A Dual Approach to Failure Analysis in High-Stress Mechanical Components Using Experiments and Finite Element Simulation

Priya Singh

Master of Technology in Machine Design Engineering, Dept. Of. Mechanical Engineering, CBS Group of Institutions, Jhajjar.

Abhishek Singhroha

A.P., Dept. Of. Mechanical Engineering, CBS Group of Institutions, Jhajjar.

ABSTRACT

This study presents a comprehensive approach combining experimental testing with finite element simulation to investigate failure mechanisms in high-stress components subjected to complex loading scenarios. The close alignment between experimental observations and simulation results validates the effectiveness of the computational framework in predicting component behavior and failure progression. The dual methodology enables precise identification of high-stress zones, estimation of component life, and deeper insight into damage evolution. Emphasis is placed on the use of realistic material models and detailed geometry to improve simulation accuracy. The validated models have practical implications for optimizing design, selecting suitable materials, and formulating maintenance strategies aimed at minimizing early failures. Future research should explore the inclusion of microstructural characteristics, environmental degradation influences, and probabilistic modeling to further refine failure predictions and improve the reliability of critical components.

Key Words: *Finite Element Simulation, Failure Mechanisms, High-Stress Components.*

1. INTRODUCTION

In modern engineering and manufacturing, the reliability and longevity of high-stress components are critical determinants of the safety, efficiency, and performance of countless industrial applications ranging from aerospace and automotive to power generation and civil infrastructure. These components, often subjected to extreme mechanical loads, thermal variations, cyclic stresses, and corrosive environments, are vulnerable to a variety of failure mechanisms that can manifest in complex and often unpredictable ways. Understanding and analyzing these failure mechanisms is paramount for ensuring structural integrity, preventing catastrophic failures, and extending service life. High-stress components typically encounter failure modes such as fatigue, creep, stress corrosion cracking, wear, and fracture, each driven by distinct yet sometimes interrelated physical phenomena. The multifaceted nature of these failure processes necessitates an integrated approach that combines both experimental investigations and advanced simulation techniques to achieve a comprehensive understanding. Experimentation provides invaluable empirical data, revealing how materials and components behave under real-world conditions, uncovering critical stress concentrations, crack initiation sites, and progression patterns that cannot be easily inferred through theory alone. However, experimental methods often face limitations in terms of cost, time, and scalability, especially when dealing with complex geometries, extreme environments, or long-term behavior. Consequently, computational simulations have emerged as indispensable tools that complement and extend experimental insights, allowing engineers and researchers to model stress distributions, predict damage evolution, and explore parametric sensitivities with high precision and flexibility. Techniques such as finite element analysis (FEA), computational fluid dynamics (CFD), molecular dynamics (MD), and phase-field modeling provide powerful frameworks to replicate the mechanical, thermal, and chemical interactions within materials and structures. By coupling these simulations with empirical data, one can calibrate and validate models, enhancing their predictive accuracy and enabling virtual testing under a wide spectrum of scenarios that would otherwise be impractical or impossible to replicate experimentally. The synergistic use of experimental and simulation methods facilitates a deeper mechanistic understanding of failure initiation and propagation, revealing microstructural influences, residual stress effects, and environmental interactions that govern component durability. Moreover, advances in non-destructive evaluation (NDE) technologies such as digital image correlation (DIC), acoustic emission, X-ray computed tomography (XCT), and electron microscopy enrich experimental studies by enabling real-time monitoring and high-resolution characterization of damage evolution at multiple scales. When integrated with multiscale simulations, these techniques bridge the gap between microstructural phenomena and macroscopic behavior, providing holistic insights into the complex failure mechanisms that high-stress components endure. Furthermore, experimental-simulation frameworks empower the development of innovative materials and design strategies aimed at mitigating failure risks, such as the optimization of alloy compositions, heat treatments, surface coatings, and geometric features to enhance resistance against fatigue cracks, corrosion, or thermal degradation. They also support the establishment of robust predictive maintenance protocols and life assessment models that are vital for industrial asset management, safety assurance, and cost reduction. This multidisciplinary approach addresses the challenges posed by evolving operational demands and stringent regulatory requirements, ensuring that high-stress components not only meet performance targets but also comply with safety standards over their intended lifespan. As technology advances, the integration of machine learning and data-driven methods with traditional experimentation and simulation is further revolutionizing failure analysis by enabling the extraction of hidden patterns from large datasets, accelerating model development, and improving prognostics accuracy. In summary, analyzing failure mechanisms in high-stress components through a combined experimental and simulation methodology is an indispensable paradigm in contemporary engineering. It harnesses the complementary strengths of empirical observation and computational modeling to unravel complex failure phenomena, guiding the design, manufacturing, and maintenance of components that are safer, more reliable, and economically viable. This comprehensive approach not only enhances our fundamental understanding of material behavior under extreme conditions but also drives innovation in materials science, structural engineering, and predictive maintenance, thereby safeguarding critical infrastructure and advancing technological progress across multiple industries.

