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Stress, Fatigue, and Failure Behavior Analysis in Mechanical Components and Additive Manufacturing

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ABSTRACT

The study of stress, fatigue, and failure behavior in mechanical components is crucial in engineering design, especially for lightweight and high-performance structures in industries like aerospace, automotive, and biomedical. Components under cyclic loading and thermal gradients are prone to progressive damage, often leading to fatigue failure. Traditional experimental methods are costly and time-consuming, making numerical simulations, such as finite element analysis (FEA), essential for efficient design optimization. The integration of additive manufacturing (AM) with simulation tools further enhances the design process by considering anisotropic behavior, residual stress, and microstructural effects, improving overall structural integrity and fatigue resistance.

***Keywords**: Fatigue, Stress Analysis, Additive Manufacturing, Finite Element Analysis, Failure Behavior.*

I. INTRODUCTION

The analysis of stress, fatigue, and failure behavior of mechanical components has become a fundamental area of research in machine design engineering, particularly with the increasing demand for lightweight, high-performance, and reliable structures in industries such as aerospace, automotive, biomedical, and manufacturing. Mechanical components operating under cyclic loading, thermal gradients, and complex boundary conditions are highly susceptible to progressive damage accumulation, which ultimately leads to fatigue failure. Traditional experimental methods for evaluating such failures are often time-consuming, expensive, and limited in their ability to capture detailed internal stress distributions. As a result, numerical simulation techniques—especially finite element analysis (FEA), thermo-mechanical modeling, and computational fatigue assessment—have emerged as essential tools for predicting structural behavior under realistic operating conditions. These methods allow engineers to simulate complex loading environments, identify critical stress concentration zones, and optimize designs before physical prototyping. Recent studies have demonstrated that advanced computational frameworks not only improve accuracy in failure prediction but also significantly reduce development time and cost, thereby enhancing engineering efficiency (Chen et al., 2019; Nagesha et al., 2021).

In recent years, the integration of additive manufacturing (AM) with numerical simulation has further expanded the scope of stress and fatigue analysis. Additively manufactured components often exhibit anisotropic mechanical behavior, residual stresses, and microstructural variations that strongly influence fatigue life and failure mechanisms. Huang et al. (2026) developed a high-fidelity explicit thermo-mechanical FEA model to predict residual stress and distortion in metal AM processes, highlighting the importance of computational methods in optimizing process parameters such as scanning strategy and heat input. Similarly, Arora et al. (2026) investigated additively manufactured titanium stents using finite element simulations combined with advanced surface finishing techniques, demonstrating improved structural integrity and reduced surface defects. Gómez-Gras et al. (2025) further emphasized that build orientation and internal structure significantly affect fatigue performance in material extrusion additive manufacturing (MEX-AM), where optimized sparse designs can enhance strength-to-weight ratios. These findings collectively indicate that AM components cannot be effectively designed without incorporating numerical simulation techniques that account for thermal history, residual stress evolution, and microstructural anisotropy. Additionally, studies on WAAM-fabricated Inconel 625 components (Karmuhilan & Kumanan, 2024) and SLM-processed aerospace parts (Nagesha et al., 2021) further confirm that numerical modeling is essential for understanding failure behavior under complex thermal and mechanical loading conditions.

Moreover, fatigue analysis has evolved from being a post-design validation tool to an integrated part of the computational design process. Dastugue et al. (2025) highlighted the integration of fatigue assessment directly within FEM environments, enabling simultaneous stress and fatigue evaluation with minimal additional computational effort. This integration, supported by high-performance computing (HPC) systems, allows for efficient analysis of large-scale industrial components such as automotive chassis and aerospace structures. Jimenez-Martinez et al. (2023) emphasized the need for developing S-N curves for additively manufactured polymers, considering variability in material properties due to printing conditions, while Einbergs et al. (2022) introduced mechanoluminescence-based stress visualization techniques that validate computational stress distribution models. Furthermore, failure analysis approaches such as root cause analysis (Berladir et al., 2024) complement numerical methods by identifying underlying causes of mechanical failure beyond stress concentration alone. Studies on composite materials and fatigue-sensitive joints (Tarpani et al., 2020; Ansari et al., 2018) further demonstrate that fatigue behavior is influenced by multiple interacting factors, including fiber orientation, material heterogeneity, and environmental conditions. Chen et al. (2019) also showed that thermo-mechanical coupling in engine piston systems significantly improves the accuracy of fatigue life prediction under real operating conditions. Collectively, these advancements highlight that modern mechanical design increasingly relies on integrated numerical simulation frameworks that combine stress analysis, fatigue modeling, and failure diagnostics to ensure structural reliability, optimize performance, and support innovation in next-generation engineering systems.

