Dissipation	33
3.2 Discussion of Thermal Performance Simulations	35
3.2.1 Mechanical Performance Simulations	37
3.2.2 Deformation Profile	39
3.3 Discussion of Mechanical Performance Simulations	40
4.0 Thermal Fatigue and the Significance of Deformation	42
4.1 Disk Cracking and Failure Due to Thermal Stress	43
4.1.1 Mechanisms of Crack Formation	43
4.1.2 Crack Initiation	44

4.2 Boundary Conditions (Extended Analysis at Elevated Temperatures)	45
4.2.1 Thermal Analysis Results:.....	46
4.3 Discussion of Heat flux:.....	47
4.4 Mechanical Deformation Analysis.....	49
4.4.1 Metal Iron Brake Disc.....	49
4.4.2 Carbon-Ceramic Brake Disc	49
4.4.3 Carbon-carbon Brake Disc.....	50
4.5 Discussion of Deformation Profiles at elevated temperature (1000°C)	51
4.5.1 Metal Iron Disc Deformation:	51
4.5.2 Carbon-based brake disc	53
4.6 Determining Cut-off Point for Metal-based brake disc	54
4.6.1 Microstructure and Graphite Flakes.....	54
4.6.2 Practical Implications for Thermal Cut-Off Point.....	55
5.0 Detailed Circuit-Based Simulation Analysis.....	56
5.1 Turn number Clarification.....	59
5.2 Deformation Analysis	60
5.3 Turn-by-Turn Analysis.....	62
5.3.1 Acque Minerali (MoTec Turn 9)	62
5.3.2 1 st Rivazza complex (MoTec Turn 12 Initial Section + Str 12-13 + Turn 13)	63
5.4 Brake Performance:	64
5.4.1 Justification for Focusing on Rivazza complex over Turn 1	65
5.5 Graphs and Visualisation of Deformation	66
5.5.1 Metal Iron Brake Disc.....	66
5.5.2 Carbon-Ceramic Brake Disc	67
5.5.3 Carbon-carbon Brake Disc	67
5.6 Brief Discussion of Deformation Analysis	68
6.0 Overall Summary and Conclusions.....	69
6.1 Summary of Key findings.....	69
6.2 Implications for Practical Applications	70
6.3 Critical Reflection of Limitations	71
6.4 Standpoint on Material Innovation in Motorsport Engineering	72
6.5 Future Research Directions.....	72
6.6 Closing Remarks.....	73
REFERENCES	74

List of Figures & Tables

(Figure 1. 2D axisymmetric FEA brake disc model, Day et al., 1991)	20
(Figure 2. 2D visualisation of brake disc model used in the ANSYS FEA simulation)	21
(Figure 3. Material properties of metal iron)	22
(Figure 4. Material properties of Carbon-Ceramic)	23
(Figure 5. Material properties of Carbon-Carbon)	23
(Figure 6. ANSYS workspace screenshot of the rotational direction and velocity)	24
(Figure 7. Original brake rotor sample used for modelling)	25
(Figure 8. Brake rotor modelled in Shapr3d)	25
(Figure 9. Original brake pad sample used for modelling)	26
(Figure 10. Brake pad modelled in Shapr3d)	26
(Figure 11. Brake system design illustration 3D view)	27
(Figure 12. Brake system design illustration side view showing back-plate, pad friction material and disc)	27
(Figure 13. 2D Schematic representation of the sample metal rod)	28
(Figure 14. Heat Transfer for maximum mesh size of 0.1m, showing 95.002W.)	29
(Figure 15. Heat Transfer for maximum mesh size of 0.007m, showing 95.033W.)	29
(Figure 16. Mesh Independence study graph showing varying mesh size vs heat transfer results)	30
(Figure 17. ANSYS Temperature Profile result of Metal Iron Brake Disc)	31
(Figure 18. ANSYS Temperature Profile result of Carbon-Ceramic Brake Disc)	32
(Figure 19. ANSYS Temperature Profile result of Carbon-Carbon Brake Disc)	32
(Figure 20. ANSYS Heat flux result of Metal Iron Brake Disc)	33
(Figure 21. ANSYS Heat flux result of Carbon-Ceramic Brake Disc)	33
(Figure 22. ANSYS Heat flux result of Carbon-Carbon Brake Disc)	34
(Figure 23. Maximum Heat Dissipation Chart of the 3 materials)	35
(Figure 24. General disc brake friction coefficient μ vs Temperature graph, Bellini et al.,2023)	36
(Figure 25. ANSYS Stress Profile result of Metal Iron Brake Disc)	37
(Figure 26. ANSYS Stress Profile result of Carbon-Ceramic Brake Disc)	38
(Figure 27. ANSYS Stress Profile result of Carbon-Carbon Brake Disc)	38
(Figure 28. ANSYS Deformation Profile result of Metal Iron Brake Disc)	39
(Figure 29. ANSYS Deformation Profile result of Carbon-Ceramic Brake Disc)	39
(Figure 30. ANSYS Deformation Profile result of Carbon-Carbon Brake Disc)	40
(Figure 31. Visual Inspection of network cracking on a failed lorry brake disc. (a). Photograph of failed brake disc. (b). Section blocks of the disc part. (c-d). Closed-up network cracking on the disc surface, Luo et al. 2024)	43
(Figure 32. Thermal-induced cracking in grey cast iron brake disc surface, Day & Bryant, 2022)	44
(Figure 33. FEA analysis of metal iron brake disc. Arrow pointing at the outer edge of the disc where maximum deformation occurred.)	45

(Figure 34. ANSYS Heat flux result of Metal Iron Brake Disc at Elevated Temperature)	46
(Figure 35. ANSYS Heat flux result of Carbon-Ceramic Brake Disc at Elevated Temperature)	46
(Figure 36. ANSYS Heat flux result of Carbon-Carbon Brake Disc at Elevated Temperature) ..	47
(Figure 37. ANSYS Deformation result of Metal Iron Brake Disc at Elevated Temperature)	49
(Figure 38. ANSYS Deformation result of Carbon-Ceramic Brake Disc at Elevated Temperature)	49
(Figure 39. ANSYS Deformation result of Carbon-Carbon Brake Disc at Elevated Temperature)	50
(Figure 40. Disc Deformation field at the end of braking simulation, Day et al., 1991)	52
(Figure 41. Disc Temperature field at the end of braking simulation, Day et al., 1991)	52
(Figure 42. Optical micrographs of grey cast iron brake disc showing the microstructures of the graphite flakes at a depth of 2mm, Luo et al. 2024)	55
(Figure 43. Summary of survey results of different racing simulator software, de Frutos & Castro, 2021)	56
(Figure 44. Imola Track Map showing each turn)	57
(Figure 45. MoTec i2 Pro screenshot showing the raw data of the 718 gt4 race car in a lap of Imola.)	58
(Figure 46. Motec i2 Pro Imola Track map)	59
(Figure 47. Table of data analysis of target lap)	60
(Figure 48. Deformation vs Turns graph)	62
(Figure 49. MoTec illustration of relative speed reached before max braking applied)	63
(Figure 50. MoTec illustration of maximum bulk temperature reached towards the end of braking zone)	64
(Figure 51. MoTec illustration of max brake disc bulk temperature in previous lap)	65
(Figure 52. ANSYS Deformation result of Metal Iron Brake Disc at Turn 9)	66
(Figure 53. ANSYS Deformation result of Carbon-Ceramic Brake Disc at Turn 9)	67
(Figure 54. ANSYS Deformation result of Carbon-Carbon Brake Disc at Turn 9)	67

(Table 1. Table showing ρ , C and K values of the 3 brake disc materials)	10
(Table 2. Thermal Calculations on the brake disc design)	13
(Table 3. Vehicle Boundary Conditions used by FEA simulations of Day et al., 1991)	20
(Table 4. Specification of sample test metal rod)	28
(Table 5. Table showing Deformation of each material for each turn)	61

Nomenclature & Abbreviations

α	Thermal Diffusivity
β	Heat partition coefficient
C	Material Specific Heat Value, J/kg*K
K	Thermal Conductivity, W/mK
T_{max}	Maximum temperature, K
T_i	Initial Temperature, K
m_{disc}	Disc Mass, kg
c_{disc}	specific heat capacity of the brake disc material, J/kg*K
$\sigma_{Critical}$	Critical stress or working stress
σ_{yield}	Tensile Yield strength of the material
$\Delta\theta$	Brake Disc Bulk Temperature rise
ΔT	Temperature gradient, K/m
ΔT	Change in Temperature, K
μ	Friction Coefficient (μ)
ρ	Material Density, kg/m ³
CCM	Ceramic Composite Material
CCB	Carbon Ceramic Brakes
FEA	Finite Element Analysis
LCA	Life Cycle Analysis
SSTR	Single Stop Temperature Rise

1.0 Introduction

1.1 Context and Motivation

In the sense of the automotive industry, braking plays a very significant role in the vehicle system used for deceleration or to stop the vehicle's motion. Braking can affect the vehicle's longitudinal and lateral motion. In motorsport, the braking system is taken into even more extreme boundaries where the brake discs are subjected not only to high temperatures and mechanical stress, but in an even more prolonged time frame. As a result, the brake rotors are subjected to extreme stress and temperature. These thermal and mechanical stresses are the main challenges when it comes to brake failures. Studies have shown that as the temperature decreases, the friction coefficient (μ) increases and significantly impacts the braking performance (Fieldhouse et al., 2011). This temperature dependency further complicates brake system design in motorsports, where rapid temperature fluctuations can influence the consistency of braking performance.

The idea of using composite materials in brake rotors, in particular carbon-carbon brake rotors originated in the aviation industry and in the highest tier of motorsport (Savage, 1993), such as Formula 1 and LEMANS series. However, one major crucial flaw in that of carbon-carbon brake disc, other than the extremely high manufacturing cost, is the high initial operating temperature needed in order for the rotor and pad material to start generating considerable friction μ (μ). Consecutively, in the late 90s, researchers have found that the addition of carbon additive to brake rotors contributes to not only lightness, but also higher heat-dissipation rate, a trait that was previously only available in carbon-carbon brake discs.

1.2 Background & Literature Review

The shift towards advanced composite materials for brake discs represents a critical evolution in the pursuit of enhanced motorsport performance. This literature review compiles and analyzes decades of research focused on the material and thermal properties of various brake disc materials. Numerous studies have highlighted the superior thermal resistance and lighter weight of carbon composites compared to traditional materials, which significantly contribute to their effectiveness in high-stress applications. The synthesis of this literature not only provides a comprehensive background for the study but also identifies gaps in current research that this thesis aims to address. By examining past and current technologies, this chapter builds a solid foundation for understanding the potential advancements in brake disc materials, emphasizing the ongoing need for innovation in the motorsport industry.

Examining previous research, we could anticipate the overall maximum temperature allowable in a gray cast iron brake disc to be around 700°C, whereas in a carbon ceramic matrix brake disc to be around 900°C (Pachauri et al., 2021). Although the study from Pachauri et al., 2021 didn't include carbon-carbon brake discs in the comparison, we can safely assume that carbon-carbon brake discs should yield an even higher operating temperature. Another hypothesis is from the conclusion of the researchers that the rate of

heat loss is also higher compared cast iron brake discs. The results indicated that cast iron brake discs are most suitable for providing moderate cooling at low temperatures for day-to-day normal automotive applications, whereas higher cooling rate of carbon-based discs is suitable for use in high performance and race cars when high temperatures are generated in a more regular basis. Based on the research, we can hypothesize that carbon-carbon brake discs, with its superior thermal properties, to outperform both cast-iron and carbon-ceramic brake discs in terms of heat dissipation and operating temperature.

The realm of motorsport demands the pinnacle of engineering innovation, particularly in the development of braking systems capable of withstanding extreme conditions. This thesis explores the material and thermal properties of three distinct types of brake discs: traditional cast iron, carbon-ceramic, and carbon-carbon. As the evolution of brake disc materials progresses from conventional iron to advanced composites, it marks a significant advancement in motorsport technology, driven by the need for improved performance and safety. This chapter sets the foundation by outlining the objectives and hypothesis of the research, emphasizing the importance of understanding how material compositions and heat management technologies influence the efficiency and reliability of brake systems in high-performance motorsports.

1.2.1 Thermal capacity of brake rotors

To understand the thermal capacity of brake rotors of each material, the density, specific heat and thermal conductivity values are extracted from the ANSYS 2024 R2 Mechanical database, illustrated in **(Fig.3, Fig.4, Fig.5)**, which is constantly being updated with international standards and references.

(Table 1. Table showing ρ , C and K values of the 3 brake disc materials)

	Metal Iron	Carbon-Ceramic	Carbon-Carbon composite
Density (ρ) kg/m ³	7800	2500	1800
Specific Heat (C) J/kg*K	460	1350	1400
Thermal Conductivity (k) W/mK	45	35	50

the temperature rise of a brake rotor is derived from the equation of conservation of energy and can be expressed as:

$$T_{max} - T_i = \frac{E_k \cdot \beta}{m_{disc} \cdot c_{disc}}$$

(Eq 1.0)

Where T_{max} is the maximum temperature; T_i is the initial temperature; m_{disc} is the mass of the disc, c_{disc} is the specific heat capacity of the brake disc material, which can be seen in (Table 1). E_k is the kinetic energy of the vehicle that's converted to thermal energy during braking. β is the heat partition coefficient, representing the fraction of the total kinetic energy dissipated by a single brake disc. Similar approach has been detailed in previous research from (Medina, 2023) to calculate temperature rise during a braking maneuver.

Looking at the specific heat capacity values of each material, with the assumptions of:

- The kinetic energy is constant at 500,000J
- (m) Mass of brake disc is constant at 10kg
- (β) Heat partition coefficient is 1 (for simplicity, to assume the pad material is the same as the brake rotor material.)

These assumption help simplify the complex dynamics of braking into manageable calculations, allowing for easier assessment of different brake discs materials. However, it is important to note these assumptions may not fully capture the variability encountered in real-world conditions. For instance, the assumption of constant brake disc mass does not account for variations in the different materials. The use of heat partition coefficient of 1 also assumes the brake pad and rotor materials are perfectly matched in terms of their thermal properties.

Carbon-Carbon Composite:

$$\Delta T_{cc} = \frac{500,000J}{10kg \cdot 1400} = \frac{500,000}{14000} = 35.71K$$

(Calc 1.0)

Carbon-Ceramic:

$$\Delta T_{sic} = \frac{500,000J}{10kg \cdot 1350} = \frac{500,000}{13500} = 37.04K$$

(Calc 1.1)

Metal Iron:

$$\Delta T_{iron} = \frac{500,000J}{10kg \cdot 460} = \frac{500,000}{4600} = 108.70K$$

(Calc 1.2)

According to published study from (Limpert, 2011), the thermal diffusivity (a) can be expressed by

$$a = \frac{k}{PC}$$

(Eq 2.0)

where k is the thermal conductivity, P is the density of the brake disc and C is the specific heat value.

In the case of substituting the Density (P), Specific Heat (C) and Thermal Conductivity (k) values of cast iron, carbon-carbon composite and ceramic composite, we could see the following results of thermal diffusivity.

- **Metal Iron**
 $a = 45 / (7800 * 460) = 50 / 3312000 \approx 1.25 \times 10^{-5} \text{ m}^2/\text{s}$
- **Ceramic Composite**
 $a = 35 / (2500 * 1350) = 12 / 2080000 \approx 1.03 \times 10^{-5} \text{ m}^2/\text{s}$
- **Carbon-Carbon composite**
 $a = 50 / (1800 * 1400) = 60 / 1136000 \approx 1.98 \times 10^{-5} \text{ m}^2/\text{s}$

Another theoretical approach is by looking at Fourier's Law of Heat Conduction, it is a description of the process in which heat energy is transferred through a material due to a temperature gradient. It states that the rate of heat transfer through a material is proportional to the negative gradient of temperatures and the area through which the heat flows. Mathematically, Fourier's Law is expressed as:

$$Q = -k\Delta T$$

(Eq 3.0)

where:

- Q is the heat flux (W/m^2)
- k is the thermal conductivity ($\text{W}/\text{m}\cdot\text{K}$)
- ΔT is the temperature gradient (K/m) *

* ΔT is the expected temperature drop taken from the experimental boundary conditions;
 $\therefore$ From 600°C to 20°C , $\Delta T = 580^\circ\text{C}$.

In the context of brake discs, Fourier's Law helps in understanding how different materials dissipate heat during braking. Materials with higher thermal conductivity (k) will transfer heat more effectively, leading to lower operating temperatures and improved performance (Grześ, 2014). This principle is crucial when selecting materials for high-performance brake systems in motorsport applications, where rapid heat dissipation is essential to prevent brake fade and ensure safety.

Additionally, the heat capacity which is a general engineering concept to observe heat transfer and change in temperature and mass (Lumen Learning, 2021), can be expressed by the equation:

$$Q = mc\Delta T$$

(Eq 4.0)

Where:

- m is the mass (kg) *
- c is the specific heat capacity (J/kg·K)
- ΔT is the change in temperature (K)

*Mass is considered as 10kg from boundary conditions for all discs of different materials.

The above provided equations are solved for the properties provided in table 1.

(Table 2. Thermal Calculations on the brake disc design)

	Heat Conduction (W/m ²)	Heat Capacity (J)	Thermal Diffusivity (m ² /s)
Metal Iron	−26100	2668000	1.25E-05
Carbon-Ceramic	−20300	7830000	1.03E-05
Carbon-Carbon	−29000	8120000	1.98E-05

The results of the calculations are then plotted in (Table 2). The crux of the theoretical study highlights the behavior of each material disc, conducting the calculations before the simulation study helps identify the fundamentals of the situation and also confirms the validity and correctness of our simulations.

1.2.2 Theoretical Proof

Higher thermal diffusivity implies faster heat dissipation:

- **Carbon-Carbon** has the highest thermal diffusivity, indicating it will dissipate heat the fastest.

- **Carbon-Ceramic** also shows the least thermal diffusivity due to a relatively lower thermal conductivity.
- **Metal Iron** has a moderate thermal diffusivity.

Comparison of Heat Dissipation

Using the calculated thermal properties and diffusivity, we can deduce that Carbon-Carbon brake discs, with their high thermal conductivity and diffusivity, will dissipate heat more effectively than Carbon-Ceramic and Metal Iron discs. This is critical for high-performance applications like Formula 1, where rapid heat dissipation is essential.

1.3 Problem statement

The scope of this project aims to not only benefit the motorsport industry, but also through discovering new insights, contributes to the safety and effectiveness of road-going vehicles in the automotive industry.

One of the many reasons that material evolution is needed in the brake rotors is because of higher thermal shock and mechanical resistance. In basic physics terms, a brake rotor of larger diameter, due to its larger surface area, contributes to not only to more stopping power because of the bigger contact surface of the brake pad and rotor area, but also higher thermal boundary, thus higher heat holding capacity.

However, there are many instances or scenarios where a larger diameter brake rotor cannot be fitted, most commonly due to the limitation in size of the vehicle wheel diameter, the design of the brake caliper and manufacturing cost etc. In such scenarios where the size of the brake rotor is fixed and cannot be changed, it derives the need for brake rotor material change.

1.4 Objective

The primary objective of this study is to conduct a comparative analysis of the thermal and mechanical performance of the three distinct brake disc materials of Metal-Iron, Carbon-Ceramic and Carbon-Carbon, which are widely used in motorsport applications. This study aims to evaluate how each material responds to high-stress conditions typical of racing environments, with focus of key performance indicators such as heat dissipation, thermal fatigue and deformation.

Using ANSYS Mechanical for simulations, the study seeks to model the behaviour of these materials under conditions that replicate full-braking scenarios in a race vehicle travelling at high speeds. The objective is to assess the overall performance of each material and understand the potential implications of their unique properties on braking efficiency and durability in motorsport settings.

The initial part of the simulation employs the Single Stop Temperature Rise (SSTR) approach, focusing on the typical lower operating temperatures, the software simulation

from ANSYS Mechanical create a full scenario where a vehicle at constant speed, in a full-braking manner, creates heat in the rotating brake disc. The simulation then takes the temperature to elevated levels with the aim to explore the behaviour of these materials under more extreme conditions and find out the limitations of each material and to assess performance degradation under intensified thermal stress. Lastly, the study includes a detailed circuit-based simulation analysis using data exported from a realistic race simulation. The approach integrates telemetry data from the Imola circuit to provide a more practical assessment of each brake disc material under racing conditions. This comprehensive methodology ensures that the comparative analysis captures a wide range of thermal and mechanical stress, to provide insights into the suitability of each material in motorsport applications.