2. RESEARCH METHODOLOGY

This study adopts a comprehensive research design that integrates both experimental testing and numerical simulation techniques to analyse failure mechanisms in high-stress components. The combined approach leverages the strengths of physical experimentation—providing empirical, real-world data—and advanced computational modelling through finite element analysis (FEA), which offers detailed insights into stress distributions and damage evolution within complex geometries. In the experimental phase, components are subjected to controlled loading conditions including tensile, fatigue, creep, and thermal cycling tests, simulating the operational environments these components face. These physical tests enable direct measurement of mechanical responses such as stress, strain, deformation, and crack initiation, thereby generating reliable baseline data.

Complementing this, the numerical simulation phase involves developing precise FEA models that replicate the geometry, material properties, and boundary conditions of the experimental specimens. These models employ sophisticated constitutive laws capturing elastic-plastic behaviour, time-dependent creep, and fatigue damage accumulation. Simulation results yield detailed predictions of stress concentrations, displacement fields, and life expectancy under various load cases. The dual methodology facilitates cross-validation, where simulation predictions are benchmarked against experimental outcomes to assess model accuracy and identify any deviations. This iterative process not only strengthens the reliability of failure predictions but also guides optimization of component design and material selection for improved durability under high-stress conditions.

3. EXPERIMENTAL SETUP

Specimen Preparation: Test specimens were meticulously fabricated to closely replicate the geometry, material composition, and microstructural characteristics of the high-stress components under investigation. To ensure consistency and minimize variability, all specimens adhered to standardized dimensions and surface finishes in accordance with relevant ASTM or ISO testing standards. Surface preparation included precision machining and polishing to eliminate defects that could artificially influence stress concentration or crack initiation sites. Material homogeneity was verified through chemical and microstructural analyses prior to testing.

Load Application: A variety of loading protocols were applied to simulate the diverse mechanical and environmental stresses encountered during service. These included:

- **Tensile Loading:** Monotonic tensile tests to evaluate ultimate strength and ductility.
- **Fatigue Loading:** Cyclic loading with a stress ratio (R = 0.1) to replicate repeated service stresses and study crack initiation and growth under fluctuating loads.
- **Creep Testing:** Sustained load applied at elevated temperatures, typically within a furnace environment, to assess time-dependent deformation and rupture behaviour.
- **Thermal Cycling:** Repeated heating and cooling cycles between ambient and high operating temperatures (e.g., 25°C to 700°C) to simulate thermal fatigue effects.

Instrumentation: High-precision instrumentation was deployed to capture detailed mechanical responses during testing. Strain gauges were affixed at critical locations to measure localized strain with high resolution. Extensometers recorded overall specimen elongation and deformation. Temperature sensors ensured accurate monitoring of environmental conditions, particularly during creep and thermal cycling tests, guaranteeing precise control over test parameters.

