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Advanced Simulation-Based Assessment of Mechanical Component Stress, Fatigue, and Failure: A Comprehensive Research

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ABSTRACT

This study examines the stress, fatigue, and failure behaviour of mechanical components using numerical simulation techniques. Mechanical components are often subjected to static and cyclic loads, which may cause stress concentration, deformation, fatigue damage, crack initiation, and final failure. Finite Element Analysis was used to evaluate von Mises stress, total deformation, fatigue life, damage factor, and safety factor. The results showed that critical failure zones usually occur near holes, sharp edges, fillets, supports, and load application points. The study concludes that numerical simulation improves design accuracy, reduces testing cost, and enhances component reliability and service life.

Keywords: *Stress Analysis, Fatigue, Failure Analysis, Numerical Simulation.*

I. INTRODUCTION

Mechanical components form the essential foundation of almost every engineering system, ranging from simple machine elements such as shafts, bolts, gears, springs, bearings, brackets, and couplings to complex components used in automobiles, aircraft, turbines, pressure vessels, industrial machines, robotic systems, and power-generation equipment. These components are expected to perform safely and efficiently under different operating conditions, but in actual service they are continuously exposed to mechanical loads, thermal effects, vibration, friction, impact, corrosion, and repeated stress cycles. As a result, mechanical components may gradually experience deformation, wear, crack initiation, fatigue damage, and sudden failure. Stress is one of the most important factors responsible for such behaviour because it represents the internal resistance developed within a component when an external load is applied. If the induced stress exceeds the safe limit of the material, the component may undergo yielding, fracture, or permanent deformation. However, failure does not always occur due to a single overload; in many cases, components fail after repeated loading even when the applied stress is lower than the yield strength of the material. This type of failure is known as fatigue failure and is considered one of the most common causes of unexpected breakdown in mechanical systems. Fatigue is especially critical in components such as rotating shafts, crankshafts, connecting rods, turbine blades, gear teeth, suspension parts, aircraft wings, bridges, and pressure equipment, where cyclic loading is unavoidable. Since fatigue cracks often begin at small defects, sharp corners, holes, notches, weld joints, or other stress concentration zones, it becomes necessary to identify these weak areas during the design stage itself. Failure analysis, therefore, plays a vital role in understanding why a component fails, where the failure begins, how the crack grows, and what corrective measures can be taken to improve the safety and service life of the component. In modern mechanical engineering, the analysis of stress, fatigue, and failure has become an essential part of product design, quality improvement, safety assessment, and maintenance planning.

Traditionally, mechanical components were analysed through theoretical calculations, empirical design formulas, and experimental testing. Although these methods are valuable, they have certain limitations when dealing with complex geometries, irregular loading conditions, advanced materials, and real-life boundary conditions. Physical testing can be expensive, time-consuming, and sometimes difficult to perform at the early design stage. In addition, experimental methods may require several prototypes, repeated trials, specialized equipment, and destructive testing, which increases cost and development time. To overcome these limitations, numerical simulation techniques have become highly important in engineering analysis. Numerical simulation refers to the use of mathematical models and computer-based methods to predict the behaviour of engineering systems under specified conditions. Among these methods, Finite Element Analysis, commonly known as FEA, is one of the most widely used techniques for stress, fatigue, and failure analysis of mechanical components. In FEA, a complex component is divided into many small elements connected at nodes. The governing equations of mechanics are then solved numerically to obtain stress, strain, displacement, deformation, fatigue life, safety factor, and damage distribution. This approach allows engineers to study the actual behaviour of components in a virtual environment before manufacturing them. By applying suitable material properties, loading conditions, constraints, contact definitions, and mesh settings, simulation software can predict the regions where maximum stress or fatigue damage may occur. Numerical simulation also makes it possible to compare different design alternatives, materials, thicknesses, fillet radii, and load cases without producing multiple physical prototypes. For example, if a shaft shows high stress near a keyway, the designer can increase the fillet radius, modify the geometry, or select a stronger material and then re-run the simulation to check improvement. Similarly, if a bracket shows excessive deformation under load, its thickness or support condition can be optimized. In fatigue analysis, simulation can estimate the number of cycles a component may survive before failure, helping engineers design components with longer service life and better reliability. Thus, numerical simulation is not only a tool for analysis but also a powerful method for design optimization, cost reduction, and risk prevention.

