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Integrated Thermal–Structural Risk Assessment of Slotted Brake Disc Manufacturing Using FEA and FMEA Techniques

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Abstract

Slotted brake discs are widely adopted in high-performance automotive braking systems owing to their superior heat dissipation characteristics and improved wet-weather performance. However, the introduction of slot features creates stress concentration zones that may lead to thermal fatigue, crack initiation, and premature structural failure of the brake disc. This paper presents an integrated Risk Assessment and Method Statement (RAMS) framework that combines Finite Element Analysis (FEA) for thermal and structural simulations with Failure Mode and Effects Analysis (FMEA) for systematic risk assessment and quantification. Temperature distributions and Von Mises stress fields are obtained through coupled computational analysis under realistic braking conditions. Ten critical failure modes are identified and ranked using the Risk Priority Number (RPN) methodology. The parametric study compares solid, six-slot, and eight-slot disc configurations fabricated from grey cast iron (IS 210 Gr. FG 260). The results show that slot geometry significantly reduces peak disc temperature while simultaneously increasing localised stress concentrations at the slot edges. The highest RPN recorded is 144 for slot surface wear, while the eight-slot configuration demonstrates the best thermal performance. The proposed RAMS framework provides a structured approach for brake disc geometry optimisation, manufacturing quality planning, and engineering decision-making.

Keywords: RAMS; FMEA; Brake Disc; FEA; Thermal Stress; Von Mises Stress; Risk Priority Number (RPN); Slot Geometry; ANSYS.

1. Introduction

Disc brake systems are among the most safety-critical components in modern automotive engineering, directly influencing vehicle safety, braking efficiency, and operational reliability. Among various brake disc configurations, slotted brake discs have gained widespread industrial application owing to their ability to dissipate heat efficiently, remove frictional gases and debris, and improve braking performance under demanding operating conditions. Despite these advantages, the introduction of slot features creates geometric discontinuities that act as stress concentration regions under combined thermal and mechanical loading, increasing the likelihood of thermal fatigue, crack initiation, and structural degradation [1].

Advances in computational engineering have enabled the extensive use of Finite Element Analysis (FEA) for evaluating the thermal and structural behaviour of brake discs under realistic operating conditions. FEA provides valuable insights into temperature distribution, thermal stresses, deformation, and structural integrity, thereby reducing the dependence on costly experimental investigations during the design stage. However, many existing studies primarily focus on either thermal performance or structural behaviour independently, with comparatively limited emphasis on integrating simulation results with structured engineering risk assessment methodologies [2], [3].

Failure Mode and Effects Analysis (FMEA) is a systematic reliability assessment technique widely employed to identify potential failure modes, evaluate their consequences, and prioritise corrective actions using the Risk Priority Number (RPN). Recent studies have demonstrated the successful application of FMEA and Design Failure Mode and Effects Analysis (DFMEA) in improving the reliability of engineering systems, including renewable energy systems and lithium-ion battery packs, through structured risk assessment and design optimisation [11], [12]. These studies highlight the growing importance of integrating engineering simulations with quantitative risk evaluation to support informed design and manufacturing decisions.

This paper addresses this research gap by presenting an integrated Risk Assessment and Method Statement (RAMS)-based evaluation framework for slotted brake disc manufacturing. The objectives of this study are: (i) to model and simulate the thermal and structural behaviour of slotted brake discs under representative braking conditions using FEA; (ii) to identify and prioritise potential failure modes through FMEA; and (iii) to compare solid, six-slot, and eight-slot brake disc configurations to recommend an optimised design for improved thermal performance, structural reliability, and manufacturing quality.

2. Literature review

Belhocine and Bouchetara [1] conducted a transient thermal analysis of solid ventilated brake discs under single-stop braking conditions. Their finite element model predicted maximum surface temperatures exceeding 300 °C and identified the rotor-hat interface as a critical hotspot region. Similarly, Talati and Jalalifar [3] investigated heat conduction within disc brake systems and demonstrated the significant influence of convective cooling on reducing rotor temperatures, particularly at the outer friction surface.

Limpert [7] established a comprehensive analytical framework for brake thermal calculations and developed the fundamental heat flux relationships that continue to serve as the basis for many simulation-based investigations. Lee [10] further employed numerical simulations to predict temperature distributions in brake discs and validated the numerical results through brake dynamometer experiments, demonstrating good agreement between simulation and experimental observations.

