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***Finite Element Investigation of the Effect of Ventilated Brake Disc Design on
Temperature Distribution and Thermal Stress under Repeated Braking
Conditions***

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Program: MSc Automotive/Motorsport/Motorcycle Engineering

Engineering Module: Research Methods

Module code: ACHA7027

Date: 19/04/2026

Abstract

Brake disc performance under repeated braking is governed not only by peak temperature but by the spatial distribution of thermal loads, which directly drive stress development and long-term durability. While existing studies confirm the presence of non-uniform temperature fields and thermo-elastic instability, many remain limited by simplified geometries or single-event simulations, reducing their relevance to realistic operating conditions. This study evaluates the influence of ventilated brake disc geometry on temperature distribution and thermal stress under repeated braking using a finite element framework. A controlled comparative approach is adopted in which geometry is isolated as the primary variable, while material properties and boundary conditions are held constant. Key evaluation metrics include peak temperature, thermal uniformity and stress concentration. By explicitly linking geometric design to thermo-mechanical response under transient loading, the study addresses a gap between thermal analysis and design-oriented evaluation. The work provides decision-relevant insight into geometry-driven brake performance while maintaining a realistic interpretation of modelling limitations.

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1. Introduction

Among the most safety-oriented components in vehicle design are brake systems. Brakes are responsible for decelerating the vehicle. In disk brakes, friction at the contact between the brake pads and the brake disc turns kinetic energy into heat energy. With prolonged braking, there will be extreme thermal loads, causing significant temperature gradients in the brake disc. Temperature distribution is crucial in developing temperature hot spots, resulting in uneven heating and thermal stresses. This causes distortion of the parts. Research using infrared imaging and thermoelastic analysis indicates that the temperature distribution is not even on the brake surface under normal operating conditions (Goo, 2018).

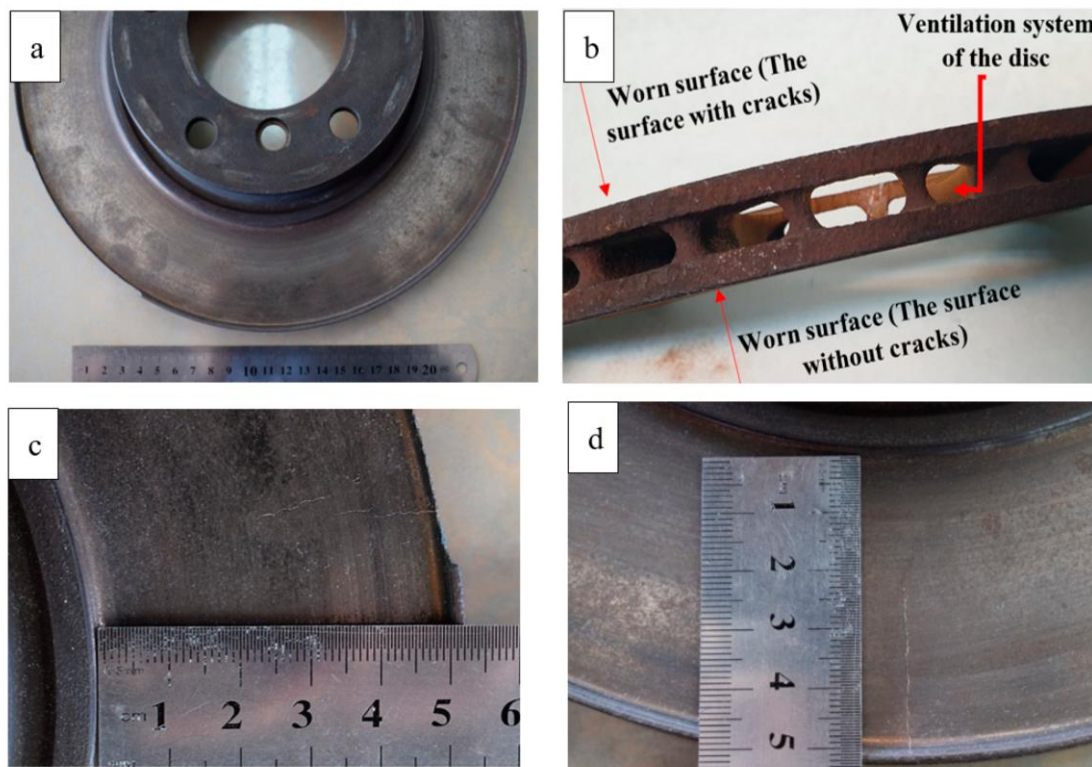


*Figure 1. Surface distress and radial cracking in a ventilated automotive brake disc.
Source: Adapted from Mohammadnejad et al. (2019).*