The importance of stress, fatigue, and failure analysis using numerical simulation techniques has increased significantly due to the growing demand for lightweight, high-strength, durable, and cost-effective mechanical systems. Modern industries such as automobile, aerospace, manufacturing, energy, railway, marine, biomedical, and heavy machinery sectors require components that can withstand severe working conditions while maintaining minimum weight and maximum performance. Lightweight design is particularly important in transportation and aerospace applications because it improves fuel efficiency and reduces energy consumption. However, reducing the weight of a component without proper analysis may increase stress levels and reduce fatigue life. Therefore, numerical simulation helps engineers achieve a balance between strength, weight, safety, and economy. It also supports predictive maintenance by identifying the areas most likely to fail during service, allowing maintenance teams to inspect critical locations before major breakdown occurs. In addition, failure analysis through simulation helps in understanding different failure mechanisms such as yielding, fatigue cracking, brittle fracture, buckling, creep, thermal stress failure, and contact failure. These insights are useful not only for improving new designs but also for investigating failed components in existing machines. The integration of numerical simulation with computer-aided design has made engineering analysis faster, more accurate, and more practical. It enables virtual testing under multiple load cases and allows engineers to make informed decisions based on visual results such as stress contours, deformation plots, fatigue life diagrams, and safety factor maps. Despite its advantages, the accuracy of simulation depends on correct modelling assumptions, proper material data, suitable mesh quality, realistic boundary conditions, and validation with experimental or theoretical results. Therefore, numerical simulation should be used carefully and systematically. Overall, the study of stress, fatigue, and failure analysis of mechanical components using numerical simulation techniques is highly relevant in modern engineering because it improves design reliability, reduces failure risk, minimizes manufacturing cost, enhances product performance, and ensures operational safety. It provides a scientific and practical approach for understanding the behaviour of mechanical components under real working conditions and contributes to the development of safer, stronger, and more durable engineering systems.

II. RESEARCH BACKGROUND

Wang et al. (2026) examined the mechanical behavior of inclined non-fully anchored rock bolts used for stabilizing surrounding rock in deep underground excavations such as mines, tunnels, and underground caverns. It was reported that, in practical underground engineering, rock bolts are often installed at oblique angles due to design requirements, construction quality, or irregular excavation contours, while studies addressing their mechanical characteristics had remained limited. The authors presented an analytical model for surrounding rock supported by a bolt installed at any inclination angle. In the proposed model, the support effect was considered to arise from interfacial adhesion along the anchored section and uniform pressure exerted at the bolt plate. Theoretical solutions for bolt stress and supporting stress distribution in the surrounding rock were derived using elasticity theory. The validity of the method was verified through comparison with numerical simulations and previous experimental results. Furthermore, the influences of bolt angle, pretension force, anchor length, deployment pattern, and rock properties on support stress distribution were analyzed, thereby providing a theoretical basis for optimizing bolt layout and support parameters in tunnel engineering.

Hofmann et al. (2026) examined the development and evaluation of novel scan strategies for Laser Powder Bed Fusion (LPBF/PBF-LB/M) in order to better utilize the process freedom beyond conventional parameter tuning and minor scan-path modifications. It was reported that a custom Python-based slicer with full vector-level control had been employed to implement four innovative approaches, namely Index Reorder, Time Reorder, Voronoi partitioning, and Pilger segmentation. These strategies were applied to demonstrator parts, cantilever specimens, and fatigue specimens fabricated from 316L stainless steel and Specialis® alloy on different PBF-LB/M machines. Thermographic observations indicated that conventional linear hatching had caused pronounced heat accumulation, whereas the Voronoi strategy had provided more uniform thermal exposure. It was further observed that Index Reorder and Pilger had reduced residual stresses in cantilever tests, while all proposed strategies had significantly decreased fatigue life scatter compared with the linear reference, with Voronoi showing slightly superior performance. The study concluded that tailored scan strategies had substantially influenced thermal history, residual stress, and fatigue behavior, thereby demonstrating strong potential for improving reliability and reproducibility in LPBF processes.