1.5 Delimitation

This research primarily focuses on comparing the thermal, material and mechanical performances of the three different brake disc materials, which are metal-iron, carbon-ceramic and carbon-carbon. The scope of this study was refined to provide a comparative analysis of these three widely used materials in motorsport applications. The study relies on simulation tools such as ANSYS Mechanical and Assetto Corsa Competizione to model and analyse the behaviour of these materials under high-stress conditions typical of motorsport environments.

While these tools provide valuable insights, it is important to acknowledge the inherent limitations and potential inaccuracies in the simulation process. The CAD model, material parameters and environmental conditions used in the simulations may not fully replicate real-world scenarios. Consequently, the results, while logical and aligned with established theories, should be interpreted with caution.

The decision of using ANSYS Mechanical to perform thermal-mechanical simulations instead of real-life testing as methodology was chosen due to the limitations in laboratory facilities, including the unavailability of a dynamometer test rig and the challenges associated with acquiring brake rotors of identical size (outer diameter, inner diameter, total surface area and thickness) and varying materials. Additionally, the specific contents and compositions of carbon-carbon brake discs are largely classified information by manufacturers which might give potential complications when identifying theories. Furthermore, multiple types of carbon-ceramic brakes exist in the industry, such as CCM (Ceramic Composite Material) and CCB (Carbon Ceramic Brakes) technologies (CarbonCeramicBrakes, 2024), as discussed in this study. Each type of Carbon-Ceramic brakes varies in its composition and performance characteristics, which could lead to differences in the end result of how these materials behave under stress. Those variations are something that this study's simulation may not fully or capable to capture.

As a result, the material properties taken from the ANSYS material database, although from the most updated 2024 R2 version and constantly being updated with industrial standards, only provides general insights and cannot capture those variations of specific contents in real-world brake disc products. This means the simulations may not entirely reflect the performance of actual carbon-carbon and carbon-ceramic discs used in high-level motorsport.

From a critical analysis perspective, this study recognises that no experimental or simulation process is perfect. There may be gaps and inaccuracies in the data, particularly when comparing simulation results to real-world performance due to the complexity of reverse engineering different types of data. These potential discrepancies are accounted for in the analysis, with the focus of outcome on identifying trends and patterns that remain consistent with established theories and previous research.

While the absolute values obtained from the simulation may not be entirely accurate, the general trends observed in the behaviour of different materials provide valuable insights and continuation of previous studies. These trends are consistent with theoretical expectations of initial analytical approaches and support the broader understanding of how different brake disc materials perform under extreme conditions.

1.6 Methodology

This research employs a robust methodology combining simulations and previous experimental results to investigate the thermal and material properties of different brake disc materials. Utilizing software like ANSYS for simulations, the study aims to mirror the extreme environments of motorsport applications and predict how different materials respond to such conditions. Complementary experimental testing will validate these computational models. This chapter details the experimental setup, the parameters set for the simulations, and the criteria for evaluating outcomes, ensuring a systematic approach to understanding the comparative performance of each brake disc type. By integrating both theoretical and empirical approaches, the methodology seeks to provide a comprehensive analysis of the thermal and material behaviors of the brake discs under study.

Use of ANSYS Mechanical for simulating in a scenario where a car is cruising, then heavy braking was applied, thus heating up the rotating brake disc. The thermal analysis projects how quickly each brake discs dissipate heat and also which disc helps in better braking. The simulation from ANSYS Mechanical will be able to show the mechanical integrity and also thermal properties. While the actual experiment will be used to cross-checked thermal dissipation, ultimately proving that the simulation-based results for the brake disc integrity and thermal properties are accurate.

1.6.1 Brake Thermal Analysis Using Computational Methods

The idea of using computational methods for brake thermal analysis such as FEA is discussed by (Day & Bryant, 2022). The use of FEA enables the prediction of bulk component temperature, stress and deformation profiles with much higher accuracy and realism than traditional analytical methods. The use of FEA allows for detailed modelling of component geometry, material properties and boundary conditions to simulate hard to achieve real-world thermal and mechanical behaviours.

1.6.2 Failure criteria Prediction using analytical methods

Analytical methods for predicting material failure have been used for many years. The failure criteria for brake discs can be determined based on reaching a critical stress value or a maximum allowable deformation. The critical/working stress is the safe stress that is taken within the elastic range of the material (Mechanical Engineering Online, 2016).

We consider the critical stress ($\sigma_{critical}$) values for the 3 different brake disc materials as the foundational predictor of their performance under high thermal and mechanical stress.

The governing equation for calculating critical stress can be expressed by the formula:

$$\sigma_{critical} = \frac{\sigma_{yield}}{Safety\ Factor}$$

(Eq 5.0)

Where:

- $\sigma_{Critical}$ is the critical stress or working stress.
- σ_{yield} is the yield strength of the material
- Safety Factor is typically chosen based on the application requirements (usually between 1.5 and 2)

Metal Iron:

Tensile Yield Strength (σ_{yield}): 2.5×10^8 Pa

(Data from **Fig.3***)

Safety Factor: 1.5

$$\sigma_{Critical} = \frac{\sigma_{yield}}{Safety\ Factor} = \frac{2.5 \times 10^8\ Pa}{1.5} = 1.67 \times 10^8$$

Carbon-Ceramic:

Tensile Yield Strength (σ_{yield}): 2.9×10^9 Pa

(Data from **Fig.4***)

Safety Factor: 1.5

$$\sigma_{Critical} = \frac{\sigma_{yield}}{Safety\ Factor} = \frac{2.9 \times 10^9\ Pa}{1.5} = 1.93 \times 10^9$$

Carbon-Carbon:

Tensile Yield Strength (σ_{yield}): 3.5×10^9 Pa

(Data from **Fig.5***)

Safety Factor: 1.5

$$\sigma_{Critical} = \frac{\sigma_{yield}}{Safety\ Factor} = \frac{3.5 \times 10^9\ Pa}{1.5} = 2.33 \times 10^9$$

These critical stress values indicate that Carbon-Carbon and Carbon-Ceramic materials can endure significantly higher stress before approaching failure, compared to Metal Iron.

These analytical results provide an early indication of how each material might behave under the high thermal and mechanical loads experienced in later simulations. Metal-Iron, with the lowest critical stress, is predicted to experience the greatest deformation under similar stress conditions.

In contrast, the Carbon-based materials, with their much higher critical stress values, demonstrate a greater capacity to withstand far more stress without undergoing significant

deformation, at least not under similar mechanical and thermal conditions as metal iron. This suggests that even under prolonged high-temperature conditions, Carbon-Ceramic and Carbon-Carbon discs should be less likely to reach the point of structural compromise, with Carbon-Carbon ranking even slightly above Carbon-Ceramic.

However, it's important to note that these critical stress values represent idealised conditions which is why further simulations are needed to be done. In real-world applications, factors such as thermal fatigue, microstructural flaws, and repeated cyclic loading could cause deviations from this theoretical approach.

1.6.3 Single Stop Temperature Rise (SSTR) and Thermal Analysis

A key component of this thermal analysis is the Single Stop Temperature Rise method which will be employed primarily in the first phase of this research's simulation. This method simulates the temperature increase of a brake disc during a single braking event in this study, ANSYS simulations were used to replicate the SSTR approach, by applying 50,000N on each side of the brake disc at a rotational speed of 209.44 rad/s. The temperature rise was observed over time, and the bulk temperature rise $\Delta\theta$ was calculated with the following equation, as suggested by (Day & Bryant, 2022):

$$\Delta\theta = \frac{Q}{mC_p}$$

(Eq 4.1)

Where:

Q is the heat energy generated during braking (J)

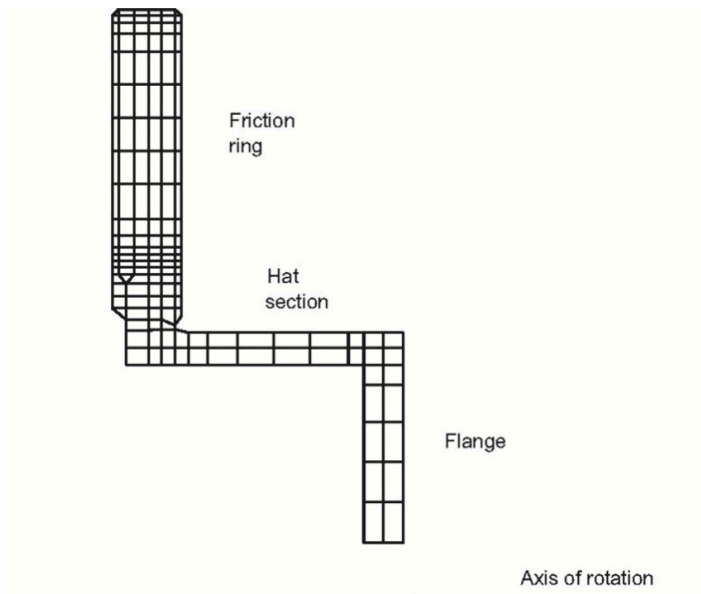
m is the mass of the brake component (kg)

C_p is the specific heat capacity of the material

This equation suggested by (Day & Bryant, 2022) of calculating the rise in bulk temperature validates the equation of (Eq 4.0) $Q = mc\Delta T$ in the previous section. As outlined by (Day & Bryant, 2022), this calculation of bulk temperature rise is essential for predicting the thermal performance of brake discs under high-stress conditions. In fact, from the 2D axisymmetric FEA brake disc modelled by (Day et al, 1991) that was described by (Day & Bryant, 2022), the frictional heat input assumed that 98.4% of the total braking energy enters the disc. Numerical calculations of temperature typically employ axisymmetric models, which are effective in predicting temperature distribution in braking systems (Talati and Jalalifar 2008, 2009) (Yevtushenko and Grzes 2014). Below shows the boundary conditions (Table 3) and the FEA brake disc model (**Fig. 1**) modelled by (Day et al 1991).

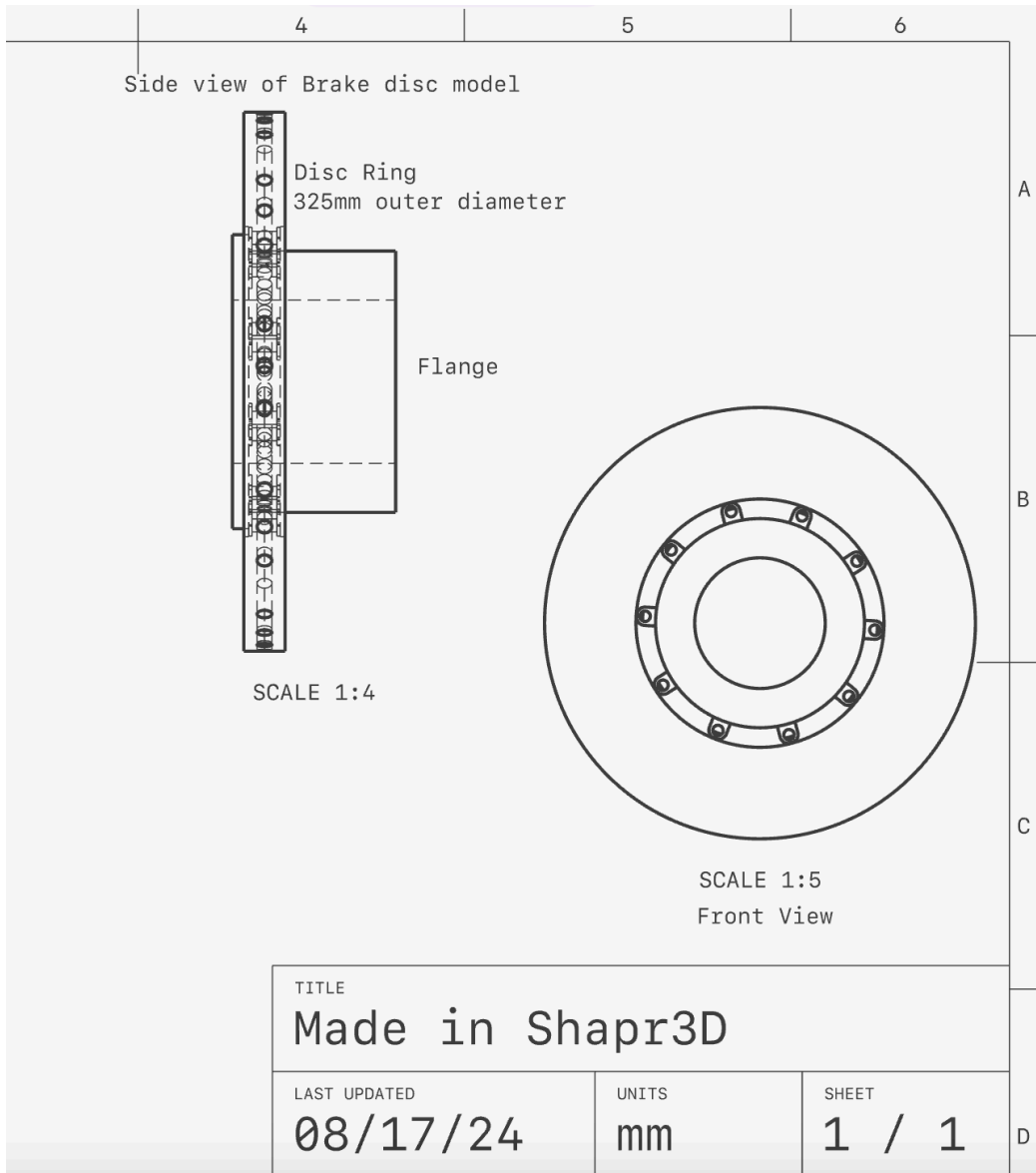
(Table 3. Vehicle Boundary Conditions used by FEA simulations of Day et al., 1991)

Vehicle characteristics	
Vehicle mass	1300 kg
Brake force distribution X_1/X_2	66/34
Brake application characteristics	
Initial vehicle speed	100 km/h (28 m/s)
Final vehicle speed	0
Duration of brake application	4 s
Average deceleration	7 m/s ² (0.7 g)
Initial brake temperature	20°C
Front brake discs (Solid)	
Disc outer diameter	227 mm
Disc ring inner diameter	127 mm
Disc thickness	11 mm
Total disc mass	3 kg
Disc ring mass	2.2 kg



(Figure 1. 2D axisymmetric FEA brake disc model, Day et al., 1991)

The model developed in this study (**Fig.2**) thus closely resembles the 2D axisymmetric FEA brake disc model described by (Day et al., 1991). Both models utilize a friction ring and hat section to accurately represent the geometry of the brake disc and simulate its response to thermal and mechanical loads in a similar manner.



(Figure 2. 2D visualisation of brake disc model used in the ANSYS FEA simulation)

The boundary conditions listed in the next section applied in this simulation also took reference to the vehicle characteristics highlight by (Day & Bryant, 2022). The vehicle mass, brake force distribution and brake application parameters were considered when setting up the simulation. In specific, reference was made to the vehicle's initial speed, average deceleration to ensure that the simulation reflects realistic operating conditions. These parameters were critical in determining the heat generation and distribution across the brake disc during the simulated braking event.

1.7 Design of Experiment

1.7.1 Evaluation of ANSYS Mechanical FEA approach

Finite Element Analysis is a computational technique that is widely used in the engineering field to predict how structures work and behave under various physical conditions. ANSYS Mechanical, which is a leading FEA software, offers robust tools for detailed thermal and mechanical analysis.

Detailed Procedure for analysis

1. Geometry and Mesh Generation

Create Geometry:

- Model the brake disc and brake pad geometry in ANSYS.
- Ensure accurate dimensions, especially for the 325 mm outer diameter disc.

Mesh Generation:

- Apply a fine mesh to capture the temperature gradients and stress distribution accurately.
- Use tetrahedral elements for complex geometries.

2. Material Assignment

Define Materials:

- Assign the predefined material properties to the brake disc and brake pad.

Material Properties:

All material properties values have been extracted from the latest version of ANSYS 2024 R2 workbench database (shown below)

Properties of Outline Row 5: Metal Iron			
	A	B	C
1	Property	Value	Unit
2	Material Field Variables	Table	
3	Density	7800	kg m ⁻³
4	Isotropic Secant Coefficient of Thermal Expansion		
5	Coefficient of Thermal Expansion	1.1E-05	C ⁻¹
6	Isotropic Elasticity		
7	Derive from	Young's Modulus and Poisso...	
8	Young's Modulus	2.1E+11	Pa
9	Poisson's Ratio	0.28	
10	Bulk Modulus	1.5909E+11	Pa
11	Shear Modulus	8.2031E+10	Pa
12	Tensile Yield Strength	2.5E+08	Pa
13	Compressive Yield Strength	0	Pa
14	Tensile Ultimate Strength	2.5E+08	Pa
15	Compressive Ultimate Strength	8.2E+08	Pa
16	Isotropic Thermal Conductivity	45	W m ⁻¹ K ⁻¹
17	Specific Heat Constant Pressure, C _p	460	J kg ⁻¹ K ⁻¹

(Figure 3. Material properties of metal iron)

Properties of Outline Row 4: Carbon-Ceramic			
	A	B	C
1	Property	Value	Unit
2	Material Field Variables	Table	
3	Density	2500	kg m ⁻³
4	Isotropic Secant Coefficient of Thermal Expansion		
5	Coefficient of Thermal Expansion	2.5E-06	C ⁻¹
6	Isotropic Elasticity		
7	Derive from	Young's Modulus and Poisso...	
8	Young's Modulus	2.5E+10	Pa
9	Poisson's Ratio	0.2	
10	Bulk Modulus	1.3889E+10	Pa
11	Shear Modulus	1.0417E+10	Pa
12	Tensile Yield Strength	2.9E+09	Pa
13	Compressive Yield Strength	0	Pa
14	Tensile Ultimate Strength	3E+09	Pa
15	Compressive Ultimate Strength	8.2E+09	Pa
16	Isotropic Thermal Conductivity	35	W m ⁻¹ K ⁻¹
17	Specific Heat Constant Pressure, C _p	1350	J kg ⁻¹ K ⁻¹

(Figure 4. Material properties of Carbon-Ceramic)

Properties of Outline Row 3: Carbon-Carbon			
	A	B	C
1	Property	Value	Unit
2	Material Field Variables	Table	
3	Density	1800	kg m ⁻³
4	Isotropic Secant Coefficient of Thermal Expansion		
5	Coefficient of Thermal Expansion	3.3E-06	C ⁻¹
6	Isotropic Elasticity		
7	Derive from	Young's Modulus and Poisso...	
8	Young's Modulus	3E+10	Pa
9	Poisson's Ratio	0.3	
10	Bulk Modulus	2.5E+10	Pa
11	Shear Modulus	1.1538E+10	Pa
12	Tensile Yield Strength	3.5E+09	Pa
13	Compressive Yield Strength	0	Pa
14	Tensile Ultimate Strength	3.6E+09	Pa
15	Compressive Ultimate Strength	8.2E+09	Pa
16	Isotropic Thermal Conductivity	50	W m ⁻¹ K ⁻¹
17	Specific Heat Constant Pressure, C _p	1400	J kg ⁻¹ K ⁻¹

(Figure 5. Material properties of Carbon-Carbon)

- Metal Iron: Density 7800 kg/m³, Thermal Conductivity 45 W/m·K, Specific Heat 460 J/kg·K.
- Carbon-Ceramic: Density 2500 kg/m³, Thermal Conductivity 35 W/m·K, Specific Heat 1350 J/kg·K.
- Carbon-Carbon: Density 1800 kg/m³, Thermal Conductivity 50 W/m·K, Specific Heat 1400 J/kg·K.
- Brake Pad (Carbon-Carbon): Add as a custom material if not predefined.

3. Boundary Conditions

Thermal Analysis:

- Apply initial temperature of 20°C.
- Apply thermal load to simulate braking, increasing the temperature to 600°C.
- Convection boundary conditions to simulate heat dissipation to the surroundings.

- Convection Coefficient: $20 \text{ W/m}^2 \cdot \text{K}$.
- Mass is considered as 10kg on an average for all discs of different materials

Structural Analysis:

1.7.2 Calculation of Rotational velocity from specified RPM

1. Convert RPM to revolutions per second (RPS):

$$\text{RPS} = \text{RPM}/60 = 2000/60 \approx 33.33 \text{ revolutions per second}$$

2. Convert revolutions per second to radians per second:

$$\text{Rotational velocity (rad/s)} = \text{RPS} \times 2\pi \approx 33.33 \times 2\pi \approx 209.44 \text{ rad/s}$$

Thus, the rotational velocity of the disc at 2000 RPM is approximately **209.44 rad/s**.