However, there are two issues here, beyond the fact that brake discs can heat up. One problem is their tendency to heat unevenly, which will lead to thermal gradient generation. In turn, thermal gradients will result in uneven thermal expansion. Over time, uneven heating may contribute to thermo-mechanical damage such as thermal fatigue and cracking.

It has been established experimentally that failure analysis reveals the influence of thermo-mechanical loadings on crack initiation and propagation (Mackin et al., 2002; Mohammadnejad et al., 2019).

The widespread use of ventilated brake discs results from their increased cooling capabilities due to vane-shaped geometry and the enhanced ability to reject heat from the rotor surface due to air circulation through the disc. Nevertheless, there are considerable differences between ventilation efficiencies for various configurations since internal geometry determines flow path lines, thermal convection, and the thermo-mechanical response. Numerical investigations have recently proven that the geometric design of brake discs significantly impacts heat dissipation and stress distribution (Park et al., 2022; Huang, Chiu and Wu, 2022).

The research focuses on the influence of the geometry of the ventilated brake disc on its temperature distribution and thermal stress when the vehicle experiences frequent braking. Unlike other research, the project examines geometry as the key factor, not material. Such a research approach provides an opportunity to isolate the design effect clearly. The aim remains technologically challenging yet realistic to complete in the given time allocated by the dissertation. Incorporating both geometry and material into the variables will lead to a much wider research scope, making it harder to achieve any engineering results.

It is worth noting that the braking process itself is always variable. The process involves a few braking events. Moreover, different kinds of contact pressures, changing environmental conditions, and a range of other factors contribute to the variability of the heat generation process. As a result, the process requires the examination of the thermal behaviour of brake discs in their transient state. This kind of knowledge is crucial for further improvements since contemporary cars move faster and become more massive, thus increasing thermal loads in brake discs.

The present research creates a technically robust and feasible research plan. It is built on existing scientific knowledge about brake heat generation and serves as a basis for the whole dissertation research. While previous scientific studies describe the general effect of geometry on brake heat distribution, the current one investigates which ventilated brake disc geometry works best under frequent braking and why.

2. Research Rationale

The proposed study is justified on three levels: engineering relevance, academic value and methodological suitability. As seen from the engineering viewpoint, brake discs are subjected to cyclic thermo-mechanical loading, while issues associated with heat build-up have been of high relevance. Issues such as thermal fracture, hot spots, and non-uniform wear do not concern researchers only as a matter of theory but are also encountered in practice (Mackin et al., 2002; Mohammadnejad et al., 2019; Xu et al., 2024).

From an academic perspective, this topic remains worthwhile. Previous research has not fully closed the gap between thermal behaviour, geometric design, and durability-relevant stress. Some studies focus on infrared measurement and thermo-elastic behaviour. Others emphasise design optimisation or airflow modelling. Few offer tightly scoped comparative studies. There are a few that evaluate selected ventilated geometries under the same repeated-braking assumptions using a consistent FE framework and a small set of durability-relevant outputs (Goo, 2018; Park et al., 2022; Vdovin and Le Gigan, 2020).

This topic is also timely from an engineering perspective. Automotive design calls for braking components that are lighter and more durable. Components must perform under repeated or severe thermal loads. In this context, thermal management is not only about avoiding overheating. It also prevents uneven heat distribution, local stress, and structural degradation. This shows that geometric design inside the rotor remains an active and meaningful problem—not a closed question.

Methodologically, finite element modelling is suitable because it enables the study of temperature and stress fields under controlled conditions. It does not require the time, cost, or instrumentation of a full experimental programme. However, the method must be used carefully. Brake cooling simulation is very sensitive to boundary conditions, especially heat input, convection, and effects from neighbouring parts. For this reason, this study is presented as a comparative FE investigation rather than a prediction of the exact crack life (Vdovin and Le Gigan, 2020; Belhocine and Bouchetara, 2013).