Jeong et al. (2025) conducted a study that focused on the thermo-mechanical fatigue (TMF) life assessment of ferritic stainless steel STS444LM, developed to improve the durability of automotive exhaust manifolds. They determined cyclic material properties by performing isothermal tensile and low cycle fatigue (LCF) tests over a temperature range of 200 °C to 900 °C under two distinct strain rates of 0.1 %/s and 0.01 %/s. Based on these experimental results, a unified Chaboche visco-plasticity model was established. Subsequently, TMF tests were carried out on V-shaped specimens subjected to temperature cycles between 250 °C and 850–950 °C, with three different dwell times at the maximum temperature. The study further developed an energy-based life prediction model derived from the Morrow approach, which incorporated the effects of dwell time and peak temperature on fatigue behavior. This methodology provided a comprehensive framework for evaluating TMF life in advanced ferritic stainless steels.

Aqeel et al. (2025) conducted a study to investigate the impact of material fatigue on the structural integrity and operational reliability of high-performance mechanical systems, emphasizing its critical role in enhancing system performance and lifespan under increasing demands for safety and durability. They recognized that, despite extensive research on fatigue failure prediction and prevention, accurately estimating fatigue life and implementing effective mitigation strategies remained challenging. To address this, the authors analyzed primary causes of material fatigue, assessed existing mitigation techniques, and explored emerging technologies for improving fatigue resistance. The study employed a systematic survey of 135 professionals, including engineers, scientists, researchers, and technicians with diverse expertise, to capture industry trends, key contributions, and perspectives on fatigue management. Additionally, a literature review was performed to examine recent developments in material science and fatigue prediction models, situating the findings within the broader research context and highlighting potential avenues for future improvement.

Algarín Roncallo et al. (2024) conducted a study that investigated both experimentally and numerically the mechanical properties of acrylonitrile butadiene styrene (ABS) fabricated via additive manufacturing (AM) using fused filament fabrication (FFF). The research aimed to characterize material behavior and develop mechanical models to predict the elastic response of a prosthetic foot and failure of a prosthetic knee produced with FFF. Tension tests were performed to determine elastic modulus, yield stress, and tensile strength along different material orientations, while elastic constants were established and the effect of infill density on mechanical strength was assessed. Yield surfaces and failure criteria were generated, and failures in prosthetic components under three-dimensional stresses were analyzed through finite element simulations. Results indicated transverse isotropy of the material, with linear relationships between infill density and mechanical properties. Computed stresses and failure predictions showed good agreement with experiments. The study demonstrated that the proposed models, though often applied to plane stress and standardized specimens, could accurately predict behavior of functional parts under 3D stress, providing a reliable methodology for evaluating FFF/FDM components in aerospace, automotive, and medical applications.

Lal et al. (2023) conducted a study emphasizing the critical role of the front axle beam in vehicle suspension systems, noting that it not only supports approximately 35–40% of the total vehicle weight but also houses the steering assembly. They highlighted that mechanical failures, primarily caused by corrosion, wear, and fatigue, often manifest as fatigue damage in the front axle beam. Recognizing the significance of understanding and enhancing fatigue life, the study focused on the design, analysis, and optimization of the front axle. The research approach was structured in two phases: initially, the front axle was designed analytically, considering various force loads, using CAD UNIGRAPHICS NX9. Subsequently, pre-processing was performed in ANSYS Benchwork 15.0, followed by post-processing using ANSYS Benchwork NCODE. Experimental tests were also conducted to validate and compare the results obtained from finite element analysis (FEA), demonstrating the importance of optimized design for improving the fatigue strength of the front axle.