- Apply rotational velocity: For 2000 RPM, rotational velocity is approximately 209.44 rad/s.
- Apply frictional contact between the brake disc and brake pad.
- Coefficient of friction for metal iron: 0.35.
- Constraint boundary conditions at the disc's mounting points.

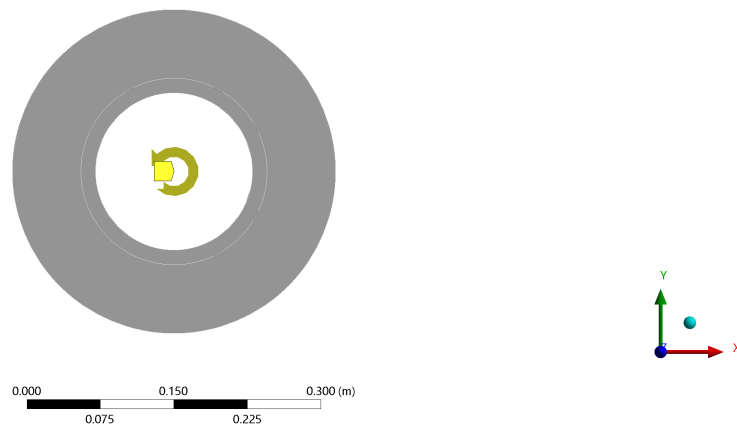
B: Static Structural

Rotational Velocity

Time: 1. s

27/07/2024 1:11 pm

Rotational Velocity: 200. rad/s
Location: 2.3624e-010, -2.3667e-010, -1.265e-002 m



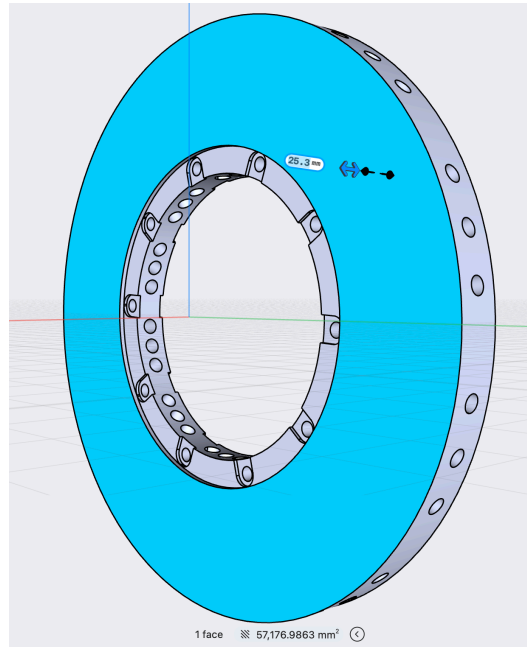
(Figure 6. ANSYS workspace screenshot of the rotational direction and velocity)

1.7.3 Brake Rotor modelling

In order to simulate the brake rotors in ANSYS Mechanical, the brake rotor is being modelled in CAD software, Shapr3D. The brake rotor used in the simulation is modelled after a 325 mm diameter, 25.3 mm thick carbon-carbon brake disc manufactured by HITCO.



(Figure 7. Original brake rotor sample used for modelling)



(Figure 8. Brake rotor modelled in Shapr3d)

1.7.4 Brake Pad modelling



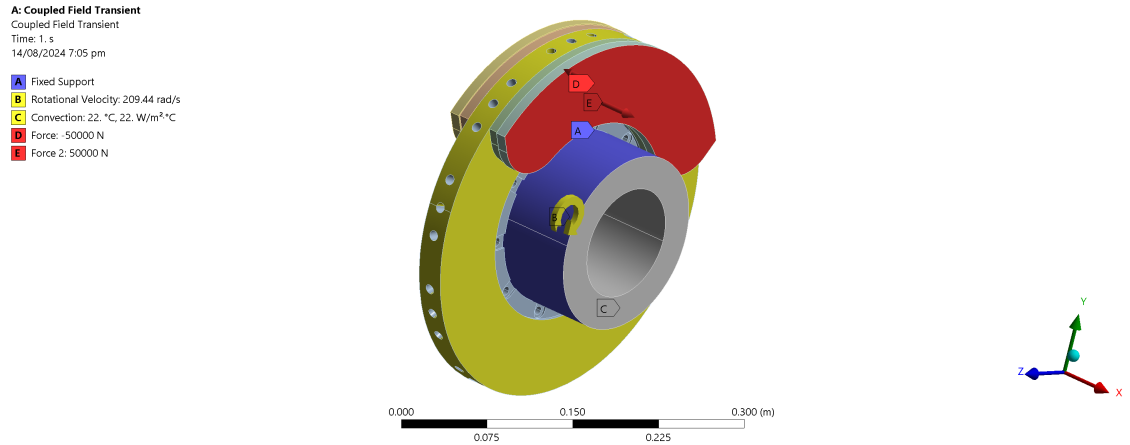
(Figure 9. Original brake pad sample used for modelling)



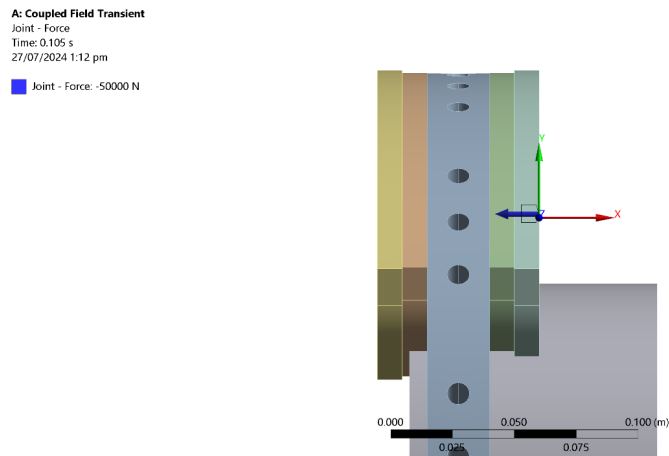
(Figure 10. Brake pad modelled in Shapr3d)

1.7.5 Brake system design (components)

To simulate the braking force for each brake discs, the setup of the brake system is shown below in the following figure. Both sides of the brake disc have been applied 50000 N of force to simulate braking force.



(Figure 11. Brake system design illustration 3D view)



(Figure 12. Brake system design illustration side view showing back-plate, pad friction material and disc)

2.0 Validation of ANSYS Thermal Simulation

To validate the ability and accuracy of ANSYS thermal simulation, a simple conduction simulation was carried out on a metal rod. The objective was to compare the results of the simulation with theoretical calculations, ensuring that the simulation results align with the expected values.

The schematic representation of the metal rod is shown in **(Fig.13)** with its basic specification listed in (Table 4.) A metal rod of length 3.0m and diameter of 0.2m was considered. The temperature at one end (T1) was set to 200°C, while the other end (T2) was at 50°C. The thermal conductivity K of the material is 60.5 W/mK. Cross-sectional area (A) was calculated using the formula $A = \pi r^2$. So $A = \pi \times (\frac{D}{2})^2$, equals 0.031416 m².



(Figure 13. 2D Schematic representation of the sample metal rod)

(Table 4. Specification of sample test metal rod)

Thermal Conductivity (K)	60.50 W/mK
Cross-Sectional Area (A)	0.031416 m ²
Hot side temperature End 1 (T1)	200.00°C
Cold side temperature End 2 (T2)	50.00°C
Length (L)	3.00 m
Diameter (D)	0.20 m

The theoretical heat transfer Q was determined using Fourier's thermal conduction formula:

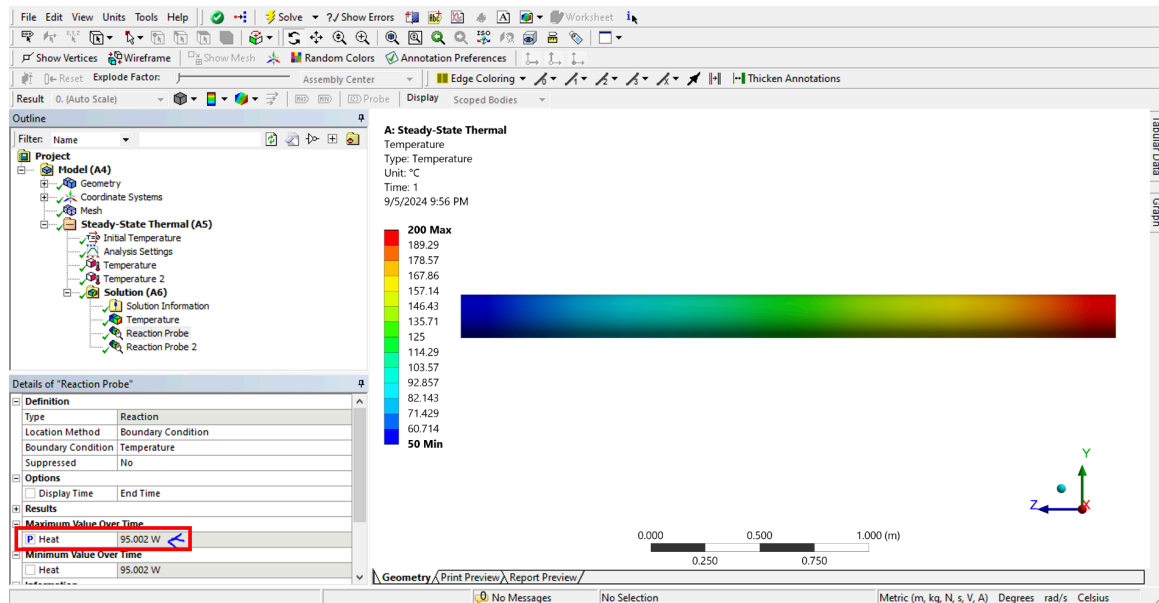
$$Q = \frac{k \cdot A \cdot (T1 - T2)}{L}$$

Where:

- k is the thermal conductivity (W/mK)
- A is the cross-sectional area
- $T1$ and $T2$ are the temperatures at the two ends of the rod
- L is the length of the rod

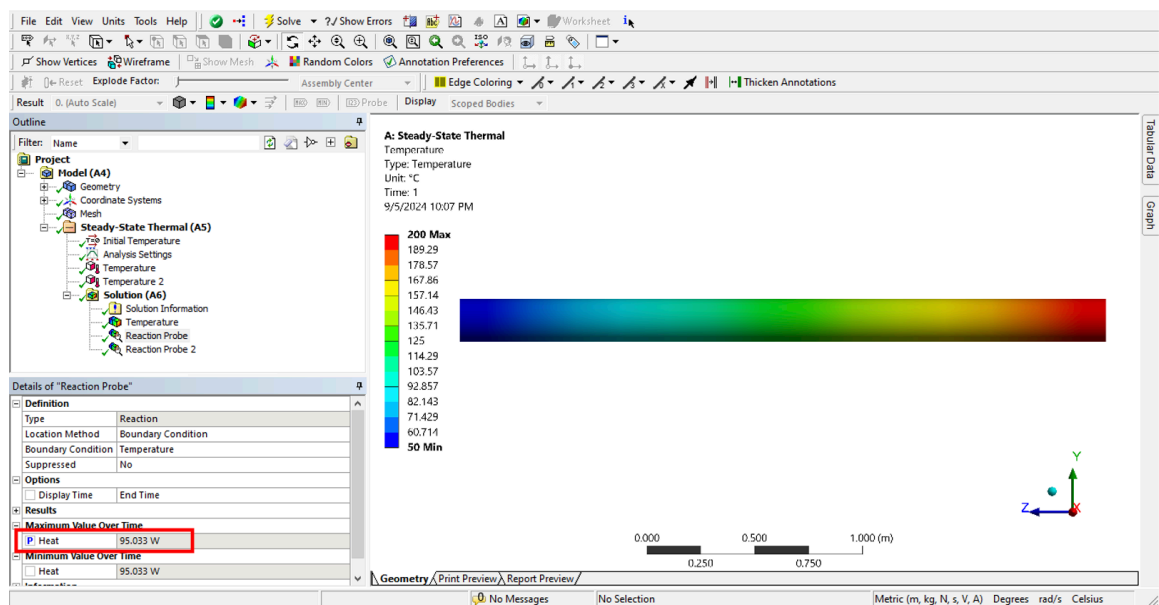
Plugging in the values into the formula calculates a thermal conductivity value to be 95.03317777 W.

The same case is then simulated in the ANSYS Thermal Analysis Module. The following results were obtained for:



(Figure 14. Heat Transfer for maximum mesh size of 0.1m, showing 95.002W.)

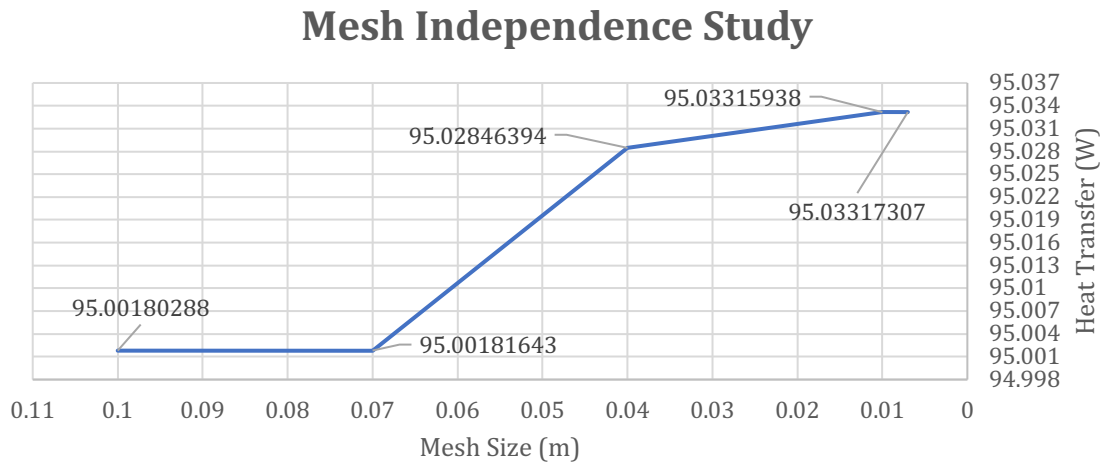
(Fig. 14) shows the heat transfer result obtained with a mesh size of 0.1m. The simulation yielded a heat transfer rate of 95.002 W, closely aligning with the theoretical value.



(Figure 15. Heat Transfer for maximum mesh size of 0.007m, showing 95.033W.)

Further refinement of the mesh size to 0.007m, shown in **(Fig. 15)**, shows tiny improvement in accuracy, resulting in heat transfer rate of 95.033W, but still nearly identical to values obtained in **(Fig.14)** and to the theoretical calculation.

A detailed mesh independence study of varying mesh sizes was conducted to see how the results vary based on the mesh. **(Fig.16)** shows the graph that gives mesh independent results.



(Figure 16. Mesh Independence study graph showing varying mesh size vs heat transfer results)

The mesh independence study graph shows how varying the mesh size can affect the accuracy of the heat transfer results. However, after a certain size, there isn't too much more accuracy to be gained, which is already close to the theoretical value calculated up to 4 decimal places.

This validation confirms that the simulations carried out by ANSYS is accurate and can be considered reliable in place of the theoretical calculations.

3.0 Results

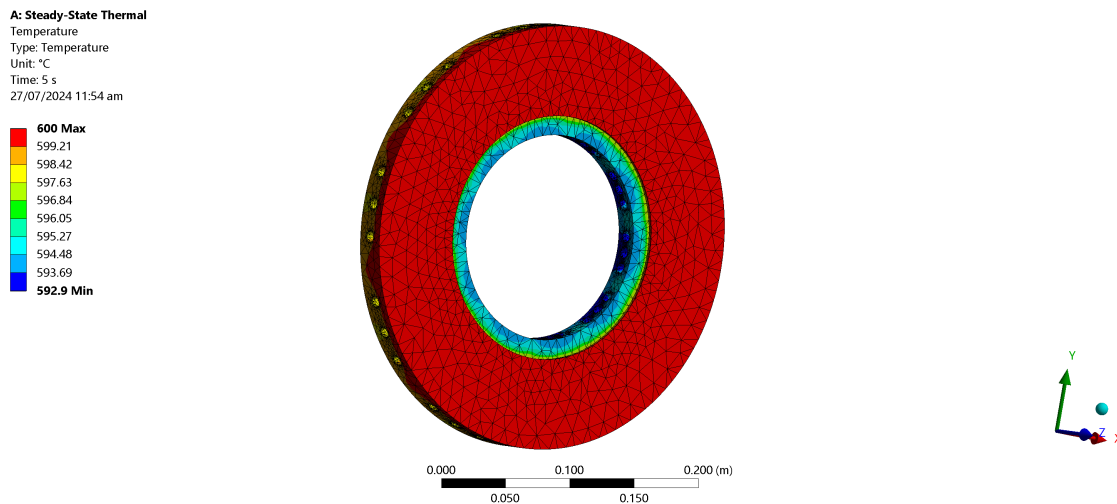
3.1 Preliminary Results

3.1.1 Thermal Performance Simulations

The following data shows the results of the ANSYS thermal simulations carried out on the 3 brake discs. The analysis did not account for the brake pads, instead the same conditions were applied directly to the brake disc.

Temperature Profile: (Braking 50000 N on both sides of the disc surfaces; Revolutions of 209.44 rad/s)

Metal Iron Brake Disc



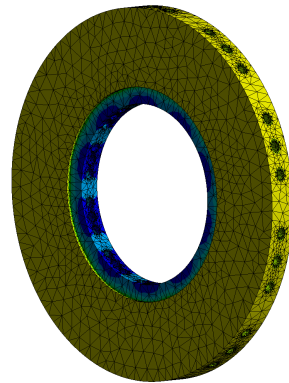
(Figure 17. ANSYS Temperature Profile result of Metal Iron Brake Disc)

For Metal Iron Brake Disc, the temperature contour shows the maximum temperature reached by the brake disc during braking at 600°C.

Carbon-Ceramic Brake Disc

A: Steady-State Thermal
Temperature
Type: Temperature
Unit: °C
Time: 5 s
27/07/2024 12:24 pm

525
524.13
523 Max
521.53
520.67
519.8
518.94
518.07
517.2 Min



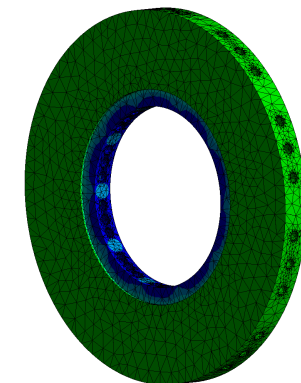
(Figure 18. ANSYS Temperature Profile result of Carbon-Ceramic Brake Disc)

The temperature profile showed the peak temperature reached by Carbon-Ceramic brake disc to be 523°C.

Carbon-Carbon Brake Disc

A: Steady-State Thermal
Temperature
Type: Temperature
Unit: °C
Time: 5 s
27/07/2024 12:22 pm

505
503.84
502.68
501.52
500 Max
498.03
496.87
495.71
494.55 Min

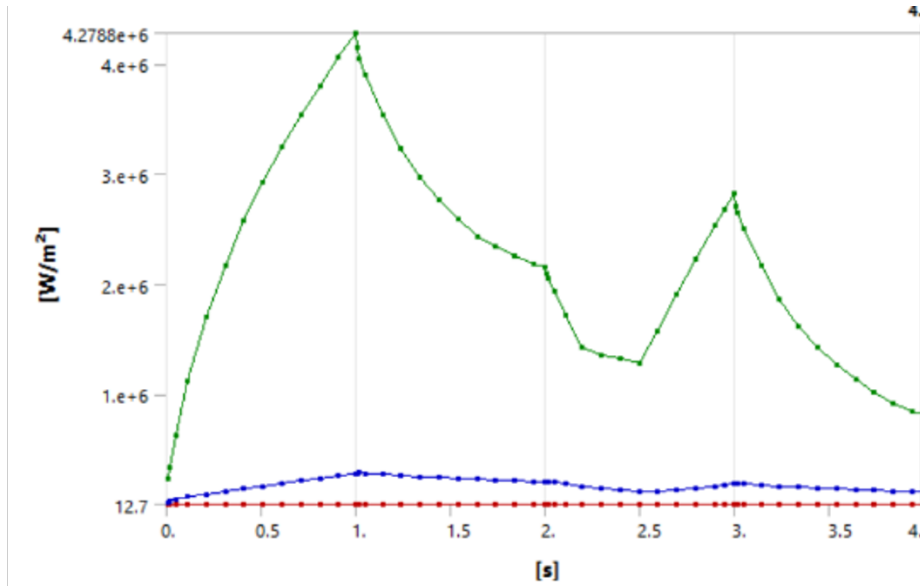


(Figure 19. ANSYS Temperature Profile result of Carbon-Carbon Brake Disc)

The maximum temperature shown in the temperature contour reached for Carbon-Carbon brake disc is 500°C.