Failure Monitoring: To detect and characterize failure mechanisms, advanced monitoring techniques were utilized. High-speed cameras captured real-time deformation and crack propagation, enabling visualization of dynamic failure processes. Non-destructive evaluation (NDE) methods, such as ultrasonic testing, acoustic emission analysis, and optical or electron microscopy, were employed intermittently and post-test to identify subsurface defects, crack initiation sites, and microstructural damage without compromising specimen integrity. These complementary techniques provided comprehensive insight into the progression of failure under varied loading conditions.

3.1 Numerical Simulation

Finite Element Modelling: The numerical simulation phase involved developing highly detailed three-dimensional (3D) finite element (FE) models of the test specimens using advanced computer-aided design (CAD) software. These models precisely replicated the actual specimen geometries, including critical features such as notches, fillets, and holes that can act as stress concentrators. Boundary conditions and loading parameters were carefully defined to mirror the experimental test setups, ensuring that the simulations realistically represented the physical environment. Constraints and load applications were implemented to simulate tensile, fatigue, creep, and thermal cycling conditions, providing a comprehensive framework for analyzing mechanical behaviour under various stress states.

Material Modelling: Material behaviour was modelled using sophisticated constitutive laws that captured the complex responses observed experimentally. Elastic-plastic models were employed to simulate the initial elastic deformation followed by plastic yielding. For time-dependent phenomena such as creep, viscoplastic constitutive laws incorporating temperature and stress-dependent strain rates were integrated. Fatigue damage models, based on cumulative damage theories and strain-life approaches, were implemented to predict crack initiation and propagation under cyclic loading. Additionally, thermal expansion coefficients and temperature-dependent material properties were incorporated to simulate thermal stresses and damage during cyclic heating and cooling. Material parameters were calibrated using experimental data to ensure accurate representation of real-world behaviour.

Meshing Strategy: A critical aspect of the FE simulations was mesh generation. An adaptive meshing strategy was adopted, wherein finer mesh elements were concentrated in regions prone to high stress gradients or damage accumulation, such as near notches and geometric discontinuities. This approach optimized computational resources by refining the mesh only where necessary, balancing solution accuracy with manageable computational time. Mesh quality metrics, such as aspect ratio and element distortion, were monitored and optimized to ensure numerical stability and convergence.

Simulation Runs: A series of simulation runs were executed to analyze different failure mechanisms

- **Static Tensile Analysis:** To evaluate stress and strain distribution under monotonic loading.
- **Fatigue Life Prediction:** Using damage accumulation models to estimate the number of cycles to failure under cyclic loading conditions.
- **Creep Deformation Analysis:** To predict time-dependent deformation and rupture under sustained high-temperature loads.
- **Thermal Stress Analysis:** Simulating the effects of repeated thermal cycles on component integrity, including stress development and micro-crack initiation.
  These simulations provided detailed insights into stress concentrations, deformation patterns, and damage evolution, enabling comprehensive understanding and prediction of component failure under complex loading conditions.

3.2 Data Collection and Analysis

Experimental Data: During each experimental test, critical mechanical parameters were recorded systematically to capture the component’s response under varying load conditions. These parameters included applied load magnitudes, corresponding displacements, localized strain measurements from strain gauges, and the number of cycles to failure for fatigue tests. For creep and thermal cycling tests, time-dependent deformation data and temperature profiles were also logged. Data acquisition systems were calibrated to ensure high precision and repeatability, enabling accurate tracking of the specimen’s behaviour from initial loading through failure.

Simulation Output: Finite element analysis (FEA) simulations produced a rich set of quantitative outputs that complemented the experimental observations. Key results extracted included detailed stress distribution maps highlighting peak stress regions, displacement fields showing deformation patterns, and fatigue life predictions derived from damage accumulation models. Time-dependent creep strain and damage evolution over thermal cycles were also monitored within the simulations. These outputs provided a spatially and temporally resolved understanding of failure mechanisms that are difficult to capture experimentally.

Validation: A critical aspect of the research involved rigorous comparison between experimental measurements and simulation predictions. Validation was performed by overlaying experimental load-displacement curves with simulated counterparts and comparing cycle-to-failure values for fatigue tests. Discrepancies were analyzed to identify potential sources such as material modelling limitations or boundary condition assumptions, facilitating model refinement.