A further justification for this study is the increasing use of simulation-driven design in the automotive industry. Engineering decisions are increasingly supported by computational

modelling, especially in early-stage design. Physical prototyping is costly and time-consuming. Finite element analysis allows for rapid evaluation of design alternatives. By focusing on thermal distribution and stress concentration, this study matches simulation outputs with engineering targets. These include durability, reliability and safety. In this way, the research contributes to both academic understanding and engineering practice. It shows how controlled modelling can inform design choices without adding unnecessary complexity.

3. Research Problem, Aim and Questions

The central research problem is that repeated braking can create high, non-uniform thermal loads in a ventilated brake disc, leading to hot spots, thermal stress concentration, distortion, and reduced durability. Existing research confirms the importance of these phenomena, but there is still room for a focused comparison of internal ventilated geometries under repeated braking using a consistent thermo-mechanical FE approach (Goo, 2018; Park et al., 2022; Wang et al., 2022).

The aim of this study is to investigate the effect of ventilated brake disc geometry on temperature distribution and thermal stress under repeated braking conditions using finite element analysis.

The objectives of the study are as follows:

- To review the literature on brake-disc thermal behaviour, hot spots, thermo-elastic response and thermal cracking.
- To develop a three-dimensional finite element model of a ventilated automotive brake disc.
- To apply repeated braking thermal loading under consistent and justified boundary conditions.
- To compare selected ventilated disc geometries within a controlled modelling framework.
- To evaluate peak temperature, temperature uniformity and thermal stress concentration as durability-relevant indicators.
- To identify which geometry demonstrates improved thermo-mechanical performance under repeated braking.

The research questions are:

- How does ventilated brake disc geometry affect temperature distribution during repeated braking?
- Which design produces the lowest peak temperature?
- Which design produces the most uniform thermal field?
- Which design reduces thermal stress concentration most effectively?

The research problem has been articulated within the design paradigm, emphasizing the translation of knowledge regarding thermal behaviour into comparative design studies, as opposed to merely maintaining a theoretical perspective. This approach allows for the demonstration of both depth and applicability, which should be evident at the postgraduate level. The formulation of research questions based on tangible outputs like temperature and stress distribution enables direct applications in engineering decisions.

4. Literature Review

4.1 Brake-disc thermal behaviour

The literature is clear that brake-disc temperature is transient, highly local and strongly dependent on braking history. Goo used infrared imaging alongside finite element analysis to demonstrate that ventilated cast-iron brake discs develop ring-shaped thermal patterns rather than simple uniform heating. This matters because the thermal field determines the subsequent stress field. In other words, temperature is not only a thermal issue but the driver of structural behaviour in the disc (Goo, 2018).

Brake failure analysis further underscores this issue. Mackin et al. describe thermal cracking in disc brakes as a failure problem associated with severe braking events and repeated thermal cycling. Likewise, Mohammadnejad et al. documented radial cracking in a ventilated automotive brake disc and linked the failure to long-term service and loading conditions. Together, these studies show that thermal loading is not a minor secondary effect: it is central to brake durability (Mackin et al., 2002; Mohammadnejad et al., 2019).

In addition to experimental observations, numerical studies have shown that thermal gradients are strongly influenced by braking intensity, contact conditions and material properties. Transient thermal simulations indicate that heat accumulation during repeated braking leads to progressively higher temperature levels, particularly when cooling intervals are insufficient. This reinforces the importance of considering braking history rather than isolated events. A single braking simulation may underestimate thermal severity, whereas repeated braking scenarios provide a more realistic representation of operational conditions (Belhocine and Bouchetara, 2013; Kukulski, Grzes and Adamowicz, 2023; Yevtushenko, Kuciej and Topczewska, 2021).

A critical point emerges here: many studies identify high temperature as a problem, but fewer clearly distinguish between peak temperature and the quality of the temperature distribution. For the present proposal, that distinction matters. A disc may show an acceptable average temperature while still developing damaging local thermal peaks. Therefore, thermal uniformity is not just a secondary metric; it is a core durability-relevant output.