From the perspective of engineering reliability, IEC 60812 [4] and MIL-STD-1629A [5] provide internationally recognised procedures for conducting Failure Mode and Effects Analysis (FMEA) and Failure Mode, Effects and Criticality Analysis (FMECA). These standards provide a systematic methodology for identifying potential failure modes, evaluating their consequences, and prioritising corrective actions using the Risk Priority Number (RPN).

Recent studies have extended the application of FMEA beyond conventional manufacturing processes to advanced engineering systems. Survase and Somatkar [11] applied FMEA to compare the reliability of solar photovoltaic and wind energy systems, demonstrating the effectiveness of Severity, Occurrence, and Detection rankings in evaluating engineering risks. Likewise, Jadhav *et al.* [12] integrated Design Failure Mode and Effects Analysis (DFMEA) with generative artificial intelligence to optimise lithium-ion battery pack design, illustrating how structured risk assessment can support engineering design optimisation and improve system reliability. Despite these advancements, most published studies primarily investigate the thermal and structural performance of brake discs or apply FMEA independently as a qualitative risk assessment tool. Comparatively few studies integrate Finite Element Analysis (FEA)-derived thermal and structural results directly with FMEA to establish quantitative risk priorities for brake disc manufacturing and design optimisation. This study addresses this gap by integrating thermal-structural simulation with FMEA within a unified Risk Assessment and Method Statement (RAMS) framework, thereby providing a systematic approach for evaluating brake disc performance, identifying critical failure modes, and supporting engineering decision-making.

3. Methodology

3.1. Disc geometry and material properties

A parametric CAD model of the brake disc was developed with the following baseline specifications: outer diameter of 280 mm, inner diameter of 80 mm, disc thickness of 22 mm, hat height of 38 mm, and six uniformly spaced radial slots, each having a width of 4 mm and a depth of 8 mm, machined at an angular spacing of 60°. An eight-slot configuration with slots positioned at 45° intervals was also modelled for comparative parametric analysis.

The brake disc material selected for this study was grey cast iron conforming to IS 210 Gr. FG 260, which is widely used in commercial and high-performance brake disc manufacturing because of its favourable thermal conductivity, wear resistance, and damping characteristics. The material properties used in the finite element analysis are presented in Table I.

Table 1: *Material properties of IS 210 Gr. FG 260*

Property	Value
Density (kg/m³)	7200
Thermal Conductivity (W/m·K)	48.50
Specific Heat Capacity (J/kg·K)	502.00
Young's Modulus (GPa)	138.00
Poisson's Ratio	0.26
Coeff. of Thermal Expansion ($\times 10^{-6}$/°C)	11.20
Tensile Strength (MPa)	260.00
Yield Strength (MPa)	195

3.2. Thermal analysis (FEA)

Heat generation at the brake pad-disc interface was modelled using the following heat flux relationship:

$$q = \mu P v \ldots\ldots(1)$$

where q is the heat flux (W/m²), μ is the coefficient of friction (0.38), P is the brake pad pressure (1.2 MPa), and v is the disc surface velocity. An initial disc temperature of 25 °C was assumed, while convective cooling was applied to all exposed surfaces using a heat transfer coefficient of h = 65 W/m²·K to represent rotating operating conditions. The simulation represents an emergency braking event from an initial speed of 100 km/h to rest within 4.2 s.

3.3. Structural analysis (FEA)

The temperature distribution obtained from the thermal analysis was imported into the structural model as a body load. Additional boundary conditions included a rotational speed of 1200 rpm at the hub to represent pre-braking conditions, a brake pad pressure of 1.2 MPa acting on the friction surfaces, and fixed supports at the mounting bolt holes. The finite element model was used to evaluate the Von Mises stress distribution, total deformation, and principal stress directions.

A tetrahedral mesh with a global element size of 2.5 mm was generated and locally refined to 1.0 mm around the slot edges, where high stress gradients were expected. This mesh refinement strategy ensured improved resolution of stress concentrations associated with the notch effect and enhanced the accuracy of the structural analysis.

3.4. Failure Mode and Effects Analysis (FMEA) and Risk Priority Number (RPN) calculation

Failure Mode and Effects Analysis (FMEA) was performed in accordance with the IEC 60812:2018 standard. Potential failure modes were identified through literature review, engineering analysis, and finite element simulation results. Each failure mode was evaluated using three risk parameters on a scale of 1 to 10:

- **Severity (S):** Impact of the failure on system safety and functionality.
- **Occurrence (O):** Estimated likelihood of the failure occurring.
- **Detection (D):** Probability of detecting the failure before it reaches the end user.