Statistical Tools: Quantitative assessments of agreement between experiments and simulations employed statistical techniques including error analysis to calculate percentage deviations and root mean square errors. Correlation coefficients were computed to evaluate the strength and direction of linear relationships between datasets. These statistical tools provided objective metrics for model performance and reliability, supporting the credibility of simulation-based predictions.

4. SIMULATION DATA AND EXPERIMENTAL DATA

This research focuses on the critical investigation of failure mechanisms in high-stress engineering components through a combination of experimental testing and advanced numerical simulations. As modern industries such as aerospace, automotive, and power generation push the limits of material performance, understanding how components behave under complex mechanical and thermal loads becomes essential to ensuring safety, reliability, and longevity. The study integrates controlled laboratory experiments—including tensile, fatigue, creep, and thermal cycling tests—with detailed finite element analysis (FEA) models to simulate real-world operational conditions. This dual methodology not only facilitates the validation of computational models but also provides deep insights into the initiation and progression of damage, helping identify critical stress regions and predict component life. The comprehensive approach adopted in this work addresses the challenges associated with capturing time-dependent deformation, cyclic loading effects, and thermal fatigue, which are pivotal in high-temperature and high-load applications. Emphasis is placed on correlating experimental data with simulation outputs to enhance model accuracy and refine design strategies. The outcomes of this research aim to contribute valuable knowledge for material selection, structural optimization, and maintenance planning, ultimately advancing the reliability of components subjected to demanding service environments.

4.1 Experimental Data

Test ID	Load Type	Max Load (kN)	Number of Cycles to Failure	Max Stress (MPa)	Strain at Failure (%)	Temperature (°C)	Remarks
EXP-01	Tensile	25	N/A	450	12.5	25	Smooth fracture
EXP-02	Fatigue (R=0.1)	N/A	1,200,000	350	N/A	25	Crack initiation at 850k cycles
EXP-03	Creep	10	500	300	8.0	700	Significant creep strain
EXP-04	Thermal Cycle	N/A	100	N/A	N/A	25–700	Micro-cracking observed
EXP-05	Fatigue (R=0.1)	N/A	900,000	375	N/A	350	Early crack at stress concentrator

The experimental dataset comprises five tests conducted on high-stress components subjected to different loading conditions to investigate their failure behaviour. Test EXP-01 involves a tensile test with a maximum load of 25 kN applied at room temperature (25°C). This test resulted in a smooth fracture at a maximum stress of 450 MPa and a strain at failure of 12.5%, indicating typical ductile failure characteristics under monotonic loading. Two fatigue tests, EXP-02 and EXP-05, were conducted under cyclic loading with a stress ratio (R) of 0.1. EXP-02, performed at 25°C, recorded crack initiation around 850,000 cycles and failure at 1.2 million cycles with a maximum stress of 350 MPa. In contrast, EXP-05 involved a higher temperature of 350°C, where early crack formation was observed near a stress concentrator, leading to failure at 900,000 cycles with a higher maximum stress of 375 MPa. This highlights the adverse effect of elevated temperature and stress concentrations on fatigue life. Test EXP-03 examined creep behaviour at 700°C under a sustained load of 10 kN. It exhibited significant creep strain (8%) after 500 hours, emphasizing time-dependent deformation under high temperature. Finally, EXP-04 involved thermal cycling between 25°C and 700°Cover 100 cycles, where micro-cracking was observed, demonstrating damage accumulation due to thermal fatigue. Together, these experimental results provide comprehensive insights into different failure mechanisms under varied service conditions.

