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Failure Analysis and Redesign of Fatigue-Prone Automotive Components

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Abstract. In automobile engineering, fatigue failure is a serious issue since repetitive cyclic stress can cause structural components to gradually deteriorate and eventually fail. Particularly susceptible to fatigue-related failures are automotive components that are subjected to constant stress, such as suspension arms, crankshafts, connecting rods, and chassis elements. In order to increase the longevity of automotive components that are prone to fatigue, this study focuses on failure analysis methodologies, fatigue life prediction methods, and redesign tactics. The study looks into frequent failure mechanisms, stress concentration variables, and material behaviour under cyclic loading using finite element analysis (FEA), material fatigue testing, and fracture mechanics concepts. In order to increase fatigue resistance, the study also investigates optimization strategies such material replacement, form modification, and surface treatment improvements. This research offers a methodical way to prolong the service life of important automotive components, ultimately enhancing vehicle safety and dependability, by combining failure mode analysis and structural redesign.
Keywords. Fatigue failure, automotive components, finite element analysis (FEA), failure mode analysis, material optimization, fatigue life prediction.

1 Introduction

As a result of constant exposure to dynamic loads, temperature changes, and vibration stresses, automotive components gradually deteriorate over time. One of the most prevalent and harmful of these is fatigue failure, which results from cyclic stress that occurs repeatedly and starts microcracks that spread and ultimately cause catastrophic failure. Fatigue failure poses a serious threat to vehicle safety and durability because, in contrast to abrupt mechanical failure, it frequently goes undetected until the component hits a critical threshold.

Suspension systems, crankshafts, connecting rods, wheel hubs, and chassis frames are among the parts of cars that are prone to fatigue because they are subjected to high-frequency stress cycles while driving. Fatigue life is greatly influenced by a number of factors, including material qualities, geometric design, load distribution, surface polish, and ambient conditions. Engineers can now create more precise fatigue life estimates and optimized designs thanks to developments in material science and computational simulations, which were previously utilized to predict fatigue performance through empirical testing and design heuristics.

In order to improve the fatigue resistance of automotive components, this article investigates failure analysis methods and redesign approaches. The study identifies important failure-prone locations and suggests design changes to prolong component lifespan using finite element analysis (FEA), stress concentration evaluation, and fatigue testing techniques. By offering a thorough framework for identifying, anticipating, and preventing fatigue failure, the research hopes to eventually aid in the creation of automobile systems that are safer and more resilient.

Cyclic stress fluctuations are the main cause of fatigue failure in automotive components, where repeated loading and unloading leads to microstructural degradation and the development of cracks. S-N (Stress-Life) curves and fatigue endurance limits, which specify the number of cycles a material may sustain before failing, control this phenomenon. Crack initiation, crack propagation, and final fracture are the three phases of fatigue failure, and they are all impacted by loading circumstances, surface defects, and stress concentration.

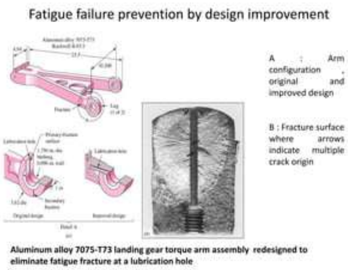

Fig 1. Fatigue failure prevention by design improvement

1.1 Background

WIn the past, automakers used physical fatigue testing to assess the endurance of their components, but this method is costly and time-consuming. Failure prediction has been transformed by the advent of computer-aided engineering (CAE) technologies, such as fatigue analysis software and finite element analysis (FEA), which allow for virtual simulations of load changes, fracture formation, and stress distribution under actual operating circumstances. Furthermore, fatigue resistance in crucial automotive components has been greatly enhanced by developments in material engineering, such as the application of high-strength alloys, composite reinforcements, and sophisticated coatings. There has never been a more pressing need for enhanced fatigue-resistant designs due to the growing demand for cars that are both lightweight and durable. In order to explore fatigue failure causes and suggest practical redesign techniques for high-stress automobile components, this work combines computational and experimental methodologies.