4.2 Hot spots, thermo-elastic behaviour and durability

Hot spots are particularly important because they create local thermal severity rather than average thermal severity. In practice, this means a disc may have an acceptable mean temperature while still suffering from damaging local peaks. Thermo-elastic behaviour is therefore central to the problem. Goo's work is useful here because it combines thermal imaging with FE analysis, showing how local surface temperatures and pressure-related behaviour can be studied together rather than separately (Goo, 2018).

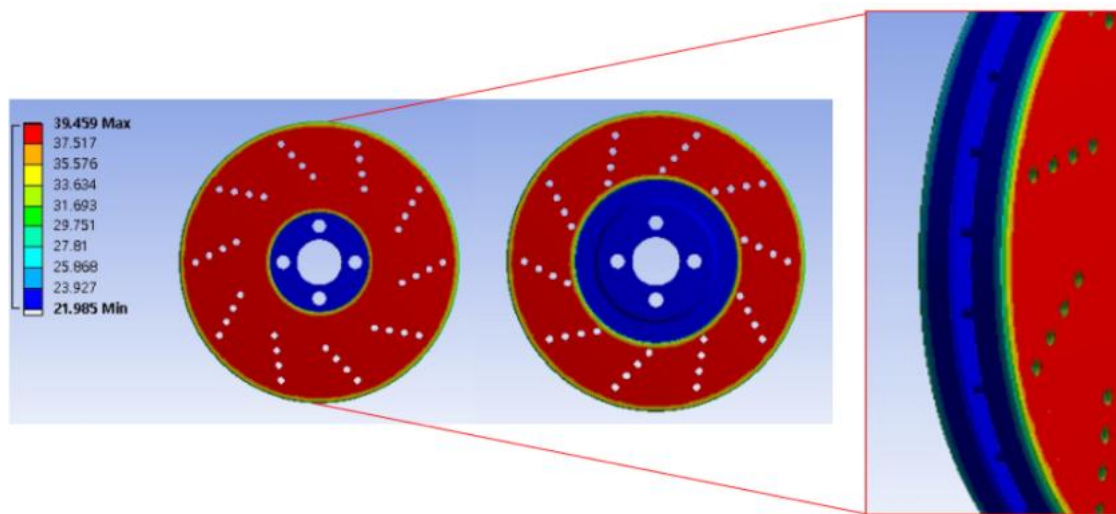


*Figure 2. FE contour plot showing non-uniform temperature distribution in a brake disc.
Source: Adapted from Belhocine and Bouchetara (2013) and Jiang et al. (2019).*

In terms of thermo-mechanical aspects, the problem of hot spots is not only related to temperature but also to structure. Due to an increase in the local temperature, there is uneven heating and expansion, which affects the change in the pattern of the distribution of pressure from the disc on the pad. As a result of this process, there is a risk that the effect will increase further, creating a kind of vicious circle. It has been proven to be an important reason for the occurrence of uneven wear and damage (Yi et al., 2012; Wang et al., 2022).

The durability implication is clear: where temperature gradients become steep, stress concentrations are likely to rise. Thermal fatigue studies in related brake applications continue to identify crack formation as a major long-term constraint, even under varying operating conditions. The key point for the present proposal is not to model every fatigue mechanism in detail, but to recognise that temperature distribution and stress concentration

are appropriate precursor indicators of thermal-risk locations (Wang et al., 2022; Xu et al., 2024).

A limitation in the literature is that thermo-elastic theory is frequently addressed conceptually but not consistently applied to practical design comparisons. This study addresses this gap by directly linking thermal behaviour to an actionable design variable, namely ventilated geometry.

4.3 Ventilated geometry and airflow

Ventilated disc geometry is one of the most practical levers available to the designer. Park et al. used FE-based structural and thermal analysis in ANSYS to optimise holes and slit patterns, explicitly aiming to reduce concentrated stress and temperature while improving heat dissipation. Their work is especially relevant because it shows that geometry can be treated as a meaningful design variable rather than a purely manufacturing detail (Park et al., 2022).