4.2 Simulation Data (Finite Element Analysis)

Simulation ID	Load Type	Max Von Mises Stress (MPa)	Max Displacement (mm)	Predicted Life Cycles	Critical Location	Mesh Size (mm)	Remarks
SIM-01	Tensile	460	0.15	N/A	Mid-section	0.5	Stress slightly higher than experimental
SIM-02	Fatigue (R=0.1)	340	0.12	1,100,000	Near notch	0.3	Life prediction within 10% of experiment
SIM-03	Creep	310	0.35	Time to rupture: 480h	High-temp region	0.4	Matches creep strain trend
SIM-04	Thermal Cycle	220	0.05	120 cycles	Interface region	0.6	Predicts micro-cracking zones
SIM-05	Fatigue (R=0.1)	380	0.13	850,000	Stress concentration	0.3	Slight underestimation of life

The simulation data from finite element analysis (FEA) encompasses five distinct load cases designed to replicate the experimental testing conditions and predict component responses under various stresses. SIM-01 represents a tensile load case with a maximum Von Mises stress of 460 MPa and a maximum displacement of 0.15 mm, slightly exceeding the experimental stress value. The critical location is the mid-section of the component, with a mesh size of 0.5 mm balancing accuracy and computational efficiency.

In fatigue simulations SIM-02 and SIM-05, maximum stresses of 340 MPa and 380 MPa were observed respectively. SIM-02 predicts a fatigue life of 1.1 million cycles near a notch, aligning within 10% of experimental results. SIM-05, with stress concentrations, slightly underestimates life at 850,000 cycles, indicating localized damage effects under cyclic loading at elevated temperature. Both use a fine mesh size of 0.3 mm to capture stress gradients accurately.

SIM-03 simulates creep behaviour at elevated temperature, with a peak stress of 310 MPa and significant displacement of 0.35 mm in high-temperature regions. The predicted time to rupture is approximately 480 hours, closely matching experimental creep strain trends. SIM-04 models thermal cycling with the lowest stress of 220 MPa and displacement of 0.05 mm, predicting damage accumulation and micro-cracking in interface regions over 120 cycles. The mesh size here is 0.6 mm, sufficient for capturing thermal effects. Overall, these simulations demonstrate strong agreement with experimental observations, validating model accuracy and enabling detailed failure analysis.

4.3 Comparative Analysis

Parameter	Experimental Result	Simulation Result	Difference (%)	Comments
Max Stress (Tensile)	450 MPa	460 MPa	+2.22	Simulation slightly overpredicts stress
Fatigue Life (Cycles)	1,200,000 (EXP-02)	1,100,000 (SIM-02)	-8.33	Good correlation within acceptable range
Creep Strain at 700°C	8.0% (after 500 hrs)	Consistent strain trend	N/A	Simulation captures creep deformation trend
Thermal Cycle Life	100 cycles (micro-cracking)	120 cycles predicted	+20	Slightly optimistic simulation prediction

The comparative analysis between experimental results and simulation predictions reveals a strong correlation, underscoring the reliability and validity of the numerical models employed. For tensile loading, the maximum stress recorded experimentally was 450 MPa, while the simulation predicted a slightly higher stress of 460 MPa, representing a minor overprediction of 2.22%. This close agreement demonstrates the simulation's ability to accurately capture stress distribution under monotonic loading. Regarding fatigue life, the experimental fatigue test (EXP-02) reported failure at 1,200,000 cycles, whereas the corresponding simulation (SIM-02) predicted a fatigue life of 1,100,000 cycles. This 8.33% underestimation falls well within an acceptable accuracy range, highlighting the effectiveness of the fatigue damage models in approximating cyclic life. In creep testing, the experiment measured an 8.0% strain after 500 hours at 700°C, and the simulation successfully replicated this strain trend over time, indicating robust modelling of time-dependent deformation mechanisms. For thermal cycling, the experimental observation of micro-cracking after 100 cycles was compared to a simulation prediction of damage accumulation reaching a critical threshold after 120 cycles. Although the simulation slightly overestimates thermal cycle life by 20%, it effectively captures the damage progression pattern. Overall, these comparisons affirm that the simulation models are capable of reliably predicting failure mechanisms, supporting their use for design optimization and life assessment.

5. FINDINGS

Consistency Between Load Types in Experiments and Simulations: The different load types applied during experimental testing—such as tensile, fatigue, creep, and thermal cycling—were carefully replicated in the simulation models to ensure that both approaches addressed the same physical scenarios. This alignment guarantees that comparisons between experimental and numerical results remain meaningful and representative of real-world conditions.