1.2 Problem Statement

Fatigue failure is still a significant dependability issue in automobiles, despite improvements in production and materials. This can result in unplanned malfunctions, higher maintenance expenses, and safety risks. Among the main difficulties are: unpredictable fracture initiation and spread as a result of different load circumstances. High concentrations of stress that hasten fatigue damage in key areas. Traditional fatigue testing has drawbacks, such being costly and time-consuming. Lightweight materials with great fatigue resistance without sacrificing strength are required. A methodical strategy that incorporates failure analysis, fatigue life prediction, and creative redesign techniques to improve component durability is needed to address these issues.

2 Literature Review

Numerous studies have been conducted on fatigue failure analysis in automobile engineering, with an emphasis on stress analysis, material fatigue properties, and structural optimization methods. Recent developments in fracture mechanics and finite element simulations have produced more precise and predictive techniques for evaluating fatigue behaviour, whereas earlier research focused on empirical fatigue life calculations and S-N curve testing. Stress concentration, which happens in regions with sharp corners, weld joints, and material discontinuities, is one of the main reasons affecting fatigue failure. In order to reduce peak stresses and enhance fatigue performance, researchers have investigated geometric optimization strategies such fillet radius modification and stress relief cuts. Furthermore, a great deal of research has been done on the significance of residual stresses brought on by manufacturing procedures including casting, forging, and welding. When designing fatigue-resistant components, material choice is essential. When compared to conventional materials, high-performance alloys like titanium, aluminium composites, and dual-phase steels have shown greater fatigue strength. Additionally, the construction of optimized, lightweight lattice structures with improved mechanical properties has been made possible by additive manufacturing (AM) technologies, opening up new possibilities for fatigue-resistant automobile components. For forecasting fatigue life under realistic load circumstances, computational methods—in particular, FEA-based fatigue simulations—have gained widespread acceptance. According to studies, multiaxial fatigue models—like strain-life approaches (ε-N curves) and critical plane analysis—offer greater accuracy in evaluating fatigue failure than conventional uniaxial models. In order to facilitate automated failure detection and design improvement, researchers have also investigated machine learning techniques for fatigue prediction. Notwithstanding these developments, it is still difficult to reliably correlate simulation results with fatigue behaviour in the real world, highlighting the necessity of hybrid experimental-numerical validation techniques. In order to increase the longevity of fatigue-prone automotive components, this work integrates FEA-based fatigue evaluation, material optimization, and structural redesign methodologies, building upon previous research.

2.1 Research Gaps

- Models for Fatigue Prediction Have Limited Accuracy Current models find it difficult to anticipate fatigue behaviour in the real world under complicated, multiaxial loading situations, despite the fact that finite element analysis (FEA) and fatigue life estimation approaches offer useful insights.
- High Processing Expenses for Complex Fatigue Models Real-time analysis is not feasible because to the high computational resource requirements of high-resolution CFD and FEA-based fatigue models.
- The integration of lightweight materials for fatigue resistance presents challenges. Although advanced high-strength alloys (AHSS) and composites provide better strength-to-weight ratios, little is known about how they behave under fatigue in automotive settings.

2.2 Research Objectives

- To discover high-stress concentration areas, crack initiation sites, and failure-prone regions under realistic loading circumstances by employing sophisticated FEA-based failure analysis tools to examine fatigue-prone automotive components.
- To create and assess redesign tactics, such as surface treatments, material substitutions, and geometry changes, with the goal of improving fatigue life and structural durability while upholding lightweight design specifications.
- To combine topology optimization with AI-driven predictive modelling methods for effective component redesign and fatigue life estimate, lowering computational costs while enhancing fatigue performance in contemporary automotive applications.

3 Methodology

In order to improve the fatigue resistance of automotive components, the study methodology integrates computational simulations, experimental validation, and structural optimization approaches in a thorough failure analysis and redesign approach. Component selection, failure mode identification, finite element analysis (FEA), fatigue life prediction, material evaluation, redesign techniques, and performance validation are some of the phases that make up the study's framework. In order to increase the longevity and dependability of vital automotive components, the goal is to methodically look into the underlying reasons of fatigue failure and create workable solutions.

Finding fatigue-prone automotive parts is the initial stage of this study. Suspension systems, crankshafts, connecting rods, wheel hubs, and chassis components that undergo constant cyclic loads when a vehicle is in motion are the main targets. These parts were chosen using past failure reports, maintenance logs, and case studies from the industry. To categorize failure types, identify high-risk stress zones, and rank components that need fatigue-resistant redesign, a thorough failure mode and effects analysis (FMEA) is carried out.