3.1.2 Heat Dissipation

Metal Iron Brake Disc

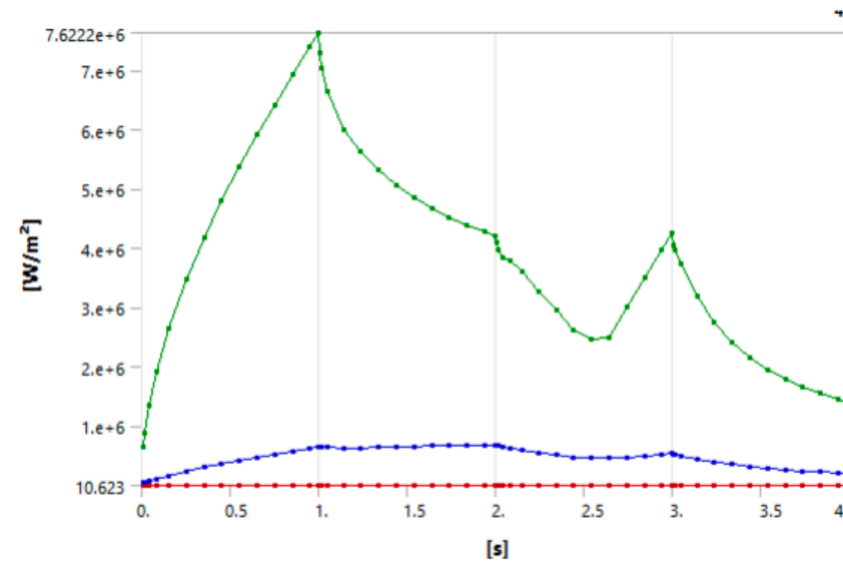


(Figure 20. ANSYS Heat flux result of Metal Iron Brake Disc)

The graph above denotes the heat flux generated by the Metal Iron Brake Disc during braking. The green line highlights the variation of heat flux.

Maximum Heat flux generated in Metal Iron disc is 4.2788E6 W/m².

Carbon-Ceramic Brake Disc

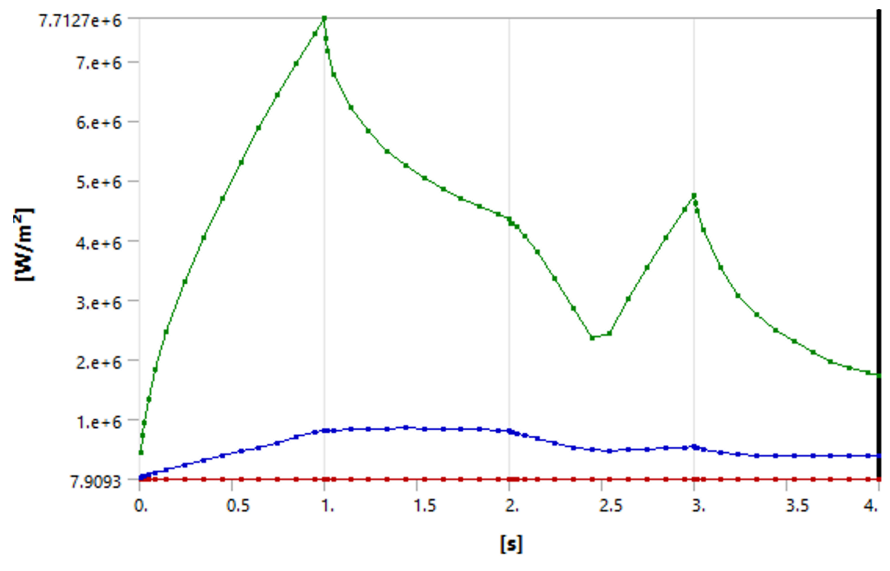


(Figure 21. ANSYS Heat flux result of Carbon-Ceramic Brake Disc)

The graph above denotes the heat flux generated by the Carbon-Ceramic Brake Disc during braking. The green line highlights the variation of heat flux

Maximum Heat flux generated in Metal Iron disc is 7.6222E6 W/m².

Carbon-Carbon Brake Disc



(Figure 22. ANSYS Heat flux result of Carbon-Carbon Brake Disc)

The graph above denotes the heat flux generated by the Carbon-Carbon Brake Disc during braking. The green line highlights the variation of heat flux

Maximum Heat flux generated in Metal Iron disc is 7.7127E6 W/m².

From the thermal analysis, it can be concluded that:

For Metal iron brake disc:

- Maximum temperature is the highest at 600°C.
- Heat dissipation is low at 4.2788E6 W/m².
- Thermal Conductivity is medium at 45 W/mK.

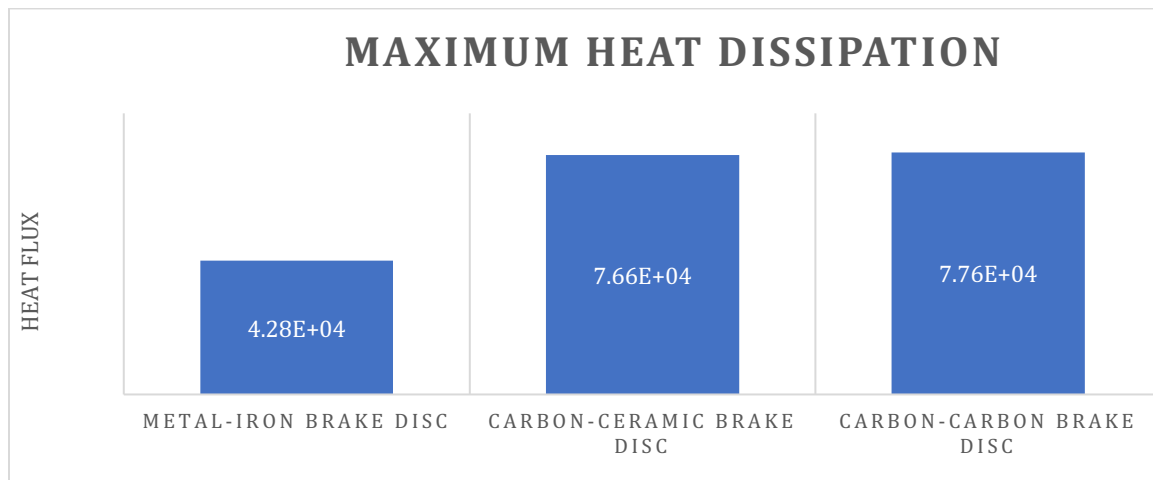
For Carbon-Ceramic brake disc:

- Maximum temperature is medium at 523°C.
- Heat dissipation is medium at 7.6222E6 W/m².
- Thermal Conductivity is low at 35 W/mk.

For Carbon-Carbon brake disc:

- Maximum temperature is the lowest at 500°C.
- Heat dissipation is high at 7.7127E6 W/m².
- Thermal Conductivity is high at 50 W/mK.

To better illustrate the max heat dissipation, the data has been put in a chart.



(Figure 23. Maximum Heat Dissipation Chart of the 3 materials)

3.2 Discussion of Thermal Performance Simulations

Based on the preliminary thermal performance simulations, the results highlight significant differences between how metal iron, carbon-ceramic and carbon-carbon brake discs respond to the same applied braking force of 50,000 N.

The importance of the maximum temperature simulation lies in its ability to reveal the heat conductivity and thermal performance of each brake disc material under identical braking conditions. In motorsport, maintaining a lower disc temperature is crucial as it provides more room of thermal capacity and prevent overheating, thus ensuring consistent performance throughout a race. The simulations show that while metal iron brake reached a high temperature of 600°C, carbon-ceramic and carbon-carbon discs remained significantly cooler, at 523°C and 500°C respectively, indicating superior thermal management.

According the thermal properties, the metal iron brake disc, with its moderate thermal conductivity of 45 W/mK and lower specific heat capacity of 460 J/kgK, struggles to dissipate the heat generated during braking as effectively as its carbon-based counterparts. This higher temperature is a direct result of these thermal properties, which limit its ability to manage heat under sustained braking conditions.

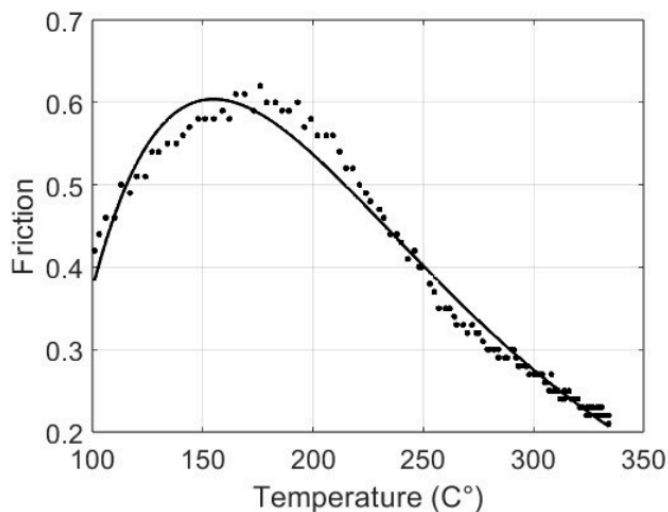
In contrast, the carbon-carbon brake disc, which features higher thermal conductivity of 50 W/mK and specific heat capacity of 1400 J/kgK demonstrates a much lower maximum temperature, which reflects its superior ability to dissipate heat. The carbon-ceramic disc, while slightly less effective than carbon-carbon, still outperforms metal iron due to its better thermal conductivity of 35 W/mk. These properties of the carbon-based discs are

crucial to managing heat more effectively, preventing excessive temperature build-up that could lead to thermal fatigue and failure.

The results of the heat dissipation simulation patterns further support these observations. The metal iron brake disc exhibited the lowest heat dissipation, which correlates with its higher temperature, while the carbon-carbon disc showed the highest heat dissipation, which is consistent with its superior thermal performance. The results align with established literature that emphasizes the importance of high thermal conductivity and specific heat capacity in brake materials, particularly in high-performance applications where rapid heat dissipation is required.

However, it's important to note that the lower rate of heating in carbon-ceramic and carbon-carbon brake discs, although beneficial in preventing thermal fatigue, can also mean that these discs may not reach their optimal operating temperature as quickly, especially in a vehicle of lighter mass and in rainy weather. The slower heating could result in lower initial friction (μ), highly affecting braking efficiency during the early stages of a race. Therefore, while these materials offer better thermal performance, usage of them also require careful consideration and monitoring to ensure they deliver the desired friction properties when needed most.

Studies like (Bellini et al.,2023) has performed physical tests with result (**Fig. 24**) showing that the friction coefficient (μ) generally for disc brakes follows the trend of increasing with temperature, reaching at optimal levels within a specific temperature range, then dropping again once it reaches the thermal headroom. However, at lower temperatures, such that those experienced before reaching operating temperature, the friction coefficient may be significantly lower, impacting braking performance.



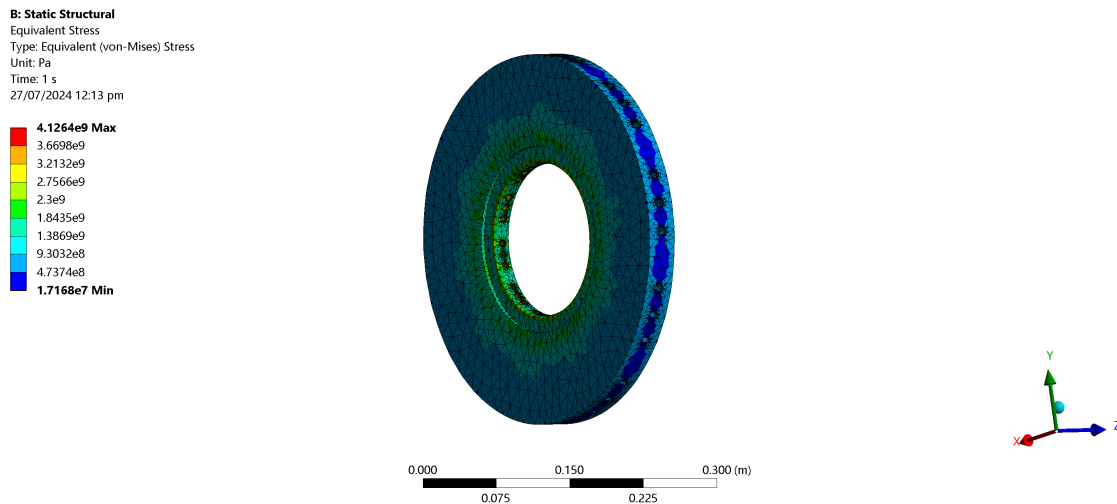
(Figure 24. General disc brake friction coefficient μ vs Temperature graph, Bellini et al.,2023)

3.2.1 Mechanical Performance Simulations

The following data shows the results of the ANSYS mechanical simulations carried out on the 3 brake discs. The analysis did not account for the brake pads, instead the same conditions were applied directly to the brake disc.

Temperature Profile: (Braking 50000 N on both sides of the disc surfaces; Revolutions of 209.44 rad/s)

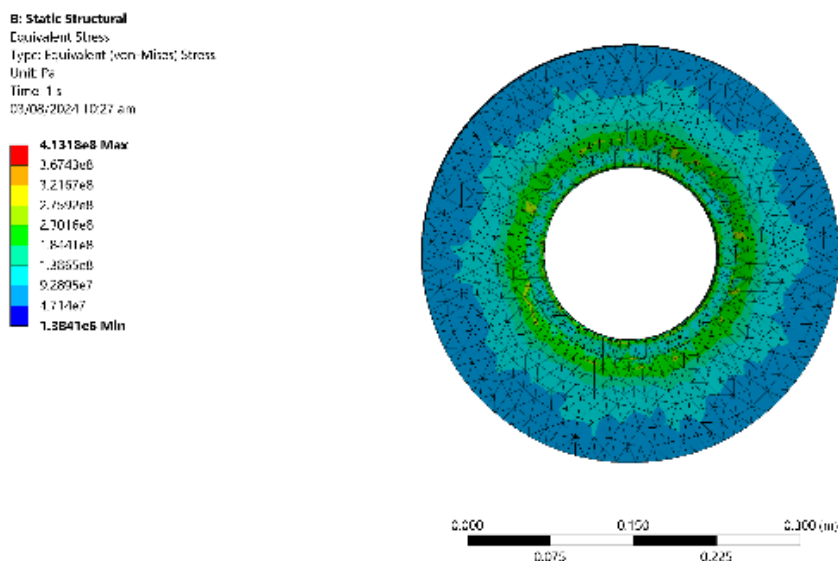
Metal Iron Brake Disc



(Figure 25. ANSYS Stress Profile result of Metal Iron Brake Disc)

The figure above shows the mechanical stress profile of Metal Iron Brake Disc, the maximum stress reached is 4.12E9 Pa.

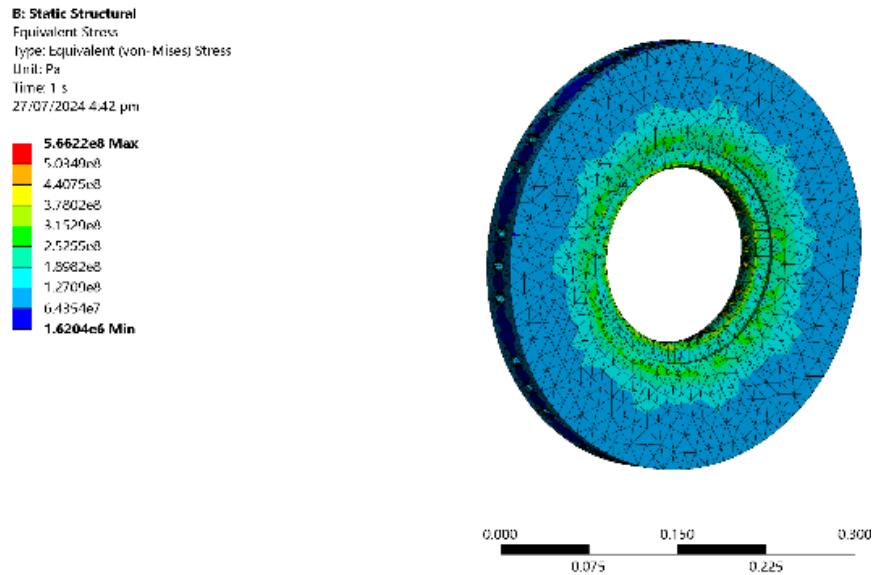
Carbon-Ceramic Brake Disc



(Figure 26. ANSYS Stress Profile result of Carbon-Ceramic Brake Disc)

The figure above shows the mechanical stress profile of Carbon-Ceramic Brake Disc, the maximum stress reached is 4.131E8 Pa.

Carbon-Carbon Brake Disc



(Figure 27. ANSYS Stress Profile result of Carbon-Carbon Brake Disc)

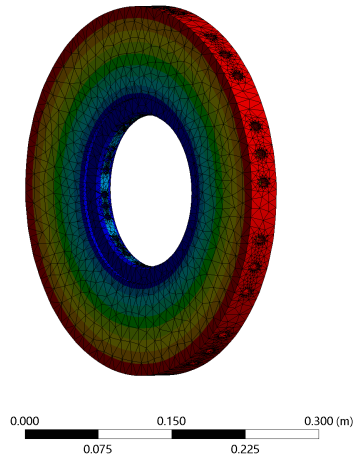
The figure above shows the mechanical stress profile of Carbon-Carbon Brake Disc, the maximum stress reached is 5.6622E8 Pa.

3.2.2 Deformation Profile

Metal Iron Brake Disc

B: Static Structural
Total Deformation
Type: Total Deformation
Unit: m
Time: 1 s
27/07/2024 12:14 pm

0.00068843 Max
0.00061194
0.00053544
0.00045895
0.00038246
0.00030597
0.00022948
0.00015298
7.6492e-5
0 Min



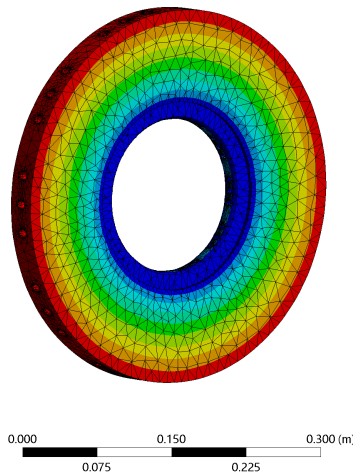
(Figure 28. ANSYS Deformation Profile result of Metal Iron Brake Disc)

The figure above denotes the deformation profile. The simulation results showed the deformation reached to be 0.68mm.