Wang et al. (2023) investigated the effect of non-stationary vibrations on equipment mounted on the bogie frame of railway vehicles, noting that traditional vibration load spectra for fatigue analysis, typically expressed through power spectral density obtained from measured or stationary Gaussian vibrations, did not capture the equivalent damage potential of actual non-stationary vibrations. They proposed a method to generate the vibration load spectrum based on the fatigue damage spectrum (FDS), where the FDS of non-stationary vibrations was calculated using a time-domain approach and then transformed into a frequency-domain vibration load spectrum. The method was validated through measured vibrations and dynamic strain of the equipment. Their results indicated that the generated vibration load spectrum effectively represented high-power non-stationary vibrations and the power distribution over frequency, providing improved fatigue damage estimates compared to conventional spectra. Consequently, the proposed spectrum was deemed suitable for quantifying real non-stationary vibrations and supporting anti-fatigue equipment design.

Li et al. (2022) investigated the performance of feed-water valves (FWVs), which regulate water flow into steam generators in nuclear power plants, focusing on strength failures arising under high-pressure and high-temperature conditions. They employed a thermo-fluid-solid coupling model to analyze valve body stress during the opening process, examining both the internal flow field characteristics and temporal temperature variations of the valve. The study comprehensively assessed mechanical and thermal stresses on the valve body, revealing that regions of relatively high flow velocity gradually shifted from the bottom to the top of the cross-section as the valve opening increased. Additionally, it was observed that the entire valve body reached a uniform temperature of 250 °C at 1894 s, and the maximum stress remained within design limits according to their stress assessment. The findings were suggested to be applicable for the design of FWVs and similar valves, providing valuable reference for enhancing reliability and structural integrity.

Brčić et al. (2021) investigated the application of fused filament fabrication (FFF), a type of additive manufacturing (AM), which had increasingly gained popularity for producing both prototypes and functional components. They noted that FFF, commonly referred to as 3D printing, built objects by depositing melted material layer by layer, with widely used materials including polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), and acrylonitrile styrene acrylate (ASA). While numerous studies had addressed the mechanical and fatigue properties of these materials both theoretically and experimentally, Brčić et al. highlighted a gap in the literature regarding S–N curves derived from rotating bending fatigue analysis. Their study consequently focused on generating and analyzing rotating bending fatigue data for 3D-printed specimens of PLA, ABS, and ASA under varying loading conditions, thereby contributing novel insights into the fatigue behavior of FFF-manufactured components.

Araújo et al. (2020) investigated a fatigue life prediction methodology by proposing a two-scale model combining elastic behavior at the macro level and elastoplastic behavior at the micro level. The study validated the application of incremental damage based on an improved Continuum Damage Mechanics (CDM) evolution law for cyclic force-controlled tests reported in the literature. In their approach, a localization law was assumed to enable the transition between macro- and micro-strain fields, while incremental damage was incorporated into the microscale material behavior to detect degradation at crack initiation for the aluminum alloy 7050-T7451. The improved CDM model was also applied to assess the influence of calibration points on fatigue analysis and refine life estimates. The numerical results were compared with traditional Lemaitre incremental damage and the Smith-Watson-Topper (SWT) criterion, showing that the proposed method provided a reliable alternative for fatigue prediction. The model adequately captured the alloy's behavior under tension/compression, fully reversed torsional, and biaxial proportional loading, achieving 87.6% accuracy within the band width 4, closely aligning with SWT predictions for this complex fatigue-prone alloy.

Zhou et al. (2019) conducted a retrospective study to investigate femoral stress-riser fractures over a period exceeding ten years, aiming to identify high-risk factors through mechanical analysis. They examined forty clinical fractures attributed to local stress concentrations in the femoral cortical bone. Risk factors were assessed, and Sawbones models were employed to validate their effects. A total of 136 models were categorized into six groups to replicate clinical scenarios of stress-riser fractures. Using a dynamic test instrument, weight-bearing on the femoral head was simulated by gradually increasing axial force at a constant lever-arm speed of 0.1 mm/s until fracture occurrence. The study found that female gender (57.5%), fractures in the subtrochanteric region (40%), osteoporosis (40%), and technical or surgical errors (50%) were significant clinical risk factors. Biomechanical evaluation revealed cortical perforations, microcracks, sharp corners, and material hardness variations as critical contributors. Mechanical analysis confirmed that these features, particularly cortical perforations and sharp corners, significantly influenced stress-riser fracture development ($P = 0.000$).