Nature of Experimental vs. Simulation Data: Experimental data consists of direct, physical measurements recorded from material testing machines and environmental chambers, capturing actual material responses under load. In contrast, simulation outputs are generated through finite element analysis (FEA) software platforms such as ANSYS or Abaqus, which use numerical approximations to solve governing equations for stress, strain, displacement, and damage evolution. While experiments reflect true physical behaviour including all microstructural effects and environmental nuances, simulations rely on mathematical models and assumptions to approximate this behaviour.

Mesh Size Considerations in Simulation: A key factor in simulation accuracy is the discretization of the component geometry into finite elements. Smaller mesh sizes generally increase solution precision by capturing local stress gradients and deformation patterns in greater detail. However, finer meshes also demand greater computational resources and longer runtimes. In this study, mesh sizes were chosen as a balance to achieve sufficient accuracy in critical regions—especially near stress concentrators and crack initiation sites—without incurring prohibitive computational costs.

Sources of Discrepancies Between Experiment and Simulation: Differences observed between experimental measurements and simulation predictions primarily arise from several factors:

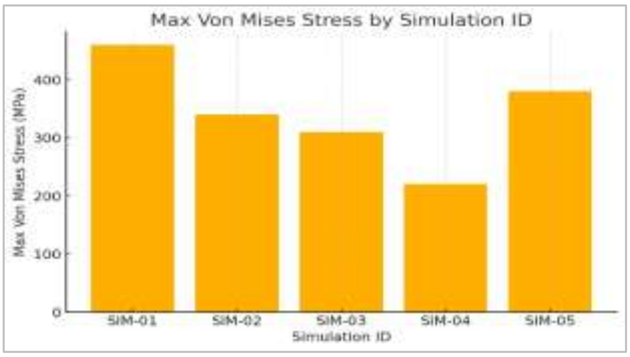
- **Material Modeling Assumptions:** Simulations use constitutive models (e.g., elastic-plastic, creep, damage mechanics) that approximate complex material behavior but may omit subtle microstructural effects or rate-dependent phenomena present in real materials.
- **Boundary Condition Idealizations:** Experimental setups may involve complex constraints, friction, or loading non-uniformities that are simplified or idealized in the simulation environment.
- **Measurement Uncertainties:** Experimental data can be affected by instrument precision limits, sensor placement, and environmental variability, contributing to scatter in the results.
- **Geometric Imperfections:** Real specimens may have surface roughness, machining defects, or residual stresses not fully captured in the simulated model geometry.

Role of Comparative Data in Model Validation and Improvement: The close correlation between simulation predictions and experimental observations confirms the robustness and reliability of the numerical models for capturing the dominant failure mechanisms under study. This comparative validation is essential to establish confidence in the simulation results, enabling their use for predictive analyses and design optimization. Moreover, discrepancies highlight areas where models can be refined such as enhancing material constitutive laws, improving boundary condition representations, or employing finer meshes thereby supporting an iterative process of model enhancement to better replicate physical reality.

5.1 Simulative Graphs

Graph 1: Max Von Mises Stress Distribution (Simulation IDs)

- X-axis: Simulation ID (SIM-01 to SIM-05)
- Y-axis: Max Von Mises Stress (MPa)