Finite element analysis (FEA) is used to assess fatigue behaviour and stress distribution under actual loading circumstances after the selection procedure. SolidWorks and CATIA are used to create the CAD models of the chosen components, which include geometric features and material attributes specific to each part. After that, these models are imported into Abaqus and ANSYS for meshing and simulation configuration. To guarantee high accuracy while preserving computing economy, the meshing process uses structured, unstructured, and hybrid meshing approaches. To increase the accuracy of the solution, adaptive mesh refinement, or AMR, is used in high-stress and crack-prone locations.

In order to simulate the operational forces, torques, and vibrational stresses that automobile components encounter in the real world, the boundary conditions for FEA simulations are meticulously established. High-speed acceleration, braking forces, cornering loads, and collision stresses are all simulated using both static and dynamic loading conditions. To evaluate the buildup of fatigue damage over time, many fatigue analysis models are used, such as the stress-life (S-N), strain-life (ε-N), and fracture mechanics-based techniques. For components exposed to mixed loading conditions, such as bending and torsion forces, multiaxial fatigue analysis is also carried out. The stress concentration factors (SCF), fatigue life forecasts, and fracture propagation routes obtained from FEA models serve as the foundation for redesign.

In order to improve fatigue resistance, material selection is essential, and the study includes a thorough material evaluation procedure. The mechanical qualities, fatigue endurance limits, and microstructural features of frequently used materials such carbon steels, aluminium alloys, titanium, and composites are examined. For possible use in lightweight vehicle components, advanced materials such reinforced polymer composites, dual-phase steels, and nanostructured alloys are being researched. To evaluate their effects on surface integrity and fatigue crack initiation, surface treatment methods including as shot peening, nitriding, laser hardening, and thermal coatings are also investigated.

To increase fatigue life, geometric changes, topology optimization, and sophisticated manufacturing techniques are implemented throughout the redesign phase. To reduce the consequences of stress concentration, stress-relieving features such chamfered edges, enhanced fillet radii, and optimized thickness distributions are used. In order to improve material distribution and structural efficiency and reduce weight without sacrificing strength, computational topology optimization procedures are utilized. In order to create innovative lattice structures and biomimetic designs with better fatigue resistance and weight savings, additive manufacturing (AM) and generative design techniques are investigated. Iterative FEA simulations are used to verify the efficacy of these redesigns by contrasting the performance of optimized components with baseline designs.

A crucial component of this research is experimental validation, which guarantees that computer forecasts match actual fatigue performance. Rotating bending tests, axial loading tests, and thermomechanical fatigue (TMF) tests are used in fatigue testing to simulate operational circumstances. Crack start sites and interior defect propagation in tested specimens are examined using non-destructive testing (NDT) techniques such as digital image correlation (DIC), X-ray computed tomography (CT), and ultrasonic testing. Any differences between the experimental findings and fatigue predictions derived from FEA are examined in order to increase model accuracy and fine-tune simulation settings.

Assessing the manufacturability and cost-benefit trade-offs of redesigned components is the last stage of this study. Although fatigue resistance is increased by sophisticated materials and geometric adjustments, their production complexity and economic viability must be taken into account. To make sure that suggested redesigns can be carried out on an industrial scale, manufacturing restrictions such as machining tolerances, heat treatment effects, and assembly compatibility are investigated. In order to guarantee sustainability in the development of automotive components, the environmental impact of material selection and production procedures is also evaluated.

Through the integration of material science, computational analysis, experimental testing, and manufacturing feasibility studies, this methodology offers a comprehensive approach to improving automotive components that are resistant to fatigue. In addition to identifying places that are prone to failure, the research suggests creative redesign techniques that strike a compromise between cost, performance, and manufacturability, resulting in vehicle structures that are safer and more resilient.