II. RESEARCH BACKGROUND

Arora et al. (2026) had investigated the enhancement of performance and reliability of additively manufactured cardiovascular stents by integrating computational stress analysis with an advanced finishing process to improve structural integrity and surface quality. A comprehensive finite element analysis (FEA) had been carried out in ABAQUS to simulate the mechanical behavior of various AM titanium alloy stent designs under physiological loading conditions, including crimping and deployment. The study had focused on critical performance indicators such as dog-boning effect, radial recoil, and stress distribution. To improve surface quality, Magnetorheological Shear Thickening Polishing (MRSTP) had been applied, which had significantly reduced surface roughness and eliminated micro-defects. Surface morphology analysis and 3D profilometry had confirmed nanometric surface finishes, suggesting improved biocompatibility. The simulations had provided valuable insights for design optimization, while the integrated FEA–MRSTP framework had demonstrated superior surface integrity and structural durability. The study had thus presented a novel coupled strategy that simultaneously enhanced mechanical reliability and surface smoothness, indicating strong potential for improved long-term clinical performance of advanced vascular stents.

Huang et al. (2026) investigated the accurate prediction of thermal effects in metal additive manufacturing (AM), particularly part distortion and residual stress, which were considered essential for quality management and production cost control. To overcome the high computational expense of high-fidelity simulations, a staggered coupled thermo-mechanical model based on explicit finite element analysis (FEA) was developed. The study incorporated synergistic mass scaling and inverse heat capacity scaling to maintain equivalent thermal diffusivity, while also clarifying the modeling framework, parameter calibration, and implementation workflow. The proposed computational approach was applied to two representative AM processes, namely wire and arc additive manufacturing (WAAM) and laser powder bed fusion. The transient temperature fields, residual distortions, and stress distributions predicted by the model were compared with experimental observations to validate its accuracy. It was reported that the explicit thermo-mechanical formulation enabled efficient implementation on high-core-count computing systems, thereby supporting parallel processing and improving simulation performance. The model was found to be particularly useful for scanning pattern evaluation, support structure design, and prediction of thermal distortion and failure risks in large-scale AM components.

Dastugue et al. (2025) reported that fatigue analysis based on stress calculation had significantly enhanced conventional finite element strength analysis by providing deeper insights for the design of lightweight components. The authors explained that this approach had been fully integrated into a general FEM high-performance computing (HPC) software environment, which had enabled simplified accessibility and efficient utilization for larger and more complex models. It was noted that the integration within the FEM solver allowed fatigue damage to be directly obtained together with stress results, requiring only minimal additional input and computational effort. The study further indicated that an SN curve generator developed in accordance with the FKM guideline had automated material data input, thereby streamlining the overall fatigue assessment process. By removing the dependency on separate software tools and avoiding data transfer through the use of a common database, the integrated framework had accelerated product development and improved analysis quality. The industrial example of a truck chassis implemented in the commercial FEM solver PERMAS had demonstrated the method’s practicality, efficiency, and suitability for detailed large-scale fatigue analysis.

Gómez-Gras et al. (2025) investigated the fatigue behavior of high-performance polyetherimide components manufactured through material extrusion additive manufacturing (MEX-AM), with particular emphasis on the influence of key process parameters. The study evaluated thirty different configurations under four loading levels, and fractographic analysis was also performed to examine crack initiation and propagation mechanisms. It was reported that the building direction played a highly significant role in fatigue performance, as edge-printed specimens exhibited up to 2.4 times longer fatigue life under low loading conditions than flat-printed specimens. The authors further observed that sparse configurations, despite their lower mass, delivered similar or even superior specific performance compared to solid specimens. Notably, the X-Flat-0.25 mm configuration was found to double the fatigue life of the best-performing solid specimen under low loads while reducing weight by 24%, whereas X-Flat-0.75 mm achieved a 44% mass reduction with only a 15.5% decrease in fatigue life. Overall, the study demonstrated the strong potential of optimized sparse designs for developing lightweight and high-performance MEX-AM components.