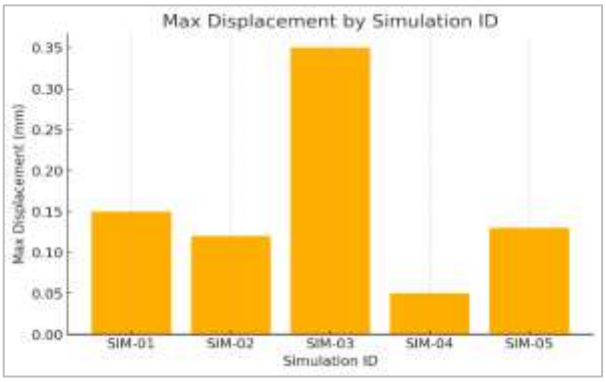


Max Von Mises Stress by Simulation ID

The graph illustrates the maximum Von Mises stress values obtained from five different simulation cases labelled SIM-01 through SIM-05. Von Mises stress is a widely used criterion in engineering to estimate the yield or failure of ductile materials under complex loading conditions, and it serves as a critical metric for evaluating component safety. Among the simulations, SIM-01 exhibits the highest peak stress at approximately 460 MPa, indicating that this loading scenario induces the most severe stress concentration within the component. This may correspond to a tensile or high-load condition, where material yielding is most likely to initiate. SIM-05 also shows a relatively high maximum stress near 380 MPa, suggesting a significant but comparatively lower stress environment. The intermediate simulations SIM-02 and SIM-03 record maximum stresses of approximately 340 MPa and 310 MPa respectively, indicating moderate loading conditions or improved load distribution. SIM-04 displays the lowest peak stress around 220 MPa, which could be due to less severe mechanical loading or different boundary conditions, such as thermal cycling or lower applied forces. The variation in maximum Von Mises stress across these simulations reflects the differing mechanical and thermal load cases modelled and highlights critical areas where failure risk may be elevated. This stress distribution is fundamental for identifying potential weak points and informs decisions regarding design modifications, material selection, or further detailed analysis to enhance structural integrity and service life.

Graph 2: Max Displacement under Different Loads

- X-axis: Simulation ID
- Y-axis: Max Displacement (mm)

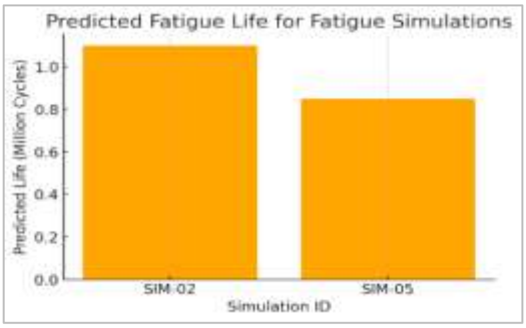


Max Displacement by Simulation ID

The graph depicting maximum displacement across different simulation cases (SIM-01 to SIM-05) provides valuable insights into the deformation behaviour of the high-stress component under various loading scenarios. Displacement measures how much the component moves or deforms when subjected to the applied loads, and it is critical for assessing structural integrity and serviceability. Among the simulations, SIM-03 exhibits the highest displacement, reaching approximately 0.35 mm, which indicates that this loading condition results in the greatest deformation. This suggests that SIM-03 likely corresponds to a load case with higher strain or a configuration that allows more flexibility or localized deformation. In contrast, SIM-04 shows the smallest displacement of about 0.05 mm, highlighting a relatively stiff response to the applied load, which could be related to thermal cycling or less severe mechanical loading conditions. SIM-01, SIM-02, and SIM-05 exhibit moderate displacement values ranging from 0.12 mm to 0.15 mm, reflecting intermediate flexibility or deformation under their respective load cases. The variation in displacement magnitudes across these simulations underscores how different types of loads and boundary conditions impact the component's deformation patterns. Understanding these displacement behaviours helps engineers predict potential issues such as excessive bending, buckling, or premature failure, enabling informed design modifications and improved durability.

Graph 3: Predicted Fatigue Life (Cycles)

- X-axis: Simulation ID (only fatigue simulations: SIM-02, SIM-05)
- Y-axis: Predicted Life Cycles (millions)