The Risk Priority Number (RPN) was calculated using:

$$RPN = S \times O \times D \ldots\ldots(2)$$

Failure modes with RPN ≥ 100 were classified as High Risk, those with RPN values between 70 and 99 were classified as Medium Risk, and those with RPN < 70 were considered Low Risk.

These classifications were subsequently used to establish the RAMS-based recommendation framework for brake disc design evaluation and manufacturing quality planning.

4. FMEA results and risk ranking

Ten critical failure modes were identified and analysed. Table II presents the complete FMEA results together with the corresponding Risk Priority Number (RPN) values. Failure modes with RPN ≥ 120 are classified as High Risk, those with 100 ≤ RPN < 120 as Medium-High Risk, and those with RPN < 100 as Acceptable Risk.

Table 2: *FMEA risk assessment for slotted brake disc manufacturing*

Failure Mode	Cause	Effect	S	O	D	RPN
Thermal Cracking at Slot Edge	Repetitive thermal cycling	Structural failure	9	4	3	108
Thermal Fatigue Fracture	High heat flux + rapid cooling	Disc fracture risk	10	3	4	120
Slot Surface Wear	Abrasive pad contact	Vibration, reduced life	6	6	4	144
Residual Stress – Machining	Improper slot tolerances	Micro-crack initiation	7	5	3	105
Uneven Heat Distribution	Asymmetric slot geometry	Brake judder	7	4	4	112
Disc Warpage	Sustained high temperature	Uneven pad wear	8	3	3	72
Material Porosity	Casting defect	Reduced tensile strength	8	2	5	80
Corrosion at Slot Groove	Moisture + salt exposure	Surface integrity loss	5	7	3	105
Fatigue at Mounting Holes	Cyclic rotational stress	Disc detachment risk	10	2	4	80
Stress at Slot Tip	Sharp corner radius	Crack propagation	9	4	2	72

The highest RPN value of 144 corresponds to Slot Surface Wear, primarily due to its relatively high occurrence rating (O = 6) resulting from continuous pad-disc contact during braking. The second-highest RPN value of 120 is associated with Thermal Fatigue Fracture, which, despite a lower occurrence rating, exhibits the highest severity (S = 10) because of its potential to cause catastrophic brake disc failure.

Corrosion at Slot Groove (RPN = 105) and Residual Stress from Machining (RPN = 105) are classified as medium-high risk failure modes and are particularly significant from a manufacturing perspective, as both can be effectively mitigated through improved process control and machining practices. In contrast, Disc Warpage and Stress at Slot Tip each have an RPN value of 72, indicating comparatively lower, yet still noteworthy, levels of risk that should be considered during design and manufacturing.

5. Simulation results

5.1. Thermal analysis results

The maximum surface temperature of the solid brake disc reached 312 °C, with the highest temperature concentrated near the outer friction radius, approximately 120 mm from the disc centre. The slotted brake discs demonstrated improved thermal performance compared with the solid disc. The six-slot configuration exhibited a peak temperature of 287 °C, corresponding to a reduction of 8.0%, while the eight-slot configuration achieved a peak temperature of 274 °C, representing a reduction of 12.2%.

The improved thermal behaviour of the slotted configurations can be attributed to enhanced convective airflow through the slot passages, which increases the effective heat transfer area and disrupts the thermal boundary layer on the friction surface. Consequently, the slotted designs provide more efficient heat dissipation under braking conditions.

5.2. Structural analysis results

The maximum Von Mises stress in the solid brake disc was 186 MPa, which remained below the material yield strength of 195 MPa, indicating safe structural performance under the simulated loading conditions. In comparison, the six-slot and eight-slot configurations exhibited higher peak stresses of 214 MPa and 231 MPa, respectively, with stress concentrations localised near the inner corners of the slot terminations.

Although the eight-slot configuration provides superior thermal performance, its maximum stress exceeds the nominal yield strength of the selected material, indicating an increased likelihood of localised plastic deformation under severe braking conditions. This observation supports the higher Severity rating assigned to the Stress at Slot Tip failure mode within the FMEA.