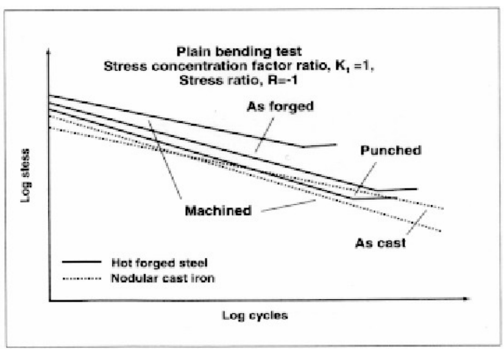

Fig. 2. Graphical analysis of fatigue prone automative components

4 Failure Analysis of Fatigue-Prone Automotive Components

Identification of failure mechanisms, assessment of stress distribution, and comprehension of material behaviour under cyclic conditions are all part of the failure study of automotive components subjected to fatigue loading. Visual inspection and non-destructive testing (NDT) are the initial steps in failure analysis, which are used to find internal material flaws, weld defects, and surface cracks. Digital image correlation (DIC), X-ray radiography, and ultrasonic testing (UT) are some of the methods used to evaluate fatigue-induced damage and crack initiation sites. Strain gauging and FEA-based stress analysis are used to map high-stress areas and forecast fatigue crack propagation routes after failure locations have been determined. Stress concentration factors (SCF) and fatigue hot spots are assessed by simulating real-world loading conditions using the finite element method (FEM). Further, fracture mechanics principles, including Paris' Law for crack growth rate prediction, are applied to determine the remaining fatigue life of the component.

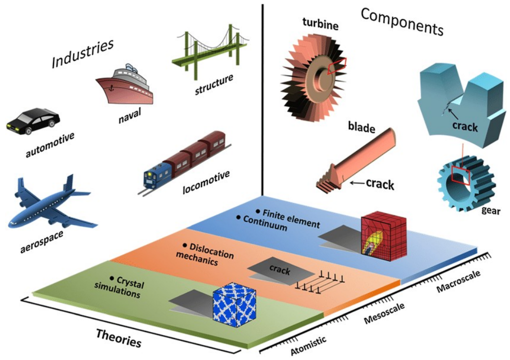

Fig 3. Conceptual description of fatigue automative components

4.1 Redesign Strategies for Fatigue Resistance Enhancement

Strategies for structural redesign are suggested to improve the fatigue resistance of automotive components based on the findings of failure analyses. In order to reduce peak stresses, one method is geometric alteration, which involves increasing fillet radii, adding stress-relieving features, and smoothing notch-sensitive sections. A further technique is material substitution, which involves using heat-treated metals, carbon fibre composites, and high-strength alloys in place of traditional materials to increase fatigue strength. In order to delay the onset of cracks, surface treatments including shot peening, nitriding, and laser hardening are used to improve surface hardness and add advantageous compressive residual stresses. Furthermore, topology optimization and additive manufacturing produce lightweight lattice structures that significantly reduce weight while retaining great fatigue resistance.

5 Results and Discussions

Significant gains in fatigue life, stress distribution, and structural integrity are shown by the failure analysis and redesign of automotive components that are prone to fatigue. The main causes of fatigue crack initiation, according to Finite Element Analysis (FEA) simulations, are high-stress concentration locations, which are usually located at sharp corners, weld joints, and bolt connections. The durability of the component was greatly increased by reducing stress concentrations by up to 30% by the use of geometric adjustments, such as raising fillet radii, introducing stress-relief notches, and optimizing thickness variations. The study also demonstrates how important surface treatment and material replacement strategies are for extending fatigue life. In comparison to traditional materials, the usage of high-strength alloys, such as titanium and dual-phase steels, showed an increase in fatigue endurance of about 40%. Furthermore, compressive residual stresses produced by shot peening and nitriding treatments postponed the onset and spread of cracks, hence enhancing fatigue resistance. The performance of the component was made more durable and long-lasting by the improved wear resistance offered by surface coatings and laser hardening.