Carbon-Ceramic Brake Disc

B: Static Structural
Total Deformation
Type: Total Deformation
Unit: m
Time: 1 s
27/07/2024 12:28 pm

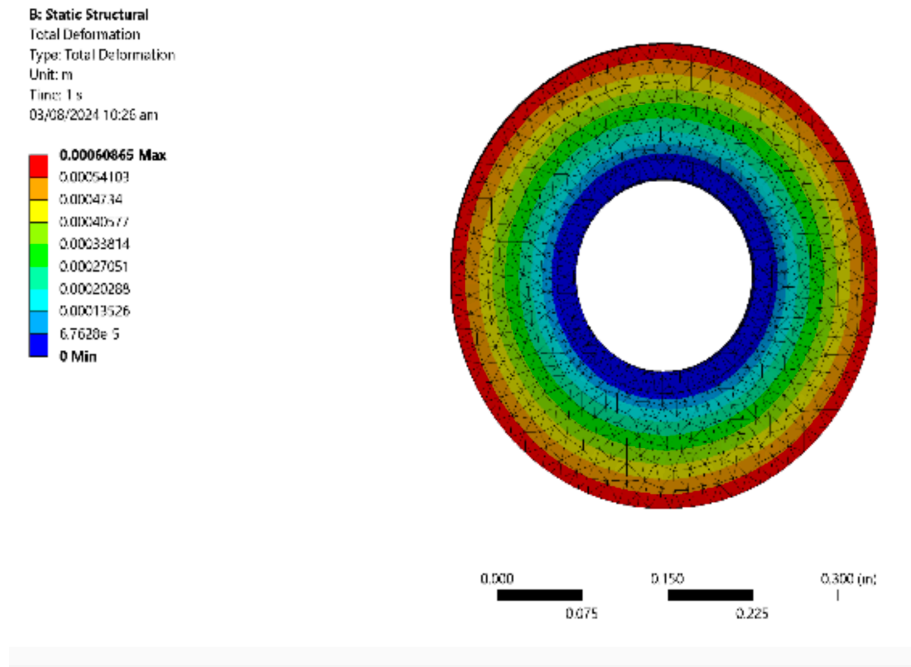
0.00063359 Max
0.00056319
0.00049279
0.00042239
0.00035199
0.0002816
0.0002112
0.0001408
7.0399e-5
0 Min



(Figure 29. ANSYS Deformation Profile result of Carbon-Ceramic Brake Disc)

The figure above denotes the deformation profile. The simulation results showed the deformation reached to be 0.63mm.

Carbon-Carbon Brake Disc



(Figure 30. ANSYS Deformation Profile result of Carbon-Carbon Brake Disc)

The figure above denotes the deformation profile. The simulation results showed the deformation reached to be 0.60mm.

3.3 Discussion of Mechanical Performance Simulations

The mechanical performance simulations provide crucial insights into the structural integrity of the brake discs under high-stress conditions. As friction energy was transferred into the brake disc from the pressure of the friction material, temperature and mechanical stress load increases. The simulation results indicate that the metal iron brake disc experiences the highest maximum stress at $4.12\text{E}9$ Pa, significantly lower than that of the maximum stress observed in the carbon-ceramic counterpart which recorded at $4.131\text{E}8$ Pa and the $5.662\text{E}8$ Pa. This difference in stress profiles suggested the varying capabilities of these materials to withstand mechanical loads during braking.

The lower maximum stress limit experienced by the metal iron brake disc is indicative of its lower resilience to thermal and mechanical load, which is also consistent with the material's moderate thermal properties. This can be attributed to its higher material density, which contributes to the greater inertia and stress under braking forces. In real life scenarios, these continuous and repeated high stress levels exceeding the material's original properties can lead to accelerated wear and potential failure if the material is subjected to

prolonged stress cycles, which will be discussed further in the next section examining thermal fatigue and significant deformation.

Deformation in material occurs when the applied stress exceeds the material's elastic limit, leading to permanent changes in shape. For metal iron, the maximum stress it can endure before deformation begins is closely tied to its yield strength, which is why when the applied stress surpasses this threshold, the metal transitions from elastic deformation to plastic deformation, meaning that permanent changes in shape occur. Once the material deforms plastically, it will begin the process where it no longer maintains its structural integrity, especially under repeated loading conditions.

The lower stress limit experienced by the metal iron brake disc indicates that it is approaching or exceeding its elastic limit, leading to the observed deformation of 0.68mm under the applied load. This deformation is higher compared to the 0.63mm and 0.60mm deformations exhibited by the carbon-ceramic and the carbon-carbon disc samples respectively. The lower deformation in carbon-based discs can be attributed to their higher yield strength and better stress distribution, which allow them to resist permanent shape changes even under significant loads.

The ultimate reason for investigating and understanding both stress levels and deformation is to fully understand the limit of each brake disc's performance. While stress levels exerted on each brake disc provides insights into predicting when the brake disc start its potential failure points. Deformation is however what is ultimately directly impacts the disc's functionality and failure of the braking system. This is why further investigating into the deformation characteristics of metal iron brake discs is necessary, particularly under increased loads and temperatures, to determine the "cut-off" point where deformation becomes too significant for the disc to operate safely.

As part of the ongoing research, additional simulations are conducted in the next section to further explore these deformation thresholds in greater detail. The results of these simulations will be discussed further in the following section, "Thermal Fatigue and the Significance of Deformation".

4.0 Thermal Fatigue and the Significance of Deformation

In this section, focus is shifted into bringing the temperature to 1000°C in order to observe the failure point of metal brake disc.

Thermal fatigue is a critical phenomenon that significantly impacts the performance and longevity of materials subjected to cyclic thermal loading, especially in high stress environments like motorsport. In brake discs, thermal fatigue arises due to the repeated heating and cooling cycles experienced during braking. This continuous fluctuation in temperature induces thermal stresses and over time lead to the formation of microcracks, which can propagate and eventually result in material failure. As stated from (Yevtushenko and Grzes, 2010), high temperatures involved in moving components in a disc brake system can cause deformations and cracks in the disc, degradation of the pad material and excessive wear of the working surfaces. From the results of the preliminary ANSYS mechanical simulations, we could see the lower maximum stress limit that can be withstand by metal iron brake disc in comparison to its carbon-based counterpart until deformation starts.

Previous studies on thermal fatigue primarily focused on metals such as steel and cast iron, as they were the most common type of metal materials used. Researchers like (Wang et al., 2022) and (Mackin et.al, 2002) both explored the mechanisms of crack initiation and propagation in these materials, highlighting the role of thermal stress in accelerating fatigue failure. Their research pointed out on how cyclic thermal loading leads to the accumulation of damage in metal components, ultimately resulting in failure. The research laid theoretical ground of how thermal fatigue influence metal.

The decision to simulate the brake disc behaviour at 1000°C is supported by existing literature. Up to date research continues to focus on failures in brake discs, with most publications centered on the phenomena of cracking and wear failures in grey cast iron brake disc (Luo et al, 2024). Recent study from (Mackin et.al, 2002) documented thermal shocks on grey cast iron discs during braking led to surface temperatures as high as 900°C, which induced cracking failures. The reseachers have found that these high temperatures caused radial cracking, networks of small circumferential cracks and significant wear deformation due to cyclic tensile-compressive stress and residual stresses. Given that metal iron brake discs are subjected to such extreme conditions in motorsport applications, simulating at 1000°C allows us to capture the potential failure point more accurately and assess the material's limits under these severe thermal loads.

As the demand for higher performance, in particularly higher thermal resistance brake applications in automotive and aerospace increased, attention shifted towards more advanced materials, in particular ceramics and composites. The development of carbon-ceramic and carbon-carbon composites marked a significant advancement in the field of thermal fatigue. In the history of carbon-ceramic brakes, CCM carbon ceramic brake rotor technology first started development in January 1997 by Brembo brakes, followed by the development of CCB technology by SGL Carbon in February 1997. In 2001, the Porsche 996

GT2 is the first ever road car to ever featured carbon-ceramic brakes (CarbonCeramicBrakes, 2024). Studies conducted such as (Gadow & Jiménez, 2019) demonstrated that these materials exhibit superior resistance to thermal fatigue when compared to traditional metals, primarily due to their lower density and high thermal conductivity. These properties enable carbon-based composites to dissipate heat more effectively, reducing the thermal gradients which contributes to stress and crack formation.

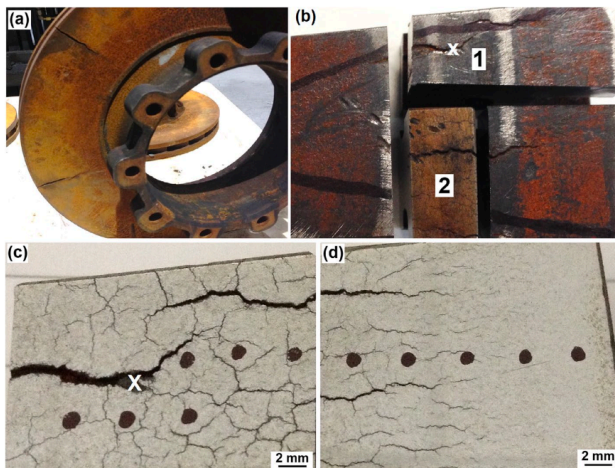
4.1 Disk Cracking and Failure Due to Thermal Stress

One of the most critical modes of failure in brake discs subjected to extreme thermal and mechanical stress is the development of cracks. These cracks, which are often initiated by thermal fatigue, lead to severe degradation of the disc's structural integrity. Rendering the component unusable. Both analytical approach and FEA computational approach confirm that these failures are more pronounced in metal-based brake discs, in particular grey cast iron discs.

4.1.1 Mechanisms of Crack Formation

Cracks form in brake discs primarily due to cyclic thermal loading experienced during braking events. As the discs rapidly heat up during braking and cool down between applications, the material undergoes repeated expansion and contraction. This cyclic thermal stress leads to the formation of microcracks, beginning from the outer part of the brake disc, which grows over time, eventually leading to macroscopic cracking and mechanical failure.

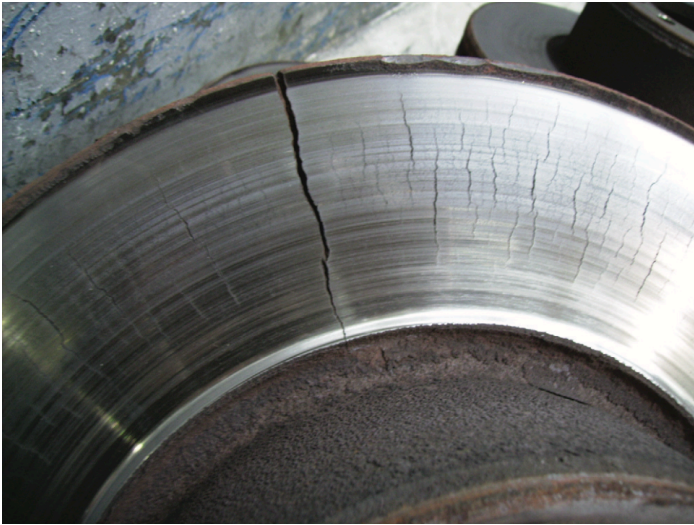
According to (Luo et al. 2024), grey cast iron discs exhibit significant cracking behaviour after repeated thermal cycling. Their study on a failed heavy-duty lorry brake disc found large radial cracks as well as smaller network cracks on the rubbing surface (**Fig 31a**).



(Figure 31. Visual Inspection of network cracking on a failed lorry brake disc. (a). Photograph of failed brake disc. (b). Section blocks of the disc part. (c-d). Closed-up network cracking on the disc surface, Luo et al. 2024)

These cracks were attributed to the graphite flakes in the grey cast iron, which acted as channels for crack propagation and internal oxidation, eventually leading to the material's structural degradation.

Similarly, (Day & Bryant, 2022) also observed thermal cracking in grey cast iron brake disc, shown in (**Fig. 32**). The study reported that high thermal stresses during braking caused radial cracks and crazing along the rubbing path of the brake disc. The researchers contributed the failure of the brake disc from the resultant stresses of where temperature gradients may cause high thermal stresses and thermal cracking on the surface of the brake disc, eventually contributing to the failure of the disc.



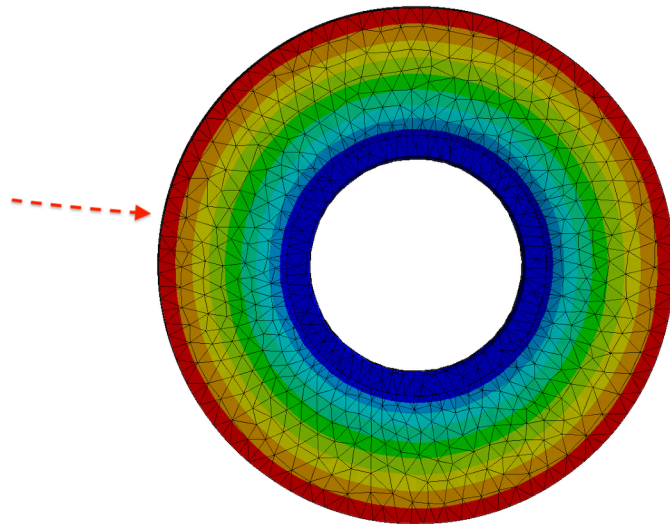
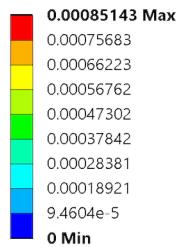
(Figure 32. Thermal-induced cracking in grey cast iron brake disc surface, Day & Bryant, 2022)

4.1.2 Crack Initiation

One of the most common locations for crack formation in brake discs subjected to thermal stress is the outer edge of the disc. This pattern of crack initiation is evident in both literature studies and computational simulations.

The cracks from (**Fig. 31a**) and (**Fig. 32**) shows that the cracks propagation direction from the perimeter, forming networks of circumferential cracks on the rubbing surface. According to (Day et al., 1991), cracking generally occurs in radial direction and can be exacerbated by the high thermal gradients and mechanical stresses experienced during braking. This cracking can propagate from the outer perimeter towards the interior of the disc, which aligns with the observations seen in the images. The outer sections of the brake disc are subjected to higher thermal gradients due to the larger surface area exposed to air and frictional forces during braking, which increases the likelihood of crack formation at the disc's perimeter. The actual observations of the empirical findings are reinforced by the results of the ANSYS simulation conducted in this study. The simulation indicates that the maximum deformation occurs at the outer edges of the disc, as shown in the FEA deformation plot (**Fig. 33**)

B: Static Structural
 Total Deformation
 Type: Total Deformation
 Unit: m
 Time: 1 s
 14/08/2024 10:30 pm



(Figure 33. FEA analysis of metal iron brake disc. Arrow pointing at the outer edge of the disc where maximum deformation occurred.)

4.2 Boundary Conditions (Extended Analysis at Elevated Temperatures)

Thermal Analysis:

Apply initial temperature of 20°C.

Apply thermal load to simulate braking, increasing the temperature to 1000°C.

Convection boundary conditions to simulate heat dissipation to the surroundings.

Convection Coefficient: 20 W/m²·K.

Structural Analysis:

- o Apply rotational velocity: For 2000 RPM, rotational velocity is approximately 209.44 rad/s.

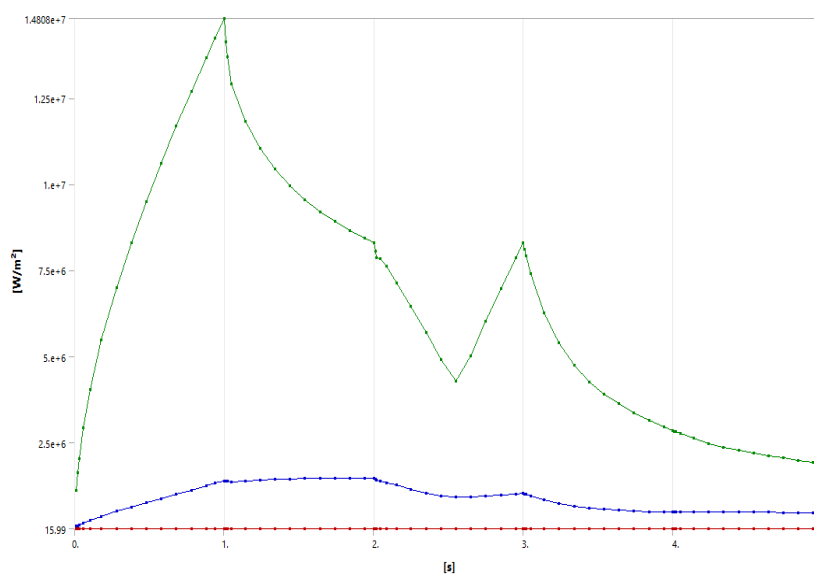
- o Apply frictional contact between the brake disc and brake pad.

- o Coefficient of friction for respective material.

- o Constraint boundary conditions at the disc's mounting points.

4.2.1 Thermal Analysis Results:

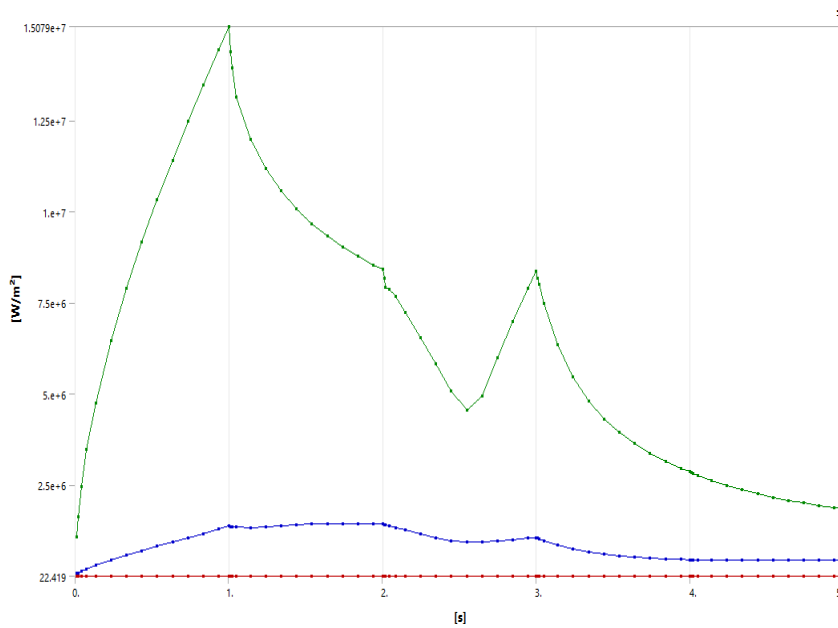
Metal Iron Brake Disc



(Figure 34. ANSYS Heat flux result of Metal Iron Brake Disc at Elevated Temperature)

The graph above denotes the heat flux generated in Metal iron Brake Disc to be 1.4808×10^7 .

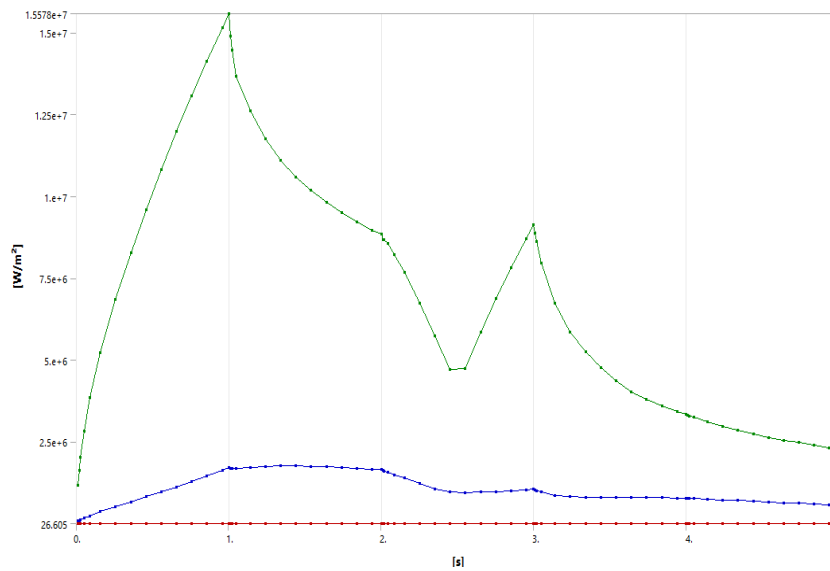
Carbon-Ceramic Brake Disc



(Figure 35. ANSYS Heat flux result of Carbon-Ceramic Brake Disc at Elevated Temperature)

The graph above shows the heat flux generated in the Carbon-Ceramic Brake Disc to be 1.5079E7.

Carbon-Carbon Brake Disc



(Figure 36. ANSYS Heat flux result of Carbon-Carbon Brake Disc at Elevated Temperature)

The graph above shows the heat flux generated in the Carbon-Carbon Brake Disc to be 1.5578E7.

4.3 Discussion of Heat flux:

The thermal performance simulation results at 1000°C for the 3 brake disc materials of metal iron, carbon-ceramic and carbon-carbon demonstrated a clear trend and consistency that aligns with the heat flux patterns observed in the initial simulations at 600°C. In both sets of simulations, carbon-carbon consistently exhibits the highest heat flux, lowest maximum temperature and excellent heat dissipation, followed by carbon-ceramic, with metal iron ranging last with the lowest values.