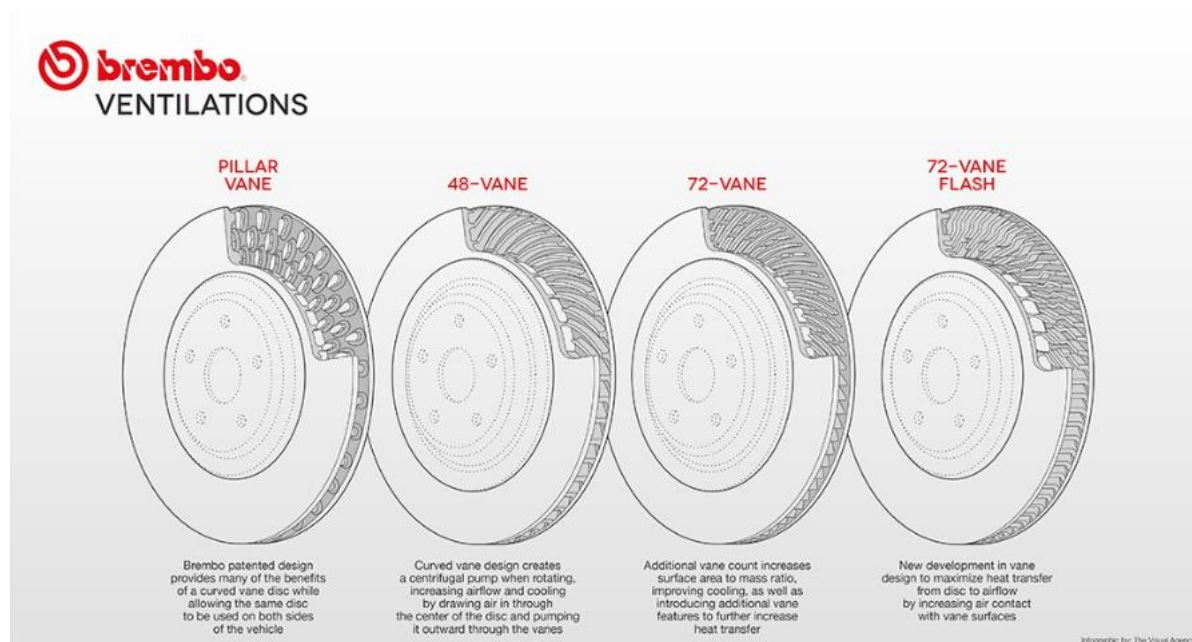


Figure 3. Comparison of ventilated vane concepts used to improve cooling and heat transfer. Source: Adapted from Park et al. (2022) and Huang, Chiu and Wu (2022).

García-León, Afanador-García, and Gómez-Camperos strengthen this point by showing that heat transfer and airflow speed are strongly linked to the performance of auto-ventilated disc brakes. Their work also highlights something important for this proposal: airflow-related

performance can be explored numerically, but the value of the model depends on choosing a manageable scope. For a three-month dissertation, a full CFD plus fully coupled structural analysis would likely be too broad. A focused FE study that compares geometry under consistent thermal boundary assumptions is more realistic and still technically valuable (García-León, Afanador-García and Gómez-Camperos, 2021; Vdovin and Le Gigan, 2020).

It is also important to recognise that airflow behaviour within ventilated discs is highly dependent on vane orientation, spacing and rotational effects. Curved vane designs are often associated with improved airflow efficiency due to centrifugal pumping effects, whereas straight vane designs may offer simpler manufacturing but reduced cooling performance. However, higher airflow doesn't always translate to better performance structurally. While better cooling can lower maximum temperatures, there is still a possibility of having unequal temperature distributions based on airflow distribution. The necessity for a balance between thermal and structural outcomes should therefore be emphasized instead of prioritizing just cooling effects.

A critical gap in the literature is that many studies focus either on airflow or on structural behaviour, with fewer investigations linking geometry, repeated thermal loading and stress development within a single controlled comparative framework. The present study addresses this gap.

4.4 FE modelling: strengths and limitations

The finite element modelling technique has been successfully implemented in brake system analysis due to its ability to allow for the investigation of temperature and stress values inside the rotor, rather than just on its surface. Modern thermo-mechanical investigations still utilize finite elements analysis techniques in assessing the functionality of different brake disc designs (Belhocine and Bouchetara, 2013; Jiang et al., 2019; Sivaprakasam et al., 2022).