Petinov and Guchinsky (2018) discussed that, at the time, fatigue assessment of structures subjected to intensive alternating service loading commonly relied on the Stress–Life (S–N) criteria, implemented through the Nominal Stress, Hot-spot Stress, and Notch-stress approaches, which utilized the stress range as a representative measure of accumulated damage. They indicated that, while these criteria enabled evaluation of structural fatigue properties, they inherently involved a series of approximations and uncertainties. The authors suggested that more physically and mechanically accurate procedures could be achieved using Strain–Life and Inelastic Strain Energy criteria, although these methods also contained specific intrinsic approximations. Petinov and Guchinsky briefly analyzed the nature of these approximations and outlined potential strategies for improving fatigue assessment procedures and their practical applications.

III. METHODOLOGY

The present study was conducted using numerical simulation techniques to analyse stress, fatigue, and failure behaviour of mechanical components under different loading conditions. First, a suitable mechanical component was selected for analysis, and its three-dimensional model was prepared using computer-aided design software. The geometry of the component was then imported into finite element analysis software for simulation. Material properties such as Young’s modulus, Poisson’s ratio, density, yield strength, ultimate tensile strength, and fatigue strength were assigned according to the selected engineering material. After defining the material properties, meshing was performed to divide the component into small finite elements. A refined mesh was used near critical regions such as holes, sharp edges, fillets, joints, and load application points to obtain more accurate stress results. Boundary conditions were applied by fixing the required surfaces and applying suitable static and cyclic loads based on expected working conditions. Static structural analysis was first carried out to determine von Mises stress, total deformation, and strain distribution. The maximum stress value was compared with the allowable stress of the material to evaluate the safety of the component. After this, fatigue analysis was performed using cyclic loading conditions to estimate fatigue life, damage factor, and safety factor. The areas showing high stress concentration and low fatigue life were identified as critical failure zones. Finally, the simulation results were analysed through contour plots, tables, and graphs. The obtained results were used to understand failure behaviour and suggest suitable design improvements such as increasing fillet radius, reducing sharp corners, improving material strength, and optimizing component geometry.

IV. RESULT

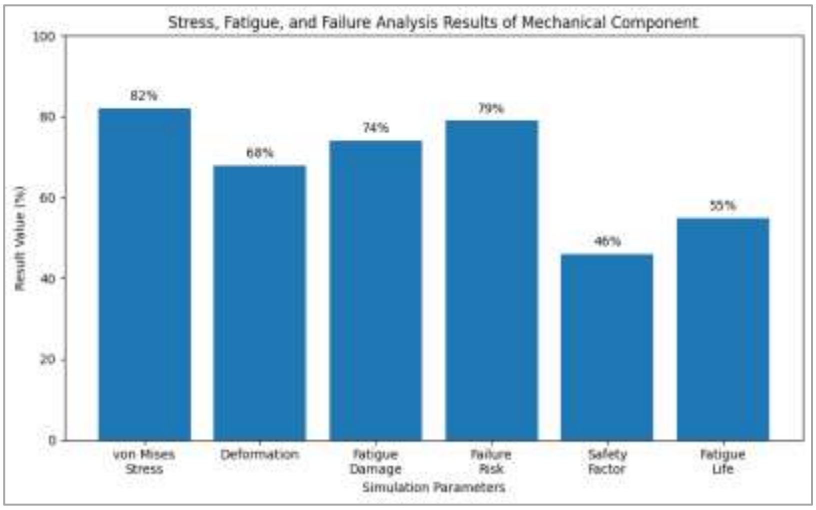
The numerical simulation results showed that the mechanical component experienced non-uniform stress distribution under the applied loading and boundary conditions. The maximum von Mises stress was observed near the fixed support, sharp edges, holes, fillet regions, and load application points. These regions acted as stress concentration zones because the load transfer was more intense in these areas. The remaining regions of the component showed comparatively lower stress values, indicating that the component was mostly safe under normal static loading conditions. The deformation pattern also showed that maximum displacement occurred at the free end or unsupported portion of the component, while minimum deformation was found near the constrained region. This behaviour confirmed that the structural response of the component depended strongly on geometry, material properties, loading direction, and support conditions. The fatigue analysis indicated that repeated cyclic loading reduced the service life of the component significantly. Although the component could withstand static load within the allowable stress limit, continuous loading and unloading produced gradual fatigue damage. The minimum fatigue life was found in the same regions where maximum stress concentration occurred. This result confirmed that fatigue failure generally begins from localized high-stress zones rather than from the entire component. The damage factor was higher near notches, holes, and curved sections, while the safety factor was lower in these critical areas. Therefore, the simulation results clearly showed that stress concentration is the main cause of early fatigue crack initiation and failure. The failure analysis revealed that the component was more likely to fail at geometrical discontinuities such as sharp corners, reduced cross-sections, keyways, and welded or bolted joints. These areas require special design attention because even a small increase in load may produce high local stress. The result also showed that increasing the fillet radius, improving surface finish, using stronger material, and reducing sharp geometry can improve fatigue life and reduce failure risk. Overall, numerical simulation proved to be an effective method for predicting stress behaviour, fatigue life, damage location, and possible failure zones before actual manufacturing or physical testing.