Previous research by (Belhocine & Bouchetara, 2012) has extensively documented the thermal behaviour of brake discs associated with managing heat flux and temperature distribution in three different types of cast iron materials of different carbon content, FG 25 AL, FG 20, FG15. Their study which also utilize ANSYS FEA simulations to model the thermal response of solid and ventilated brake discs, showed the significant impact of material thermal conductivity on heat dissipation and the subsequent risk of thermal stress and fatigue. Although, the simulations done were all based on only cast iron discs with lower thermal conductivity, it does show how higher carbon contents in those discs exhibit higher thermal conductivity, resulting in more effectively managing the heat generated during braking, thus reducing the likelihood of thermal fatigue. The same theory could be applied to represent the carbon-based discs in this study.

1. Metal Iron:

At 1000°C, the metal iron brake disc recorded the lowest heat flux of all three materials, similar to the trend observed at 600°C. The low heat flux value, coupled with the material's high density and lower thermal conductivity of 45 W/mK, suggests that metal iron is less efficient at dissipating heat during braking events. This behaviour leads to higher operating temperature, which in turn creates a cycle that increases the likelihood of thermal fatigue and failure under prolonged high-stress conditions.

2. Carbon-Ceramic:

The carbon-ceramic disc maintained a moderate heat flux in both simulations (600°C and 1000°C), reflecting its balance between thermal conductivity of 35 W/mK and specific heat capacity of 1350 J/kg K. This material's performance remained consistent across both temperature ranges, indicating its ability to handle high temperatures while still dissipating heat effectively.

3. Carbon-Carbon:

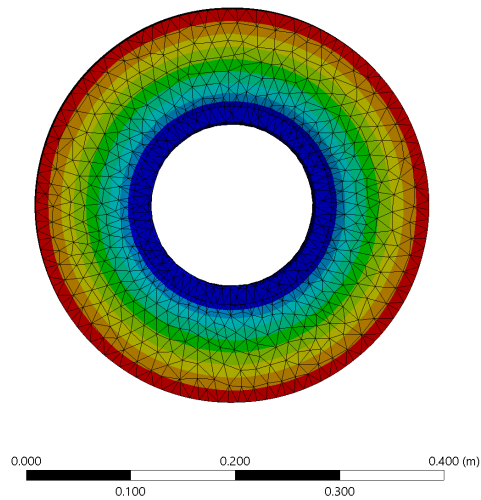
Carbon-carbon brake discs, with the highest thermal conductivity of 50 W/mK and specific heat value (1400 J/kg K), continue to outperform the other materials in terms of heat dissipation. The simulations at both 600°C and 1000°C confirm that carbon-carbon is the most efficient material for dissipating the heat generated during braking, as evidenced by the highest recorded heat flux in both simulations. The superior thermal performance minimizes the risk of thermal fatigue.

4.4 Mechanical Deformation Analysis

4.4.1 Metal Iron Brake Disc

B: Static Structural
Total Deformation
Type: Total Deformation
Unit: m
Time: 1 s
14/08/2024 10:30 pm

0.00085143 Max
0.00075683
0.00066223
0.00056762
0.00047302
0.00037842
0.00028381
0.00018921
9.4604e-5
0 Min



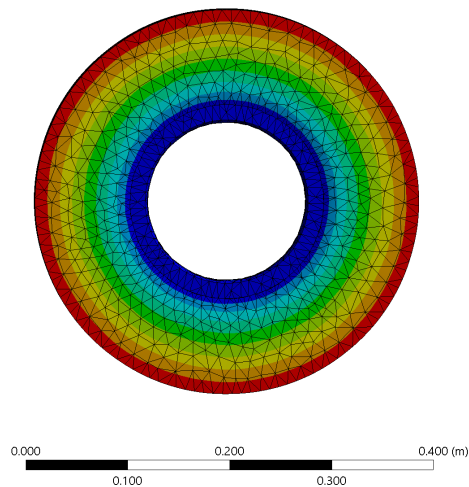
(Figure 37. ANSYS Deformation result of Metal Iron Brake Disc at Elevated Temperature)

The figure above denotes the deformation profile of metal iron brake disc at 1000°C. The simulation results showed the deformation reached to be 0.84302mm.

4.4.2 Carbon-Ceramic Brake Disc

B: Static Structural
Total Deformation
Type: Total Deformation
Unit: m
Time: 1 s
14/08/2024 10:35 pm

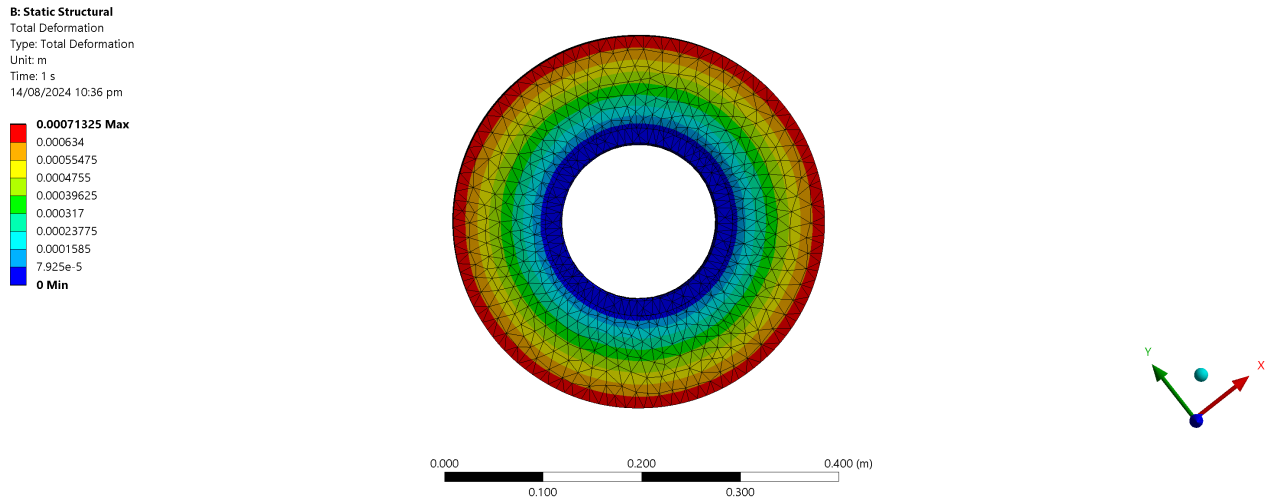
0.00074252 Max
0.00066002
0.00057752
0.00049501
0.00041251
0.00033001
0.00024751
0.000165
8.2502e-5
0 Min



(Figure 38. ANSYS Deformation result of Carbon-Ceramic Brake Disc at Elevated Temperature)

The figure above shows the deformation profile of Carbon-Ceramic brake disc at 1000°C. The simulation results showed the deformation reached to be 0.74252mm.

4.4.3 Carbon-carbon Brake Disc



(Figure 39. ANSYS Deformation result of Carbon-Carbon Brake Disc at Elevated Temperature)

The figure above shows the deformation profile of Carbon-carbon brake disc at 1000°C. the simulation results showed the deformation reached to be 0.71325mm.

4.5 Discussion of Deformation Profiles at elevated temperature (1000°C)

The deformation profiles the 1000°C simulations offer crucial insights into the mechanical limits of the brake disc materials. The aim of bringing up the simulation temperature to 1000°C was to evaluate the deformation behaviours at extreme temperatures to determine when is the point metal brake discs show significant deformation that compromises their operational integrity.

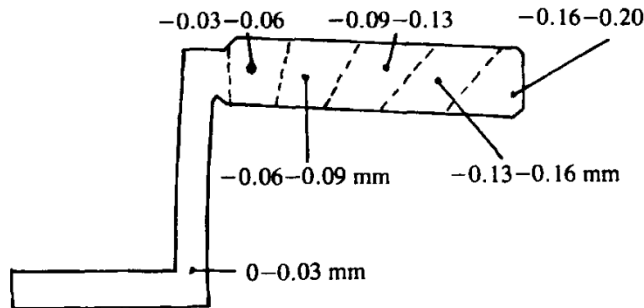
4.5.1 Metal Iron Disc Deformation:

As expected, the metal iron brake disc exhibited the most significant deformation, with a maximum of 0.84302 mm at 1000°C, compared to 0.68mm at 600°C. This substantial increase in deformation highlights the susceptibility of metal iron to mechanical distortion under extreme thermal loading. This trend suggests that the metal iron brake disc does not exhibit a linear relationship between temperature increase and deformation. Instead, the deformation accelerates rapidly as the temperature approaches 1000°C, indicating its mechanical properties degrade significantly under extreme thermal stress. This behaviour also aligns with the research by (Day & Bryant, 2022), where it states that grey cast iron typically retains its mechanical properties up to around 500°C, beyond which there is a marked reduction in strength and ductility, which is also the temperature range used (within 500-650°C) for stress relieving of grey cast iron rotors for up to 24 hours after machining. This process has been proven with no significant effect on the microstructure or mechanical properties. (Day & Bryant, 2022) also highlighted the reason behind the low fatigue strengths of metal cast iron brake discs to be due to the effects of graphite flakes on crack initiation.

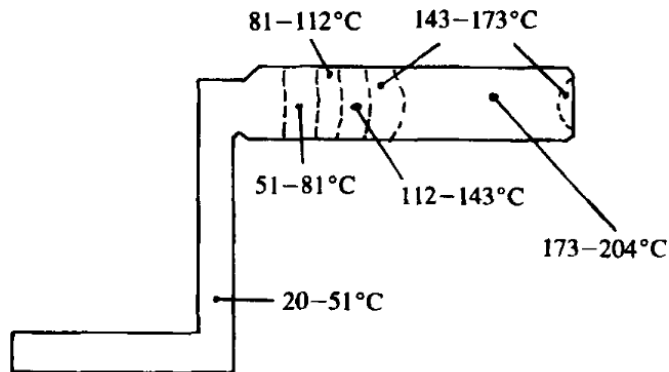
(Day et al., 1991) also explains that cast iron is a complex material with non-linear stress-strain behaviour, a property that becomes particularly significant under conditions of elevated thermal loading, which could explain the results from the elevated temperature simulation. At lower temperatures, the material's response to stress is relatively stable, which explains the modest deformation observed in preliminary simulation simulations at 600°C. However, the non-linearity of cast iron's stress-strain behaviour explains why, as the temperature rises, the material's mechanical response magnifies disproportionately, compared to its carbon-based counterparts. This is evident in the elevated temperature simulation as the brake disc reaches temperatures approaching 1000°C, at which point the stress-strain relationship in cast iron becomes far less predictable, finally resulting in disproportionately larger deformations. (Day et al., 1991) continued to highlight that the repeated heavy usage of brake discs under high temperature induces crack propagation by fatigue mechanism. This is critical as thermal fatigue results in failure under an unacceptable number of brake applications, meaning that the brake disc fails sooner than expected due to the accumulation of fatigue stress. While

normal wear and tear are natural and inevitable in metal brake discs, thermal fatigue introduces an accelerated failure rate that goes beyond the typical lifespan of the component. The researchers mentioned that as the cracks propagate further into the material, will reduce the number of safe braking applications and rendering the brake disc unusable at much faster intervals. The non-linear stress characteristics of cast iron, as discussed earlier causes a vicious cycle of further deformation effect significantly at high temperatures, magnifying the risk of premature failure.

The FEA deformation plot (**Fig. 33**) reveals the deformation pattern and a peak of 0.85413 mm at the periphery of the brake disc, which closely aligns with the areas where previous studies from (Day et al., 1991) which had also reported the initiation of cracks due to thermal stress (**Fig. 40**) (**Fig. 41**). This suggests that the outer edge of the disc, being the region most susceptible to frictional heat and mechanical loads, is the primary site for crack initiation and growth, ultimately leading to failure.



(Figure 40. Disc Deformation field at the end of braking simulation, Day et al., 1991)



(Figure 41. Disc Temperature field at the end of braking simulation, Day et al., 1991)

4.5.2 Carbon-based brake disc

By contrast, the carbon-ceramic and carbon-carbon discs demonstrated a more controlled and linear deformation behaviour as the temperature rose from 600°C to 1000°C. The carbon-ceramic disc's deformation increased from 0.63mm to 0.74252mm, while the carbon-carbon disc's deformation rose from 0.60mm to 0.713254mm. This relatively modest and consistent increase in deformation suggests that carbon-based materials have a more stable mechanical response to rising temperatures. The linearity of the deformation profile in carbon-based discs is particularly beneficial for predicting their operational limits. Because of this exact reason, it is also easier to model and anticipate at what point these materials will begin to experience structural failure under thermal and mechanical stress which is crucial in motorsport environment.

4.6 Determining Cut-off Point for Metal-based brake disc

The differences in the deformation trends no doubt highlights the significance of material properties. The metal iron discs show a disproportionate increase in deformation as temperatures approach 1000°C, indicating that it is approaching or surpassing its mechanical limits. On the other hand, carbon-based discs, not only demonstrated a lower deformation profile, but also a more consistent and predictable response to thermal loading, making them more reliable for high-performance applications where extreme temperatures are common.

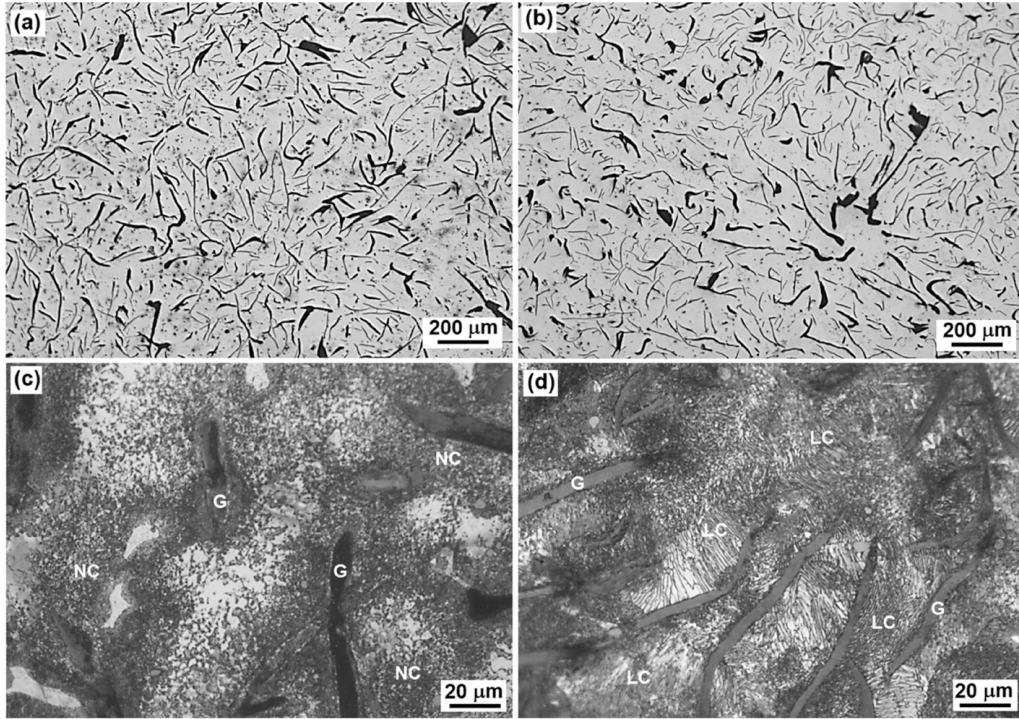
These findings confirm that while metal iron brake discs may perform adequately within moderate temperature ranges (e.g 400-700°C, as suggested in the next section by the MOTEC i2 data), they exhibit substantial degradation at higher temperatures. In contrast, carbon-ceramic and carbon-carbon discs maintain their structural integrity over a wider range of temperatures, with their linear deformation profiles making them easier to predict their operational limits, thus provide more mechanical stability.

The increased susceptibility to deformation in metal iron brake discs can be attributed to several factors, primarily down to the material's microstructure and mechanical properties at elevated temperatures.

4.6.1 Microstructure and Graphite Flakes

The optical micrographs from (**Fig. 42**) in the previous section showing the microstructures of grey cast iron brake discs reveal the presence of graphite flakes dispersed throughout the iron matrix. These graphite flakes play a crucial role in the material's performance under both thermal and mechanical loads. While graphite improves machinability and provides some lubrication at lower temperatures, it also acts as a source of stress concentration points, particularly at higher temperatures.

As Luo et al. (2024) highlight, the graphite flakes in grey cast iron act as channels for both crack propagation and internal oxidation of the ferritic matrix. Under repeated thermal cycling during braking events, these graphite flakes become initiation points for cracks, particularly at temperatures above 500°C, where the material experiences thermal softening. The study also reveals that cracks in the grey cast iron disc, once reached its temperature threshold, begins to rapidly deforms, with penetration to depths of up to 7 mm, aligning with the severity of the thermal and mechanical stresses imposed on the material during braking at elevated temperatures simulation.



(Figure 42. Optical micrographs of grey cast iron brake disc showing the microstructures of the graphite flakes at a depth of 2mm, Luo et al. 2024)

At temperatures nearing 1000°C, the ferritic matrix surrounding the graphite flakes undergoes significant degradation, leading to the formation of thermal cracks, spalling wear, and reduced hardness. The surface hardness of the material drops from HV0.3 284 in the bulk to HV0.3 247 in the rubbing surface, illustrating the material's softening under extreme thermal stress. This reduction in hardness is a likely explanation, coupled with the propagation of cracks along the graphite flakes, for the reason of the disproportionate deformation observed in the simulations. The non-linear increase in deformation—from 0.68 mm at 600°C to 0.84302 mm at 1000°C—can be attributed to the extensive microstructural changes induced by the high thermal load.

4.6.2 Practical Implications for Thermal Cut-Off Point

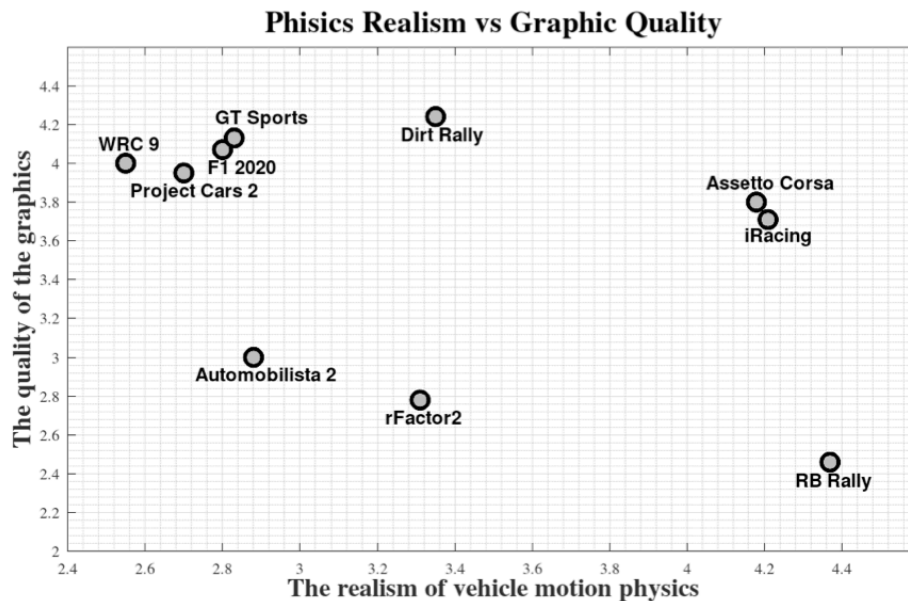
The practical implications of these findings are clear: grey cast iron brake discs are unsuitable for high-temperature applications where sustained braking leads to temperatures approaching or exceeding 1000°C. The material's tendency to crack and deform under thermal stress severely limits its operational range. As the ANSYS simulation results and the literature suggest, the operational cut-off point for grey cast iron brake discs lies between 700°C and 900°C, in which it depends on the fusion of different material elements that are being added in the metal-based brake discs. Conventionally, the higher carbon-content added, the higher the cut-off point equals. Beyond this range, the material's mechanical integrity is compromised, leading to excessive deformation and potential failure.

5.0 Detailed Circuit-Based Simulation Analysis

This section focuses on a final set of ANSYS simulations that integrate simulated circuit brake data from a 718 GT4 race car, equipped with metal brake discs used to evaluate brake disc performance under motorsport racing condition over a circuit distance.