Table 3: *Comparative simulation results*

Parameter	Solid Disc	6-Slot	8-Slot
Max Temperature (°C)	312	287	274
Max Von Mises Stress (MPa)	186	214	231
Max Deformation (mm)	0	0.27	0.31
Highest RPN	–	144	138
Avg. Heat Dissipation (W/m²)	4820	5410	5870

The deformation results follow a consistent trend, with the maximum deformation increasing from 0.21 mm for the solid disc to 0.31 mm for the eight-slot configuration, representing an increase of approximately 48%. Although the absolute deformation values remain relatively small, the observed increase may influence brake judder characteristics and disc run-out under repeated braking cycles. These structural observations provide quantitative support for the Severity ratings assigned during the FMEA process.

6. Discussion

The integrated RAMS framework adopted in this study highlights the fundamental trade-off associated with slotted brake disc design. Increasing the number of slots improves heat dissipation and reduces peak operating temperature; however, it also increases stress concentration around the slot edges, thereby influencing the structural integrity of the brake disc. The thermal and structural simulation results demonstrate that brake disc optimisation requires a balanced consideration of both cooling performance and mechanical reliability.

From an FMEA perspective, the six-slot configuration provides a more balanced compromise between thermal performance and structural behaviour. Although its average heat dissipation (5410 W/m²) is lower than that of the eight-slot configuration (5870 W/m²), the corresponding peak Von Mises stress (214 MPa) is lower than that observed in the eight-slot design (231 MPa). This indicates a comparatively lower structural risk while still providing a significant improvement in thermal performance over the solid brake disc configuration.

The highest Risk Priority Number (RPN = 144) was associated with Slot Surface Wear, indicating that surface degradation due to continuous pad-disc interaction represents the most critical failure mode. Consequently, tribological surface treatments, such as electrolytic nickel plating or plasma spray coating, may be considered to improve wear resistance and extend component service life. Similarly, Thermal Fatigue Fracture (RPN = 120) represents another significant reliability concern, suggesting that improved thermal management strategies and alternative high-performance materials, such as austempered ductile iron (ADI), may enhance brake disc durability under severe operating conditions.

From a manufacturing perspective, Residual Stress from Machining and Corrosion at Slot Groove, each with an RPN value of 105, represent medium-high risk failure modes that can be effectively mitigated through tighter machining tolerances, improved process control, and the application of appropriate corrosion-resistant surface treatments. These findings demonstrate that manufacturing quality control plays an equally important role alongside design optimisation in improving brake disc reliability.

Overall, the integration of Finite Element Analysis (FEA) with Failure Mode and Effects Analysis (FMEA) provides a systematic framework for linking computational simulation with engineering risk assessment. By incorporating simulation-derived thermal and structural results into the FMEA process, the proposed RAMS framework supports quantitative design evaluation, prioritisation of critical failure modes, and informed engineering decision-making during brake disc design and manufacturing.

7. Conclusion

This study presented an integrated Risk Assessment and Method Statement (RAMS) framework for evaluating slotted brake disc manufacturing by combining Finite Element Analysis (FEA) with Failure Mode and Effects Analysis (FMEA). Based on the thermal, structural, and risk assessment results, the following conclusions are drawn:

- Slotted brake disc configurations reduced the peak operating temperature by approximately **8–12%** compared with the solid brake disc, with the eight-slot configuration exhibiting the greatest thermal performance.
- Increasing the number of slots improved heat dissipation but also increased stress concentration around the slot edges. The eight-slot configuration exhibited the highest Von Mises stress, indicating the need for slot geometry optimisation, particularly with respect to corner radius design.
- Slot Surface Wear (RPN = 144) and Thermal Fatigue Fracture (RPN = 120) were identified as the most critical failure modes and should therefore receive priority during brake disc design, material selection, and manufacturing quality control.
- The six-slot configuration provided the most balanced compromise between thermal performance and structural reliability for conventional automotive braking applications.
- The proposed RAMS framework offers a systematic approach for integrating thermal-structural simulation with engineering risk assessment and may be applied to the design evaluation and manufacturing quality planning of other thermally loaded rotating mechanical components.

Future work should focus on experimental validation through brake dynamometer testing, Digital Image Correlation (DIC) for surface strain measurement, and comparative investigations involving advanced brake disc materials such as austempered ductile iron and carbon-ceramic composites. Furthermore, probabilistic techniques, including Monte Carlo simulation, may be employed to improve the robustness of FMEA occurrence estimation and enhance the reliability of engineering risk assessment.

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