Nevertheless, the literature also warns against overclaiming FE precision. Vdovin and Le Gigan show that brake-cooling simulations are affected by challenges that cannot always be fully captured, particularly those related to airflow, surrounding components, and boundary conditions. This means a good FE study should be framed honestly: it is best used as a comparative design tool, not as an exact replica of every physical effect. This position is academically stronger than pretending the model is perfect (Vdovin and Le Gigan, 2020).

Another important consideration in FE modelling is the sensitivity of results to boundary conditions. Minor changes in convection coefficients, assumptions about heat distribution or contacts result in substantial discrepancies between results concerning temperature and stresses generated. This uncertainty cannot be eliminated, but one could try to reduce its impact by making sure the same assumptions are made regarding all designs studied. In this way, any relative discrepancies that could arise from such assumptions would cancel out each other, allowing for proper assessment of differences in performance between two or more designs (Riva et al., 2019; Topczewska and Grzes, 2022; Sha et al., 2022).

The above-mentioned method is because the point of studying the design is not to determine service life accurately or recreate every parameter, but to assess relative performance of different designs. This strategy provides a more defensible basis for a proposal-stage project.

4.5 Research gap

The literature, therefore, points to a clear and manageable gap. There is already strong evidence that brake discs experience non-uniform thermal loading, that ventilated geometry affects heat dissipation, and that FE analysis is a valid approach to studying the coupled problem. What is less common is a tightly scoped comparison of selected ventilated automotive disc geometries under repeated braking within one consistent FE framework using temperature uniformity and thermal stress concentration as the main comparison metrics.

The significance of this gap lies not in the absence of research but in the lack of integration between existing areas of study. Thermal behaviour, airflow characteristics and structural response have often been investigated separately, resulting in a fragmented understanding. The present study addresses this limitation by combining these aspects within a single, controlled modelling framework. This integrated approach allows for a more coherent evaluation of design performance and strengthens the overall contribution of the research.

5. Methodology

This study adopts a quantitative, simulation-based methodology using finite element analysis. The method is chosen because it allows for the evaluation of temperature and stress distributions under controlled, repeatable conditions. Compared with a fully experimental approach, FE modelling is more feasible within the time available and better suited to isolating the effect of geometry while holding other assumptions constant (Vdovin and Le Gigan, 2020; Belhocine and Bouchetara, 2013).

5.1 Geometry selection and model development

A 3D model of a ventilated brake disc will be created in CAD and imported into ANSYS. The study will compare a small set of representative ventilated geometries, for example, straight-vane and curved-vane type designs, or other practical variants, depending on modelling feasibility. The aim is not to test every possible design, but to compare selected internal vane concepts under the same conditions. This keeps the study controlled and realistic for the dissertation timeframe (Park et al., 2022; Huang, Chiu and Wu, 2022).

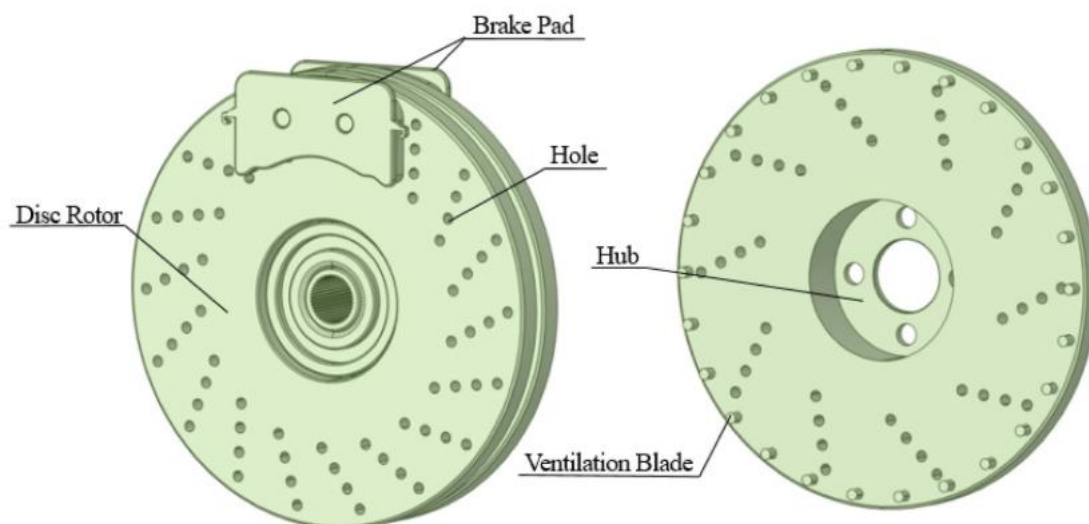


Figure 4. Labelled ventilated brake-disc geometry used to illustrate the model configuration.