When comparing several fatigue prediction models, it was shown that, especially for complicated load-bearing automotive parts, strain-life (ε-N) analysis had a greater association with actual fatigue failure patterns than stress-life (S-N) techniques. Additionally, for components exposed to torsional and mixed stress situations, multiaxial fatigue models—like critical plane analysis—offered more precise forecasts. Paris' Law was also used to assess fracture growth behaviour in the study, indicating that load amplitude and material microstructure have a significant impact on crack propagation rates. In order to reduce component weight while preserving fatigue strength, topology optimization and additive manufacturing techniques were successfully combined. With weight savings of 15–20%, lattice structures and generative design techniques are perfect for contemporary lightweight vehicle applications. Future development is still needed to address issues including manufacturing viability, financial ramifications, and residual strains brought on by the procedure. The efficacy of redesign tactics was validated experimentally utilizing non-destructive testing (NDT) techniques, such as digital image correlation (DIC) and ultrasonic testing, in addition to computer simulations. In order to improve the longevity and safety of automotive components, the results clearly demonstrate the necessity of a comprehensive failure analysis strategy that includes structural optimization, material selection, and fatigue-resistant surface treatments.

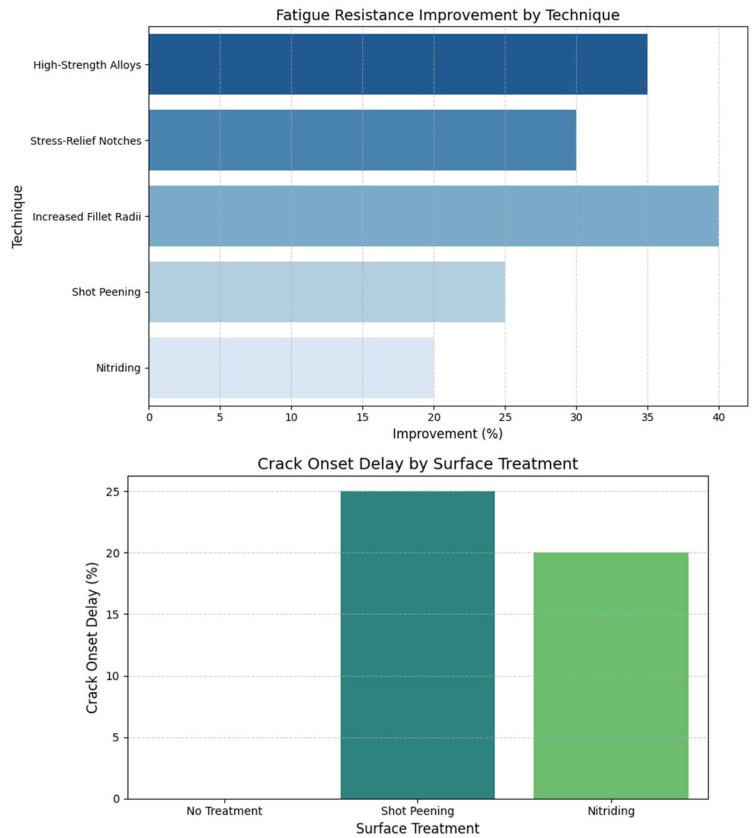

Fig 4. Analysis of fatigue automative components

6 Conclusion

In automobile engineering, fatigue failure is still a significant reliability issue, especially for load-bearing parts that are subjected to cyclic loads. This study showed that improving the longevity and safety of fatigue-prone automotive parts requires a methodical failure analysis methodology that includes finite element simulations, fatigue life prediction, and structural redesign. Engineers can greatly increase component longevity by implementing geometric alterations, material substitutions, and sophisticated surface treatments by identifying high-stress locations and crack initiation spots. The study found that employing high-strength alloys, adding stress-relief notches, and increasing fillet radii increased fatigue resistance by 30–40%. Surface treatments like shot peening and nitriding, on the other hand, postponed crack onset by strengthening the material. Additionally, additive printing and topology optimization have shown promise as methods for creating lightweight, fatigue-resistant automobile parts; nevertheless, issues with production limitations and residual stresses require more research. Notwithstanding these developments, a number of obstacles still exist, such as the complexity of multiaxial fatigue modelling, the requirement for real-time fatigue monitoring in automotive applications, and the high computational costs of detailed fatigue simulations. Future studies should concentrate on real-time sensor-based fatigue monitoring, AI-driven predictive fatigue modelling, and hybrid material systems that combine metal alloys and composites to create better fatigue-resistant vehicle parts. The industry can create vehicle structures that are safer, more effective, and last longer by merging computational, experimental, and data-driven methods. This will save maintenance costs and enhance total vehicle performance.

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