The simulation was conducted using Assetto Corsa Competizione (ACC), a professional-grade racing simulator developed by Kunos Simulazioni. ACC is being used for the official FIA Motorsport Games since 2022 in the Esports category (Federation Internationale de l'Automobile, 2022). This software is widely recognized in both eSports and professional motorsport for its realistic physics engine and real-world 3d scanned road geometry. It is also widely-accessible and has the ability to export vehicle data, making it an ideal platform for analysing brake disc performance under race conditions.

A study conducted by (de Frutos & Castro, 2021) evaluated the realism of various racing simulators, finding that both Assetto Corsa and Assetto Corsa Competizione scored very high in both physics realism and graphics quality according to a control group. As illustrated in (**Fig. 43**), the Assetto Corsa series simulator software provides a balanced combination of high-fidelity physics and top-tier graphical representation, along with the specific plugin which allows generation of data logs compatible to Motec. Making it particularly suitable for this study's simulation. The study also noted that “the program that got the best rating from users for its physics was Richard Burns (RB) Rally. Top rated for graphics quality were Assetto Corsa and Assetto Corsa Competizione. They both score very highly when it comes to physics.”, which highlights the simulator's comprehensive capabilities in providing a realistic and immersive racing experience.



(Figure 43. Summary of survey results of different racing simulator software, de Frutos & Castro, 2021)

The chosen circuit for the simulation is the Autodromo Enzo e Dino Ferrari, more commonly known as Imola. Imola is one of the most iconic and technically challenging tracks in the world of motorsport, with a rich history in Formula 1 and endurance racing. Its layout features a combination of fast straights and complexes, high-speed corners that put immense stress on braking systems. The circuit's Acque Mineralli (officially Turn 10) and 1st Rivazza complex (officially Turn 14) are notorious for demanding heavy braking and prolonged braking with Acque Mineralli especially being a corner leading from downhill, putting extra stresses into the brake systems. These sections of the track make Imola an ideal testing ground for brake disc performance, especially under conditions that replicate the rigors of high-performance motorsport environments.



(Figure 44. Imola Track Map showing each turn)

For this simulation, the Porsche 718 Cayman GT4 race car was selected. The 718 Cayman GT4 is a mid-engine sports chassis designed for the GT4 class, which gives adequate power and also neutrality. The car also has a nearly ideal 45:55 F/R axle weight distribution (Porsche, 2017). The car is equipped with traditional metal brake discs, which will provide a solid baseline for comparing the behaviour of various brake materials under demanding race conditions.

Following the completion of a full lap at Imola, telemetry data was extracted from Assetto Corsa Competizione and imported into MoTec i2 Pro, an industry-standard motorsport data analysis software, which is widely used in the motorsport industry to evaluate post-race telemetry. In this simulation, a detailed examination of key performance indicators such as brake pedal position, individual wheel speeds and brake temperature are being monitored.

Using MoTec i2 Pro, the data is being broken down into individual segments and braking zones to evaluate how the brake discs performed under circuit conditions.

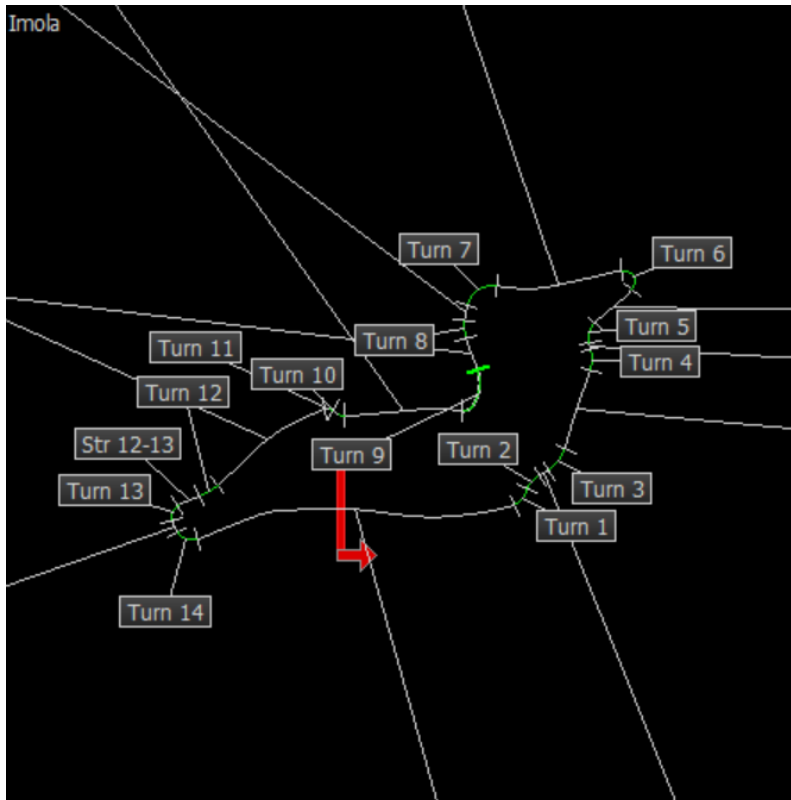


(Figure 45. MoTec i2 Pro screenshot showing the raw data of the 718 gt4 race car in a lap of Imola.)

With the setup environment allowing monitoring of brake pedal position, individual wheel speeds and brake temperatures, the clamping force and disc rotational speed have been reverse-engineered based on the different channels of data. While this reverse engineering was done in a simplified manner, the consistency of the approach ensures that the simulations remain fair and accurate, particularly as carbon-based brake discs were modelled and analysed based on the thermal properties and behaviour of metal discs under similar conditions.

5.1 Turn number Clarification

Due to the way MoTeC i2 Pro perceives and segments the different sections of the track, the turn numbers displayed in the software are not corresponded to the actual official turn numbers of the Imola Circuit. That's why it is important to clarify how the MoTeC i2 Pro software defines each turn numbers and straights, particularly since this could cause confusion when comparing data from the software with the official track layout. (**Fig. 46**) illustrates exactly how Motec i2 pro defines each corner of the circuit.



(Figure 46. Motec i2 Pro Imola Track map)

The corners that this section will be focusing includes **Acque Minerali** and the **1st Rivazza complex**, which MoTeC i2 Pro refers to **Turn 9** and **Turn 12** respectively. **Turn 9** is a key section of the track with a steep downhill entry, whereas **Turn 12** in the software represents the initial braking section leading to the 1st Rivazza complex. However, in reality, the whole braking scenario should be viewed as **Turn 12** being only a mild bend leading to the short straight (**Str 12-13**) + **Turn 13**. Therefore, a full analysis of the Rivazza complex requires considering the braking performance across these 3 segments together, and not just purely **Turn 12**.

5.2 Deformation Analysis

Braking conditions are defined by the turn number, initial and final velocities (**Fig. 47**), clamping force, and calculated angular velocities. The braking forces were recalculated based on a maximum clamping force of 60,000 N.

		, 718 Cayman GT4 MR Imola, Imola 7/31/2024, 10:13:57 PM, Lap 7 [1:53.535]													
		Turn 1	Turn 2	Turn 3	Turn 4	Turn 5	Turn 6	Turn 7	Turn 8	Turn 9	Turn 10	Turn 11	Turn 12	Turn 13	Turn 14
Corr Speed [km/h]	Min	109.1	120.5	148.0	144.7	107.5	77.0	121.6	156.4	93.1	79.6	78.3	207.4	82.9	99.9
	Max	127.7	135.4	163.9	170.3	124.0	107.7	157.9	170.8	176.4	103.4	87.9	218.7	106.8	117.1
BRAKE [%]	Min	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Max	69	0	0	90	25	69	56	0	100	21	0	100	80	44
BRAKE_TEMP_LF [°C]	Min	646	607	534	539	580	628	541	485	515	657	638	395	709	651
	Max	680	646	585	587	617	682	576	513	685	684	657	473	737	703
STEERANGLE [°]	Abs Max	105	77	88	71	89	106	101	39	98	105	112	52	115	97

(Figure 47. Table of data analysis of target lap)

Brake deformation was analysed by simulating the braking performance of the three materials.

The Analysis begins by examining the BRAKE_TEMP_LF data, which represents the temperature of the left front brake disc bulk temperature during the lap. These values were essential in reverse engineering the temperature profiles for Carbon-Ceramic and Carbon-Carbon discs. Given that both materials exhibit superior heat management compared to Metal iron disc, it is estimated their respective brake disc temperatures at each braking zone based on heat dissipation characteristics.

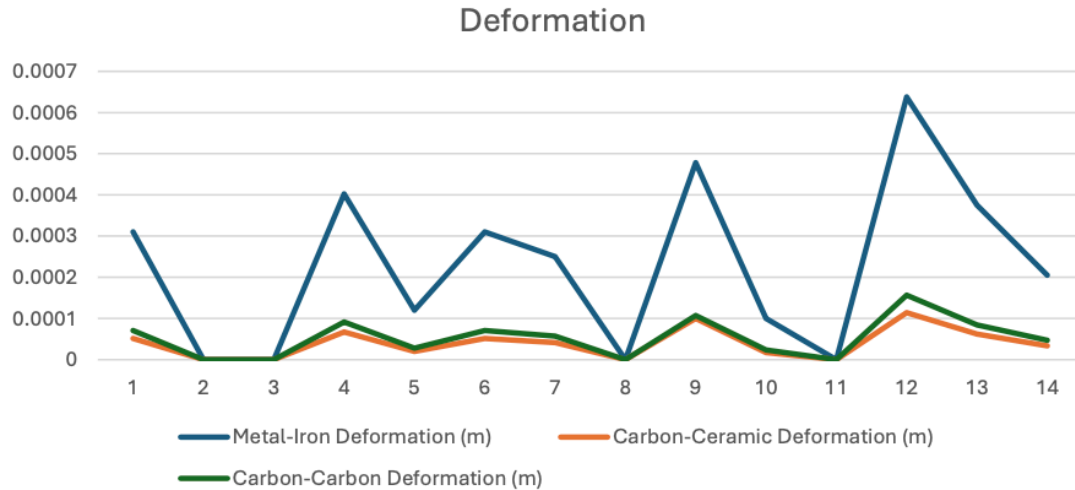
Once the temperature data was established, it was input into ANSYS to simulate the thermal-mechanical behavior of each material. The resulting deformation values are presented in the (Table 5). As the table illustrates, Metal-Iron exhibits the most significant deformation across the turns, with peak values at **Turn 9** and **Turn 12 + (Str 12-13) + Turn 13**, reaching a deformation of 0.478mm and 1.0128mm. In contrast, Carbon-Ceramic and Carbon-Carbon discs, with their higher resistance to thermal stress, show significantly lower deformation values.

(Table 5. Table showing Deformation of each material for each turn)

Turn	Initial Velocity (m/s)	Final Velocity (m/s)	Clamping Force (N)	Rad/s	Metal-Iron Deformation (m)	Carbon-Ceramic Deformation (m)	Carbon-Carbon Deformation (m)
1	109.1	127.7	41,400	118.5	0.0003100	0.0000517	0.0000706
2	120.5	135.4	0	125.7	-	-	-
3	148	163.6	0	151.6	-	-	-
4	144.7	170.3	54,000	157.8	0.0004025	0.00006714	0.0000916
5	107.5	124	15,000	115.9	0.0001200	0.0000200	0.0000280
6	77	107.7	41,400	100.2	0.0003100	0.0000517	0.0000706
7	121.6	157.9	33,600	146.5	0.0002500	0.0000417	0.0000570
8	156.4	170.8	0	157.8	-	-	-
9	93.1	176.4	60,000	163.6	0.0005219	0.00009986	0.00010753
10	79.6	103.4	12,600	93.8	0.0001000	0.0000170	0.0000238
11	78.3	87.9	0	81.5	-	-	-
12	207.4	218.7	60,000	201.7	0.0006378	0.0001142	0.00015665
13	82.9	106.8	48,000	96.7	0.0003750	0.0000620	0.0000845
14	99.9	117.1	26,400	108.9	0.0002050	0.0000340	0.0000470

Upon, inputting the calculated brake forces and corresponding temperatures for each material into ANSYS, FEA deformation plots were plotted for each material specially for each turn.

For easier visualisation, a deformation vs turn graph is being plotted below



(Figure 48. Deformation vs Turns graph)

The graph in (**Fig. 48**) illustrates the deformation of different brake materials across multiple turns. This constant expansion and contraction cycling observed, especially in metal iron, is indicative of thermal fatigue—a phenomenon discussed in detail in Section 3.0. The repeated thermal stresses can lead to material degradation over time, ultimately impacting the performance and longevity of the brake disc.

5.3 Turn-by-Turn Analysis

5.3.1 Acque Minerali (MoTec Turn 9)

The Acque Minerali section of the Imola Circuit is particularly punishing on the brakes due to its high-speed entry and steep downhill gradient. Drivers in GT category cars typically approach this turn at speeds exceeding 200km/h before sharply decelerating to around 90 km/h. During the simulated lap, Metal-Iron brake discs were subjected to significant stress at Acque Minerali. The telemetry data revealed that the brakes reached a temperature peak of 685°C and min temperature of 515°C.

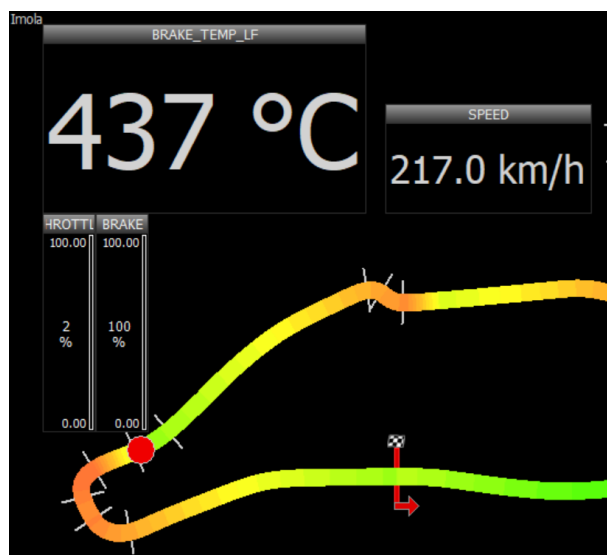
During the simulated lap, the Metal-iron Brake discs were subjected to substantial thermal stress. The telemetry data shows the brakes reaching a peak temperature of 685°C, with a minimum temperature of 515°C recorded upon exit from the corner. Notably, this significant heat buildup highlights the material's tendency to accumulate thermal energy without sufficient dissipation becoming a weakness under such a high-intensity course like Imola. ANSYS Deformation simulation of metal-iron brake discs at this stage reached 0.47842mm, reflecting the toll this material has taken in this single corner, making it difficult maintaining its structural integrity under repeated high-loading braking of more laps.

What is also observed further is even after the corner exit, temperatures did not show significant drop. Observing the subsequent brake zones in Turn 10 and Turn 11, the brake disc temperatures remained to be elevated, ranging between 657°C min and 684°C max for Turn 10 and 638°C and 657°C for Turn 11. This temperature retention suggested the onset of possible brake fade, where heat has yet to be sufficiently dissipated before the next braking event. This continued thermal strain can impair brake response, leading to unpredictability to judge braking distance, particularly after a high-stress corner like Acque Minerali. Over time, such thermal accumulation could result in significant performance degradation, potentially leading to thermal fatigue and failure if the deformation is not controlled properly for the race distance.

In contrast, the hypothetical deformation results for both Carbon-Ceramic and Carbon-Carbon brake discs exhibited much superior thermal performance at Acque Minerali. Even under the same high braking loads, these materials maintained lower peak temperatures, with deformation levels remaining significantly lower, 0.09986mm for Carbon-Ceramic and 0.10753mm for Carbon-Carbon. The enhanced thermal conductivity of carbon-based materials allows for quicker heat dissipation but also ensure they are still in their working temperature range, ensuring that the brake system remains stable, even after prolonged exposure to intense braking zones.

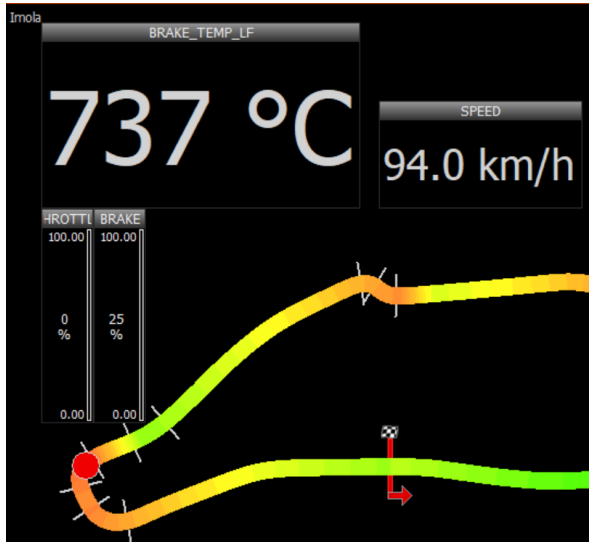
5.3.2 1st Rivazza complex (MoTec Turn 12 Initial Section + Str 12-13 + Turn 13)

The Rivazza 1 complex, referring to T12 + Str 12-13 + Turn 13, represents one of the heaviest braking zones on the circuit, with the approaching speed before the braking zone being the second highest in the whole circuit. In the simulation lap, the 718 GT4 race car reached a speed of 217 km/h before max braking force was applied.



(Figure 49. MoTec illustration of relative speed reached before max braking applied)

The telemetry data shows that at the entry of the 1st Rivazza complex, metal-iron discs reach temperatures of 737°C, the deformation estimated in ANSYS corresponded to be (0.6378+0.375), equaling a total deformation value of 1.0128mm. This highlights a real concern of the limitations of Metal-Iron discs in high-stress scenarios, as the material struggles to maintain structural integrity under extreme loads.



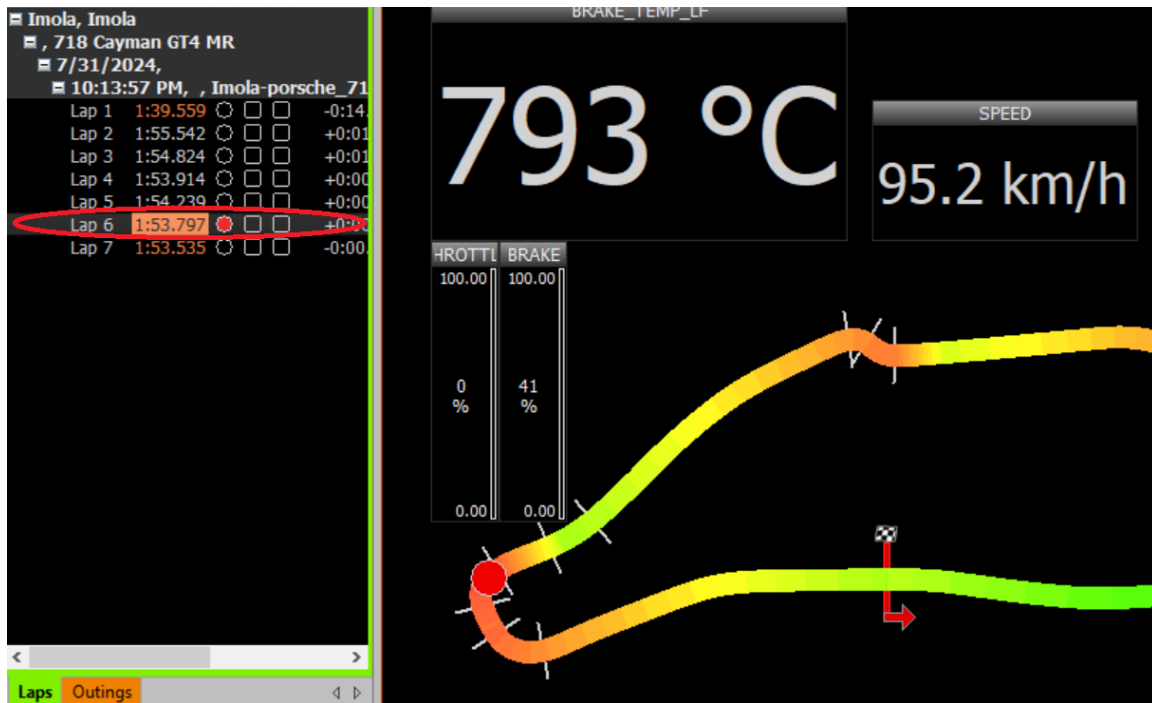
(Figure 50. MoTec illustration of maximum bulk temperature reached towards the end of braking zone)

5.4 Brake Performance:

The data shows that the brake temperature in this section reached a peak of 737°C, which is a worrying threshold considering that temperatures above 700°C begins raises concern to compromise the structural integrity of Metal-Iron brake discs.