Source: Adapted from Belhocine and Bouchetara (2013) and Jiang et al. (2019).

5.2 Material model and assumptions

The disc material will be kept constant across all compared geometries, isolating the effect of geometry. This is an important design decision. Including both geometry and material as major variables would broaden the study too much and weaken the interpretation. The material model will use literature-supported thermophysical and mechanical properties appropriate for an automotive brake rotor. A mesh-independence study will also be conducted to ensure that the key outputs are not dependent solely on mesh size (Jiang et al., 2019; Sivaprakasam et al., 2022).

Material properties such as thermal conductivity, specific heat capacity and elastic modulus are temperature-dependent in real applications. However, incorporating fully temperature-dependent material behaviour would significantly increase model complexity. Therefore, a simplified approach is adopted, using representative constant properties derived from literature. This approach balances model accuracy with computational feasibility and is appropriate for the scope of a postgraduate research proposal.

A controlled scope is adopted to maintain clarity of interpretation and feasibility within the project timeframe. In this study, geometry is prioritised over material variation because the research question focuses on design-driven thermo-mechanical behaviour under repeated braking, rather than broader brake-system optimisation.

5.3 Thermal loading and boundary conditions

Repeated braking will be represented through transient thermal loading applied at the pad track. The load will be derived from braking energy principles and implemented as a time-varying frictional heat input. Convection will be applied to exposed disc surfaces using literature-supported values and kept consistent across all designs. This is a deliberate methodological trade-off: the study sacrifices full airflow realism to achieve a fair geometry comparison within a single coherent FE framework. That trade-off is justified by the research aim (Topczewska and Grzes, 2022; Vdovin and Le Gigan, 2020).

The calculation of thermal input will be based on braking energy principles, where a proportion of the vehicle's kinetic energy is converted into heat at the disc surface. While this approach simplifies the complexities of real-world conditions, such as pad wear and friction variation, it provides a consistent, repeatable method for applying thermal loads across different geometries. This consistency is essential for ensuring that comparisons between designs are valid and not influenced by variations in loading assumptions.

Repeated braking is adopted because single-event simulations may underestimate cumulative heat buildup and fail to capture the same degree of thermal severity. This strengthens the realism of the modelling approach and ensures that the loading condition better reflects the engineering problem.

5.4 Thermo-mechanical coupling and outputs

The transient temperature distribution will be analysed structurally for the determination of thermal stress and deformations. The major parameters that will be considered include the maximum temperature value, temperature uniformity throughout the disc, von Mises stress, deformation, and location of hot-spots or stress concentrations. This is due to the relevance of these factors to the thermal effects. The study is not intended to predict the exact crack-growth life. Instead, it is intended to identify thermal-risk locations and relative design improvements. That is a stronger and more defensible scope for a proposal-stage FE study (Goo, 2018; Wang et al., 2022).

In addition to the primary outputs, a qualitative assessment of the distribution of temperature contours will be performed to identify patterns of heat concentration. Visual interpretation of contour plots can provide valuable insight into thermal behaviour that may not be fully captured through numerical values alone. This combined quantitative and qualitative approach strengthens the study's analytical depth and supports a more comprehensive interpretation of the results.

5.5 Validation strategy

Initial validation will be literature-based. The thermal and stress trends predicted by the model will be compared against published brake-disc behaviour from open literature. The proposal also leaves a clear pathway for later validation using thermocouples or infrared

thermography, which would strengthen the dissertation phase without requiring the present proposal to overpromise experimental work (Goo, 2018; Kukulski, Grzes and Adamowicz, 2023).

This validation strategy is appropriate for a proposal-stage study and avoids overstating predictive capability.

6. Expected Results and Contribution

It is expected that ventilated geometry will significantly influence both thermal distribution and structural response. Designs that support more effective cooling should show lower peak temperatures and, more importantly, more uniform thermal fields. A more uniform temperature distribution is expected to reduce local thermal gradients and, consequently, stress concentration (Park et al., 2022; García-León, Afanador-García and Gómez-Camperos, 2021).