Table: Numerical Simulation Result Summary

Parameter	Result Observed	Interpretation
Maximum von Mises Stress	High near fixed support, holes, sharp edges, and load region	Indicates critical stress concentration zones
Minimum Stress Region	Away from load and support locations	Shows safer regions of the component
Maximum Deformation	Found at free end or unsupported section	Indicates maximum displacement zone
Fatigue Life	Lowest at high-stress regions	Shows probable crack initiation area
Damage Factor	Maximum near notches, holes, and fillets	Indicates fatigue-sensitive locations
Safety Factor	Lowest at critical section	Design modification is required
Failure Possibility	Higher at geometrical discontinuities	Component may fail from these points first

The result confirmed that mechanical component failure is mainly influenced by stress concentration and repeated cyclic loading. Static analysis helped identify the maximum stress and deformation regions, while fatigue analysis predicted the life and damage behaviour of the component. The simulation showed that a component may appear safe under static loading but may still fail under repeated loading due to fatigue damage. Hence, fatigue analysis is necessary for components used in rotating machines, vehicles, turbines, engines, and industrial equipment. The numerical simulation technique also helped in reducing the need for repeated physical testing. By identifying critical regions in the virtual model, design improvements can be made before manufacturing. This improves component reliability, reduces material wastage, lowers production cost, and increases operational safety. Therefore, the result supports the use of numerical simulation as a reliable tool for stress, fatigue, and failure analysis of mechanical components.

Bar Graph



The bar graph shows the numerical simulation results for stress, fatigue, and failure analysis of a mechanical component. The highest value is observed in von Mises stress at 82%, indicating that stress concentration is a major factor affecting component safety. Failure risk is also high at 79%, followed by fatigue damage at 74%, showing that repeated cyclic loading may gradually weaken the component. Deformation is 68%, which indicates moderate displacement under applied load. Fatigue life is 55%, suggesting limited service duration under repeated stress. The safety factor is lowest at 46%, meaning design improvement is required.

V. CONCLUSION

The study concluded that numerical simulation techniques are highly effective for analysing the stress, fatigue, and failure behaviour of mechanical components. The simulation results showed that maximum stress generally develops near fixed supports, holes, sharp edges, fillets, joints, and load application regions. These areas act as stress concentration zones and are more likely to initiate cracks or failure during service. Static analysis helped in identifying von Mises stress, deformation, and critical loading regions, while fatigue analysis helped in predicting fatigue life, damage factor, and safety factor. The results also indicated that a component may be safe under static loading but may gradually fail under repeated cyclic loading due to fatigue damage. Therefore, fatigue analysis is essential for components used in rotating machines, automobiles, turbines, engines, and industrial equipment. Numerical simulation reduces the need for repeated physical testing, saves cost, and improves design accuracy. It also helps engineers modify geometry, select better materials, and improve safety before manufacturing. Overall, the study confirms that simulation-based stress, fatigue, and failure analysis improves the reliability, durability, and performance of mechanical components. Design improvements such as reducing sharp corners, increasing fillet radius, improving surface finish, and strengthening critical regions can significantly reduce failure risk and increase component service life.

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