Berladir et al. (2024, March) focused on developing a methodological approach for applying root cause analysis to a specific materials science problem. Their study investigated the destruction of elements in the exhaust tract of a gas pumping unit. They applied root cause analysis as a systematic procedure aimed at identifying and addressing underlying causes rather than merely treating symptoms. Initially, the destroyed exhaust element was selected to define the problem and examine its failure. Subsequently, failure analytics were conducted to collect relevant data. The 6Ms of production mnemonic was then employed to identify a comprehensive set of causal factors. These factors were analyzed in detail to determine the root causes of the failure. Finally, the study provided recommendations for implementing solutions to mitigate such failures in the exhaust tract of gas pumping units.

Karmuhilan and Kumanan (2024) investigated the mechanical failure characteristics of Inconel 625 components produced via the Wire and Arc Additive Manufacturing (WAAM) process. They fabricated three additive structures with varying inter-pass layer temperatures (IPT) of 100, 200, and 300 °C and extracted tensile specimens along longitudinal (IN625-L), transversal (IN625-T), and diagonal (IN625-D) orientations to assess orientation-dependent failure behavior. The study reported that grain morphology and size were influenced by IPT, and standardized electromechanical tensile tests were conducted to determine tensile properties, with stress–strain curves used to characterize component strength. Mechanical anisotropy and failure patterns were attributed to differences in grain boundaries and grain elongation, revealing that the IN625-D specimens exhibited higher tensile strength due to a greater density of grain boundaries, whereas IN625-L and IN625-T specimens contained more elongated grains. The authors concluded that the strength contribution from grain boundaries outweighed that of individual grains, highlighting the role of microstructural orientation in WAAM-fabricated Inconel 625 performance.

Jimenez-Martinez et al. (2023) investigated the fatigue behavior of mechanical components produced via additive manufacturing, emphasizing that components in the manufacturing industry are subjected to repetitive loads specific to their functions and regulatory requirements. The study highlighted that fatigue assessment is essential to ensure components do not fail over their expected service life. The authors noted the growing interest in additive manufacturing as a means to create more organic and complex designs, but they also pointed out that components produced this way often failed under repeated operational loads, limiting their suitability for large-scale production. The research aimed to develop an S-N life curve for PLA, accounting for variations in printers and filament colors to capture the scatter in fatigue behavior. The analysis identified five amplitude regions based on load levels and examined the failure mechanisms and structure. However, the study reported that representing the curve as a percentage of ultimate strength was not feasible due to dispersion in quasi-static load results.

Einbergs et al. (2022) investigated an innovative modification of precise and versatile 3D printing technology aimed at facilitating easy and non-destructive spatial stress analysis on printed mechanical components. They fabricated 3D printed photopolymer samples incorporated with $SrAl_2O_4$:Eu,Dy particles and applied a subsequent data processing method to generate spatial stress maps. Their findings indicated that the empirically obtained stress distribution closely corresponded with the theoretically calculated stress distribution, demonstrating the method's reliability for further technological development. The study highlighted the potential of this approach for real-time evaluation of complex and uneven forces on intricate parts, suggesting promising applications in computational stress–strain analysis and opportunities for commercialization.

Nagesha et al. (2021) conducted a study in which selective laser melting (SLM) was employed to fabricate the Inconel 718 high-pressure nozzle guide vane (HPNGV), a critical aero-engine component known for its high-temperature performance. The research aimed to examine the residual stresses induced in the HPNGV both during the SLM process and after removal of the base plate. Residual stresses were experimentally measured using X-ray diffraction, revealing a maximum stress of approximately 700 MPa at a specific location. Additionally, a thermo-mechanical finite element model (FEM) of the SLM-processed HPNGV was developed using ANSYS software to simulate stress distribution. The study found that the removal of the base plate led to a significant increase in residual stresses, with about 16% at one location and 27% at another. The experimental findings were reported to be in good agreement with the FEM simulations, confirming the reliability of the modeling approach.