It is also expected that different geometries will demonstrate trade-offs between cooling efficiency and structural response. For example, a design that promotes rapid heat dissipation may reduce peak temperature but could still produce localised thermal gradients if airflow distribution is uneven. Therefore, the evaluation of performance will consider not only absolute values but also the balance between thermal and structural behaviour.

The contribution of the study is not that brake-disc thermal behaviour has never been studied before. The contribution is that it provides a focused, comparative thermo-mechanical evaluation of selected ventilated automotive brake-disc geometries under repeated braking using one consistent FE approach. That contribution is important insofar as it relates geometries to outputs related to durability. From a practical, methodological, and academic perspective, this contribution exists. Practically, the paper informs designers; methodologically, the paper uses a systematic coupled FE model; and from an academic perspective, the paper closes a research gap in terms of repeated braking geometry comparisons.

The methodology used in this study is an important part of its contribution. By using a uniform modelling approach, the study provides future researchers with an easy-to-follow path to replicate the results and further extend knowledge. The value of the work, therefore, lies in decision support: it is expected to help answer an engineering design question about which internal geometry provides better thermal behaviour without overstating the model's ability to predict exact service life.

7. Evaluation, Limitations and Ethics

One of the significant advantages of this proposed research is the well-defined scope of work, keeping the study feasible and solving an engineering problem. The weaknesses of the research have been clearly specified, including assumptions about convection and heat inputs, a lack of modelling of crack propagation, and a lack of computational fluid dynamics for airflow. These limitations do not invalidate the study but define the results as comparative design evidence rather than exact failure prediction.

Exclusion of wear and frictional variation, which can influence thermal behaviour over time, is another limitation. These factors are acknowledged but excluded to maintain a focused and manageable scope. The main practical risk relates to the time required for FE setup, debugging and mesh checking, rather than theoretical considerations. Model preparation and error correction may take longer than initially anticipated, further justifying the controlled scope.

The section on ethics in the report should be brief since there is an ethics form that will be filled out separately. Nonetheless, it is prudent to be ethically aware. This experiment does not include any human subjects or confidential data. Thus, the ethics in this research concern primarily the proper documentation, referencing of sources, and depiction of limitations associated with modelling. Ethics also apply to academic honesty, such as presenting results objectively and without exaggeration. The experiment will present all results honestly and support them with the required evidence.

8. Timetable

The project will be completed over a 12-week period. The timeline is practical and provides some overlap of phases, particularly when setting up the models, doing the analysis, and writing. Extra time will be provided in FE stages for iterations and debugging.

Task	Weeks 1-2	3-4	5-6	7-8	9-10	11-12
Literature review	■					
CAD modelling		■				
FE setup and mesh study		■	■			
Transient thermal analysis			■	■		
Thermo-structural analysis				■	■	
Interpretation and writing					■	■

9. Conclusion

This proposal outlines a focused research plan to investigate the effect of ventilated brake disc geometry on temperature distribution and thermal stress during repeated braking, using finite-element analysis. The literature clearly shows that brake discs do not fail simply because they become hot; they fail because repeated braking can produce localised temperature peaks, thermal gradients, and stress concentrations that accumulate into durability problems. At the same time, open literature also shows that geometry meaningfully affects cooling and stress behaviour, while numerical brake studies remain sensitive to modelling assumptions (Goo, 2018; Park et al., 2022; Vdovin and Le Gigan, 2020).

The value of the present study is found in its controlled scope and defensible contribution. Rather than attempting to address the entire brake durability problem, the study provides a clear comparative assessment of selected ventilated geometries under repeated braking, using outputs relevant to durability such as peak temperature, temperature uniformity and thermal stress concentration. This approach ensures technical realism, academic justification and suitability for postgraduate-level investigation.

This proposal's advantage lies in the appropriate combination of technical sophistication and practicability. It eliminates unnecessary complications by tackling a significant engineering issue. This approach exhibits an adequate grasp of the fundamentals of research methodology. Its orientation towards comparative analysis guarantees that the results obtained are not only informative but also offer practical solutions. As such, the study can be classified as an appropriately designed project that will contribute significantly to theoretical and applied literature related to brake systems.

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