As highlighted in previous sections of FEA simulation and research, metal brake discs exhibit a non-linear stress-strain behaviour as temperatures approach 1000°C. This non-linearity explains why in the initial SSTR FEA simulation, deformation in metal discs is relatively modest at 600°C, but magnifies disproportionately in the subsequent SSTR simulation of 1000°C. The maximum recorded temperature of 737°C in this specific lap of simulation suggests that the material already enters a point where deformation could very quickly begin to accelerate, potentially leading to failure if the discs are exposed to such conditions for more laps under the same conditions.

It is also worth noting on the previous lap, the car was out-braked at this same corner complex, causing the lap to be invalidated as the vehicle went off track. Upon analysing the telemetry data from that invalidated lap, it was found that the brake points between the invalidated lap and the target lap were extremely similar, with a negligible difference of around 6 meters in braking distance. However, a critical difference was identified in brake temperature. In the invalidated lap, the brake temperature reached a peak of 793°C, which is significantly higher than the 737°C observed in the target lap.



(Figure 51. MoTec illustration of max brake disc bulk temperature in previous lap)

This discrepancy in brake temperature suggests that even minor increases in thermal load at this elevated temperature range can cause dramatical differences affecting brake performance, making the judgement of the brake distance incredibly tight. At this point, the brake temperature is highly likely becoming a decisive factor into whether the vehicle is able to complete the braking process and go into corner successfully. When approaching critical temperature thresholds, Metal-Iron discs are particularly vulnerable to performance degradation. As a result, the reliability of the braking system becomes highly dependent on brake temperature management, with very little margin for error as temperature rise toward the non-linear stress-strain threshold of the metal.

5.4.1 Justification for Focusing on Rivazza complex over Turn 1

While Turn 1 has the highest approach speed at 243km/h compared to the 217km/h approach speed at the T12-T13 complex, it is shown in the data that it does not generate as much thermal stress on the brake discs. This is primarily due to the long straight before Turn 1, which provides ample cooling time for the brakes. Despite the much higher approach speed and longer braking duration, the maximum brake temperature recorded in Turn 1 was only 680°C, which is significantly lower than that of 737°C seen in the 1st Rivazza complex.

This observation also highlights the impact on subsequent corners from the previous braking zone. After braking through T10 and T11, the short straight before Rivazza does not provide sufficient cooling headroom for the brake discs. This chain effect results in brake temperatures remaining elevated as the car enters the T12-T13 Rivazza complex, which compounds the thermal stress on the braking system. In contrast, carbon-based materials

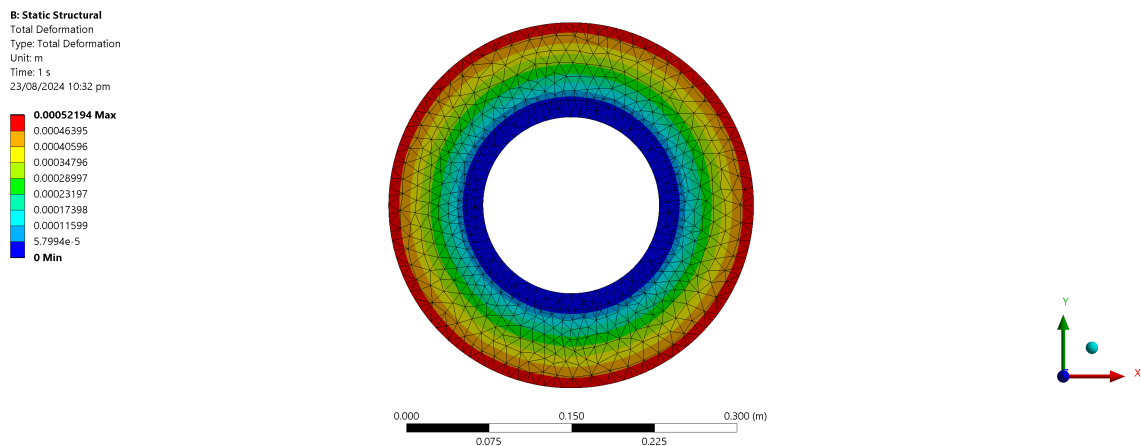
would have been much more adept at handling these conditions, maintaining their structural integrity and performance despite shorter cooling intervals.

5.5 Graphs and Visualisation of Deformation

Referring to (Table 5), we will present and discuss the graphical visualisation from the ANSYS FEA simulations, focusing on the brake disc deformations at critical points on the Imola circuit, taken as sample is Turn 9 (Acque Minerali).

At Turn 9, the braking force, with the assumption of clamping at 60,000N, combined with a peak brake temperature of 685°C, leads to significant stress on the brake discs. The following visualisations represents the total simulated deformation experienced by Metal-Iron, Carbon-Ceramic and Carbon-Carbon brake discs under these conditions.

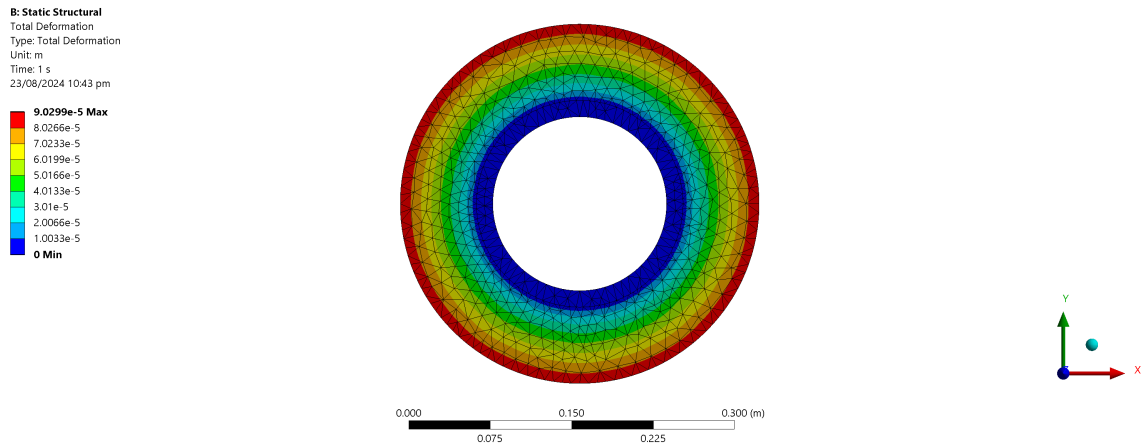
5.5.1 Metal Iron Brake Disc



(Figure 52. ANSYS Deformation result of Metal Iron Brake Disc at Turn 9)

The simulation reveals a maximum deformation of 0.00052194 meters, which is 0.52194mm. The deformation is highest at the outer edge of the disc, a common observation in brake disc behaviour as described previously, in particular metal-iron discs, due to its inherent limitations of thermal expansion properties, which leads to the highest susceptibility to deformation under repeated thermal cycling.

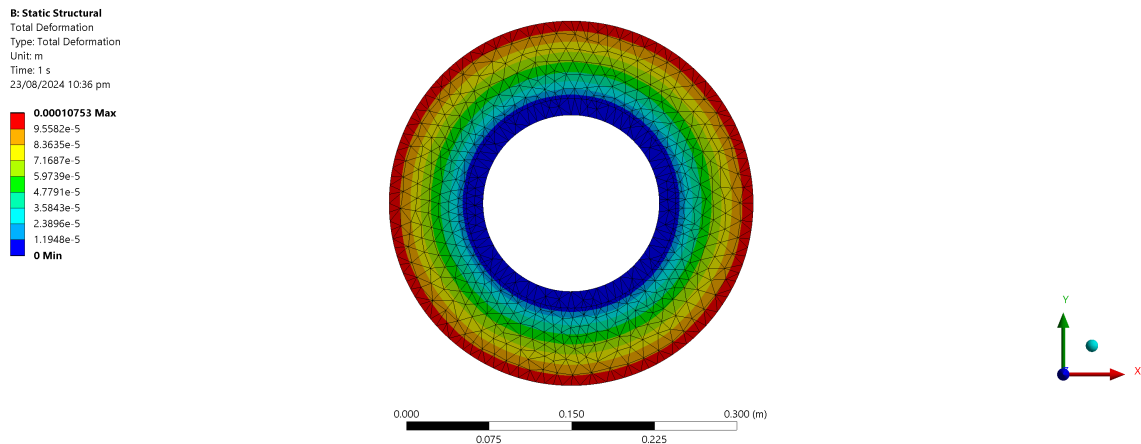
5.5.2 Carbon-Ceramic Brake Disc



(Figure 53. ANSYS Deformation result of Carbon-Ceramic Brake Disc at Turn 9)

The FEA deformation result shows a significantly lower maximum deformation than Metal Iron brake disc, giving the value of 0.000090299 meters which differs from Table 5's 0.00009986 meters value, this is due to re-running the simulation, which gives a small amount of discrepancy, however both results are close enough to 0.09 mm for Carbon-Ceramic discs. The total deformation is at a much lower value uniform across the disc, with the highest levels still concentrated at the outer edge.

5.5.3 Carbon-carbon Brake Disc



(Figure 54. ANSYS Deformation result of Carbon-Carbon Brake Disc at Turn 9)

The FEA deformation result reveals the deformation value of Carbon-Carbon brake disc to be 0.000107 meters, which is 0.107mm, the result shows a similar but slightly higher deformation value to that of Carbon-Ceramic disc's, which is a bit surprising, but not completely out of range as both the values are very close, and each simulation could yield a slightly different value but under marginal difference.

5.6 Brief Discussion of Deformation Analysis

From Turn 9's deformation simulations of the three materials, it is consistent with the initial SSTR simulations done with a slight hiccup for the deformation values between the carbon-carbon and carbon-ceramic materials.

For metal iron brake disc, it is expected that it would record the highest deformation result due to the reasons illustrated in the "Thermal Fatigue and the Significance of Deformation" section, the high thermal stress combined with Turn 9's high-speed downhill approach loads the metal-iron brake disc under even more stress, aligning with initial presumption based on the analytical approach that it would score the highest deformation.

For Carbon-Ceramic and Carbon-Carbon discs, it could be said the results are a bit surprising, given that the deformation value of Carbon-Carbon (0.107mm) is higher than that of Carbon-Ceramics (0.09mm), however this margin of error is so small that it could be seen as marginal error as each FEA simulation is a separate event and yields an ever so slightly different value each time. Otherwise, another phenomenon or assumption could be due to the temperature still haven't reached the thermal fatigue point of the carbon-based discs, which is why the real difference in performance between the Carbon-Ceramic and Carbon-Carbon discs hasn't become apparent yet. The Carbon-Carbon disc might only show its superior structural integrity over Carbon-Ceramic under even more extreme conditions, where the material's resistance to thermal fatigue would become a critical factor. This also underscores the part of this research's limitation and the importance of considering the full thermal cycle and operation limits when assessing brake disc materials for high-temperature applications.

6.0 Overall Summary and Conclusions

6.1 Summary of Key findings

The use of carbon-based materials certainly offers substantial advantages over traditional Metal-Iron in high stress motorsport applications, as discovered in this study. This research's comparative analysis of Metal-Iron, Carbon-Ceramic and Carbon-Carbon brake discs has revealed significant differences in how these materials respond to intense thermal and mechanical stress. The simulations conducted using ANSYS Mechanical, along with circuit-based telemetry data from Assetto Corsa Competizione, have provided valuable insights into the performance characteristics of each material.

The findings indicate that while Metal-Iron brake discs are still commonly used in modern day motorsport industry, despite their known disadvantages, are able to still perform adequately provided the temperature is under control within its operational boundaries. However, they demonstrate significant limitations when subjected to intense thermal and mechanical stress. In the initial phase of Single Stop Temperature Rise (SSTR) simulations, Metal-Iron discs showed moderate levels of deformation compared to Carbon-based discs, showing that it still could perform adequately given the amount stress and temperature range is still within the range. However, the behaviour was exacerbated in the elevated temperature simulations, where deformation showed a non-linear trend of increase as temperatures approached 1000°C, at that point, metal-iron discs showed high levels of deformation, particularly as temperatures exceeded normal operating ranges. These results aligned with the initial analytical approach calculations, suggest that Metal-iron discs may not be suitable for prolonged use in high-performance motorsport environments. From the lap highlighted in (**Fig. 51**), we could observe the thermal headroom of metal-iron discs is in fact quite low, as we could see how in a small difference in braking distance of 5 meters could cause the difference of the peak temperature to differ so much, rising up to 793°C as compared to 737°C on the optimal lap with the fastest laptime (**Fig. 50**), contributing into one of the factors that cause the vehicle to go off-track.

On the other hand, the theoretical estimations showed Carbon-Ceramic and Carbon-Carbon brake discs to exhibit much superior performance in terms of heat dissipation and resistance to deformation. These materials maintained their structural integrity even under extreme thermal conditions, which can be seen from both the SSTR and Circuit-based simulation results, the simulation analysis no doubt reinforced these findings, showing that Carbon-Ceramic and Carbon-Carbon discs could still stably sustain their performance across various high-stress section of the Imola Circuit and rarely drop out of their operating temperature zone. This highlights the advantages and suitability of carbon-based materials for high-performance motorsport applications, even for a GT4 class vehicle with lighter weight and only moderate power to benefit from the durability and efficiency.

6.2 Implications for Practical Applications

The implications of these findings are significant for the motorsport industry. The superior performance of Carbon-Ceramic and Carbon-Carbon brake discs suggests that these materials should be prioritized in high-performance racing applications, particularly in endurance racing where brake performance can be a decisive factor in race outcomes.

The ability of these materials to manage heat effectively and resist deformation under extreme conditions ensures not only improved performance but also enhances the safety of both the vehicle and the driver.

For manufacturers and race teams, the choice of brake disc material becomes a critical decision that can impact both performance and safety. However, in a world where most modern day motorsport series are either spec-races or governed by strict Balance of Performance (BoP) regulations, competition vehicles usually must conform to a set of standardized rules. If a race series were to switch universally from metal-based brakes to carbon-based brakes, it would significantly raise the overall cost of participation, thereby increasing the entry barriers for smaller teams and novice drivers. For instance, according to (Ritter, 2021), cast iron brake discs typically range in prices from a few hundred to over a thousand dollars, depending on the vehicle and manufacturer. In contrast, carbon-based discs are significantly more expensive, with carbon-ceramic discs costing upwards of \$8,000. Carbon-carbon discs are even more specialized and cost even more.

If the BoP does not regulate the use of brake materials, teams with higher budgets would inevitably opt for carbon-based brakes, while teams with smaller budgets would be limited to using traditional metal brakes. This discrepancy would create a substantial unfair advantage and undermine the purpose of fairness which ultimately also defeats the purpose of enhancing the safety of both the vehicle and driver, as the disparity in braking performance could lead to increased risks on track as well.

While Carbon-Ceramic and Carbon-Carbon discs offer clear performance advantages, Metal-Iron brake discs still present a cost-effective solution within the constraints of regulated racing environments. Given that metal-iron discs can perform adequately if temperatures are managed within suitable ranges, they remain a viable option for series where cost and accessibility are key considerations. This balance between performance, cost, and regulatory compliance highlights the complex decision-making process that teams and manufacturers must navigate in motorsport.

6.3 Critical Reflection of Limitations

As discussed in the opening Delimitation section, despite the valuable insights gained from this study, there are several limitations that must be acknowledged. The reliance on simulation tools no doubt provides an easier and more approachable platform compared to performing physical experiments where many more uncertainties have to be accounted, like material deficit. However, simulation-based studies also introduce certain idealisations that may not fully capture the complexities of real-world conditions. For instance, the material properties data used in the simulations were based on general data from the ANSYS database. Although data obtained from the ANSYS database are generally industrial-recognised, given the specific contents and compositions of modern day carbon-based brake discs which are usually classified data closely guarded by manufacturers, the simulations in this study would not be capable to entirely reflect the actual performance of those specific materials in real-world motorsport applications.

During the research period, the simulation progress was constantly reported to the supervisor of this project, Mr. Andrew Noble, which also suggested although the exact simulation data, such as the deformation values might not entirely reflect the actual numbers seen in real-life applications. However, the general trend of the data is indicative, and should be generally applicable in motorsport conditions and vehicles.

Additionally, 3D FEA models that incorporate rotational and frictional heat generation are very computationally resource-intensive, particularly in terms of RAM and GPU usage. Although the ANSYS Mechanical simulations in this study were run with a Nvidia RTX3080 Laptop GPU and 64Gb of ram, this is still far from the industrial level of computational power required to fully optimize such simulations. As noted also in previous studies which also incorporate rotation and frictional heat generation are “computationally intensive, even with modern computing power” (Day & Bryant, 2022). This means that simulations took significant time to run, thus limiting the feasible number of simulations that can be performed in the time frame of this study. As such, it is acknowledged that although the simulations performed in this study did its best to provide valuable insights, are limited to those constraints and might not fully capture as much amount of detail as with a greater number of simulations performed.

6.4 Standpoint on Material Innovation in Motorsport Engineering

In modern motorsport industry, material innovation is very common nowadays and plays a significant role in enhancing vehicle performance, safety and competitiveness. As discussed earlier, brake disc materials like Carbon-Ceramic and Carbon-Carbon offer a much more stable solution to address challenges posed in high-stress racing environments, such as much higher thermal headroom, heat dissipation and stress relief. These characteristics not only offer improved longevity and reduced maintenance requirements, which are crucial factors in the demanding world of motorsport.

However, with material innovation also comes the challenges of balancing with cost and manufacturability. While carbon-ceramic discs are now offered more and more in high-end supercars due to the automated manufacture process. Carbon-Carbon discs are still manufactured in low volume and most often involve human-labour processes, which unfortunately also equate to much higher production cost as a package. The complex manufacturing process seems to be a barrier to widespread adoption in the current trend of motorsport, particularly in lower-tier racing series or even in general road-going vehicle applications.

The continued evolution of brake disc materials will likely involve a combination/mixture of incremental improvements from existing technologies and the continued exploration of new materials, with anticipated lower costs. The insights gained from studies like this one aims to contribute to the ongoing discussion of how best to achieve these advancements while maintaining the balance between performance, cost and sustainability.

6.5 Future Research Directions

Building on the foundations of this project, which is also a continuation of studies of previous researches. Future researches could focus on several other key areas, such as experimental validation of the simulation results through real-world testing. Although a research of that scale would likely require more financial resources and backing from manufacturers for detailed material composition data, real-world validation would certainly provide a much more accurate assessment of the materials' performance and help identify any discrepancies between simulated and actual results. This could also involve testing under a broader range of conditions, including different track types, brake force and vehicle configurations.

Additionally, there is significant scope for exploring other materials or variations in compositions within the carbon-ceramic technologies. As nowadays, ceramic mixture into carbon-based discs is becoming more and more common in road-going vehicles which means more accessibility for the general public, which is why understanding how different compositions, manufacturing processes and more importantly surface coating treatments that could potentially lead to specific characteristics of the disc. This knowledge could benefit the general public into understanding what they need for their road-going vehicles,

again providing valuable insights into the versatility and applicability beyond motorsport context.

Lastly, researches into sustainability of advanced brake disc materials are a very focused topic in the current automotive industry trend nowadays. A Life Cycle Analysis (LCA) looks at the environmental impact of the production, use and disposal could help guide the development to a more eco-friendly manner, understanding the lifecycle impact of these high-performance materials will be essential into bringing greater sustainability.

6.6 Closing Remarks

In conclusion, this study has provided a comprehensive analysis of the three key brake disc materials, offering valuable insights into their performance under high-stress conditions typical to motorsport. The findings of this study, along with previous researches underscore the importance of careful material selection in ensuring both performance and safety in racing applications. While Metal-Iron brake discs still offer a cost-effective solution and is still commonly used, their limitations in extreme conditions are still worth highlighting for the need of popularising advanced materials like Carbon-Ceramic and Carbon-Carbon, which demonstrate far superior performance across a range of critical metrics.

The research presented here contributes to the broader understanding of brake material performance in motorsport and lays ground for future studies aimed at enhancing the safety, efficiency and sustainability of racing brake systems. As the industry continues to evolve, the insights gained from this study are responsible to inform the general public the ongoing development of innovative materials for road-going vehicle applications in a more layman fashion, while pushing the boundaries of what is possible in motorsport engineering.

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