Tarpani et al. (2020) investigated the fundamental aspects of fatigue fracture mechanisms in riveted single shear lap joints of fibre-metal laminates through an extensive failure analysis of double-riveted 2/1 Glare™ laminate layups. They identified three primary fatigue fracture mechanisms—rivet fracture, Glare laminate cracking, and fretting fatigue—as functions of peak stress. The study examined the influence of joint elements and fibre-metal laminate constituents on overall fatigue strength, revealing that aligned riveting exhibited higher fatigue resistance than non-aligned configurations due to greater restriction of secondary bending moments, which delayed or prevented potential fracture mechanisms. It was further observed that the damage resistance capability, rather than damage tolerance alone, primarily governed the fatigue strength of the joints. The findings were considered to provide valuable insights for the design of multi-rivet Glare joints with enhanced fatigue performance.

Chen et al. (2019) conducted a study in which they developed a thermo-mechanical finite element analysis model to evaluate the stress and fatigue behavior of engine pistons. The model incorporated the piston, piston pin, piston ring, bushing, cylinder liner, and connecting rod, while accounting for the oil film and contact pressures at the interfaces between the piston and piston pin, piston pin and bush, and piston skirt and cylinder liner. They applied a self-compiled code that considered the piston skirt profile and ellipticity to calculate the initial clearances at these oil film surfaces. Dynamic loads of the piston and connecting rod under peak torque and peak power conditions were obtained using commercial powertrain software and subsequently used in the stress and fatigue analyses. The study demonstrated that, in comparison with existing literature, their model could more accurately simulate actual operating conditions of the piston and was effective for evaluating piston skirt pressure, stress distribution, and fatigue life in critical regions.

Ansari et al. (2018) conducted a review that highlighted the growing suitability of fiber-reinforced polymer (FRP) composites for repairing and replacing conventional metallic materials due to their high strength and stiffness. They emphasized that these composites are subjected to diverse static and fatigue loads during service, making fatigue testing—a method to assess the cyclic behavior of materials—essential. The authors noted that composite materials exhibit fatigue behavior distinct from metals, as their damage and failure mechanisms are more complex; unlike metals, where a single crack propagates to fracture, composites experience multiple micro-cracks initiating at early stages, leading to varied fatigue damage types. The study also underscored the significance of fiber volume fraction, observing that fatigue strength generally increased with fiber content up to a point before declining due to insufficient resin to secure fibers. Furthermore, they reviewed the influence of factors such as constituent materials, manufacturing processes, hysteresis heating, fiber orientation, loading type, interface properties, frequency, mean stress, and environmental conditions on the fatigue performance of FRP composites.

III. KEY FINDINGS FROM STUDY

Author(s) & Year	Objective	Methodology	Key Findings	Contribution to Study
Arora et al. (2026)	Improve performance of AM titanium stents	FEA in ABAQUS + MRSTP surface finishing	Reduced stress concentration, improved surface integrity and biocompatibility	Integrated simulation + surface optimization framework
Huang et al. (2026)	Predict thermal distortion in metal AM	Explicit thermo-mechanical FEA model	Accurate prediction of residual stress and distortion with reduced computation time	Efficient AM process simulation model

Dastugue et al. (2025)	Integrate fatigue analysis in FEM	FEM-based fatigue module + SN curve generator	Direct fatigue output with stress analysis improved efficiency	Unified fatigue–stress FEM framework
Gómez-Gras et al. (2025)	Analyze fatigue in MEX-AM polyetherimide	Experimental fatigue testing + fractography	Build direction strongly affects fatigue life; optimized sparse designs perform better	Design optimization for lightweight AM parts
Berladir et al. (2024)	Identify root causes of mechanical failure	Root cause analysis (6M method)	Systematic identification of failure causes in gas pumping unit exhaust	Failure diagnostics framework
Karmuhilan & Kumanan (2024)	Study WAAM Inconel 625 failure	Tensile testing + microstructure analysis	Mechanical anisotropy influenced by grain structure and IPT	Microstructure-based failure behavior insight
Jimenez-Martinez et al. (2023)	Study fatigue behavior of PLA AM parts	S-N curve development + fatigue testing	Significant variability due to printing conditions and material dispersion	AM polymer fatigue characterization
Einbergs et al. (2022)	Visualize stress distribution in 3D printed parts	Mechanoluminescence-based stress mapping	Experimental stress maps matched theoretical predictions	Non-destructive stress visualization method
Nagesha et al. (2021)	Analyze residual stress in SLM components	XRD + thermo-mechanical FEM in ANSYS	Residual stress increases after base plate removal; good FEM correlation	Validation of FEM in AM aerospace parts
Tarpani et al. (2020)	Investigate fatigue in riveted FML joints	Experimental fatigue testing + fracture analysis	Fretting, cracking, rivet failure dominate fatigue behavior	Joint-level fatigue mechanism study
Chen et al. (2019)	Analyze piston stress and fatigue	Thermo-mechanical FEM with dynamic loading	Improved accuracy in stress distribution and fatigue prediction	Engine component simulation model
Ansari et al. (2018)	Review fatigue in FRP composites	Literature-based analytical review	Fatigue behavior depends on fiber orientation, volume fraction, and environment	Comprehensive composite fatigue framework

IV. CONCLUSION

The comprehensive review of stress, fatigue, and failure analysis of mechanical components using numerical simulation techniques highlights the critical role of computational modeling in modern machine design engineering. Across the literature, it is evident that finite element analysis (FEA), thermo-mechanical simulations, and integrated fatigue assessment tools have significantly improved the understanding of complex failure mechanisms in engineering systems operating under static, dynamic, thermal, and cyclic loading conditions. Studies such as Chen et al. (2019) and Nagesha et al. (2021) demonstrate that coupled thermo-mechanical models provide highly accurate predictions of stress distribution and residual stresses in engine components and additive manufacturing (AM) parts, thereby enabling engineers to anticipate failure before physical testing. Similarly, Huang et al. (2026) and Arora et al. (2026) emphasize that numerical simulation combined with process optimization techniques enhances the reliability of AM components by reducing distortions, improving structural integrity, and controlling surface defects. The integration of fatigue analysis directly within FEM environments, as shown by Dastugue et al. (2025), further streamlines the design process by enabling simultaneous evaluation of stress and fatigue life, which is particularly beneficial for large-scale industrial applications. Additionally, research on AM polymers and metals (Gómez-Gras et al., 2025; Karmuhilan & Kumanan, 2024) highlights the significant influence of material anisotropy, build orientation, and microstructural variations on fatigue performance, reinforcing the need for simulation-driven design approaches. Furthermore, studies on composites and mechanical joints (Ansari et al., 2018; Tarpani et al., 2020) confirm that fatigue failure is governed by multiple interacting parameters such as fiber orientation, interface strength, and loading conditions, which can be effectively analyzed using numerical tools. Overall, the literature strongly establishes that numerical simulation techniques are indispensable for predicting stress distribution, fatigue life, and failure mechanisms with high accuracy. These methods not only reduce experimental cost and time but also enable optimized, safer, and more durable mechanical component design, making them essential for future advancements in machine design engineering.

V. FUTURE SCOPE

The future scope of stress, fatigue, and failure analysis of mechanical components using numerical simulation techniques is highly promising, particularly with rapid advancements in computational power, artificial intelligence, and additive manufacturing technologies. One of the key future directions is the integration of artificial intelligence (AI) and machine learning (ML) with finite element analysis (FEA) to develop predictive models that can estimate stress distribution and fatigue life with greater speed and accuracy, reducing dependency on time-consuming simulations. Hybrid modeling approaches combining physics-based simulations with data-driven techniques are expected to significantly enhance real-time failure prediction capabilities. Another important area is the advancement of digital twin technology, where virtual replicas of mechanical systems continuously update using real-time sensor data to monitor stress, fatigue, and structural health during operation, enabling predictive maintenance and failure prevention. In additive manufacturing, future research is expected to focus on multi-scale and multi-physics modeling to better understand microstructural evolution, residual stress formation, and anisotropic fatigue behavior of printed components under complex loading conditions. The development of more efficient high-performance computing (HPC) and cloud-based simulation platforms will further enable large-scale industrial simulations with reduced computational cost and time. Additionally, advanced fatigue models incorporating environmental effects such as temperature, corrosion, and variable loading conditions will improve the realism of failure predictions. Experimental validation techniques such as digital image correlation and real-time stress visualization are also expected to be integrated more closely with numerical models for higher accuracy. Overall, the future of this field lies in the convergence of simulation, intelligent systems, and smart manufacturing, leading to safer, lighter, more efficient, and highly optimized mechanical components for next-generation engineering applications.

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