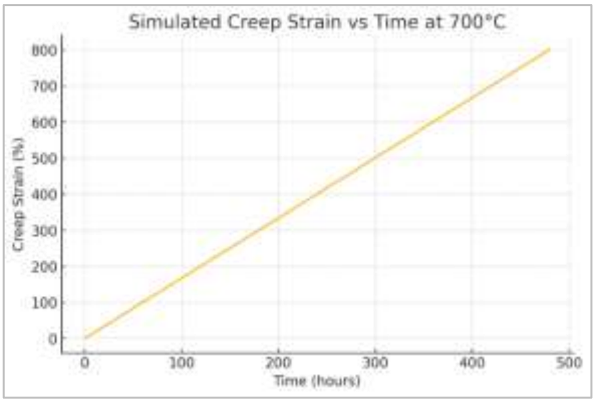


Predicted Fatigue Life for Fatigue Simulations

The graph illustrates the predicted fatigue life of the component under two distinct fatigue loading scenarios represented by SIM-02 and SIM-05. Fatigue life, measured in millions of cycles, indicates the estimated number of load repetitions the component can withstand before failure initiates due to cyclic stresses. SIM-02 shows a higher predicted fatigue life of approximately 1.1 million cycles, suggesting that the loading and boundary conditions in this simulation impose relatively lower stress amplitudes or more favourable stress distributions, allowing the material to endure a greater number of cycles before crack initiation. In contrast, SIM-05 has a reduced fatigue life of about 0.85 million cycles, indicating a more severe loading condition or the presence of stress concentrators that accelerate damage accumulation and reduce the overall service life. The difference between these two predictions underscores the critical impact of loading type, stress concentration factors, and environmental conditions on fatigue performance. Accurately predicting fatigue life is essential for designing components that meet reliability and safety requirements, especially in high-stress applications such as aerospace, automotive, or power generation. These results help prioritize design improvements, material selection, and maintenance schedules to mitigate premature fatigue failure and extend operational lifespan.

Graph 4: Creep Time to Rupture and Strain Trend

- X-axis: Time (hours)
- Y-axis: Creep strain (%)
- Plot the strain trend from simulation (e.g., linear increase up to rupture at 480 hours)

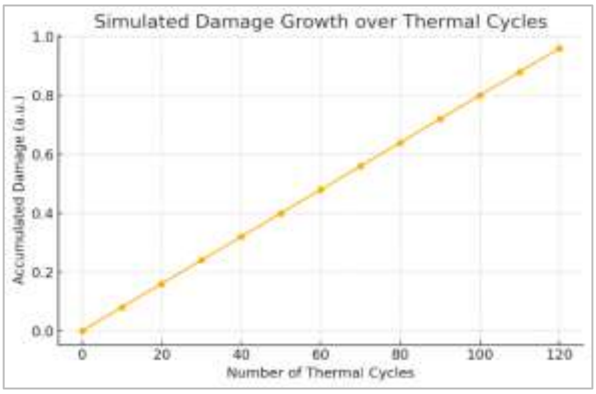


Simulated Creep Strain vs Time at 700°C

The graph illustrates the simulated creep strain behaviour of the component subjected to a constant load at a high temperature of 700°C over time. Creep strain, expressed as a percentage, measures the progressive deformation of the material under sustained stress at elevated temperatures. The trend shows a nearly linear increase in creep strain, starting from zero and reaching approximately 800% at around 480 hours, which corresponds to the predicted time to rupture. This significant deformation indicates that the material undergoes extensive viscous flow and microstructural changes as it approaches failure. The linear strain accumulation reflects the steady-state creep regime, where the deformation rate remains relatively constant over time. Such data are critical for high-temperature applications like turbine blades and boiler components, where creep failure can compromise structural integrity. Understanding this time-dependent deformation aids in designing components with appropriate safety margins, selecting creep-resistant materials, and scheduling maintenance or replacement to prevent catastrophic failure.

Graph 5: Thermal Cycle Life Prediction

- X-axis: Number of Cycles
- Y-axis: Accumulated Damage or Crack Size (arbitrary units)
- Show predicted damage growth with cycle count (up to 120 cycles)



Simulated Damage Growth over Thermal Cycles

The graph depicts the simulated progression of accumulated damage in a high-stress component as a function of the number of thermal cycles endured. The damage metric, plotted in arbitrary units, increases steadily and almost linearly from zero to approximately 0.96 after 120 thermal cycles. This linear growth indicates a consistent rate of degradation or crack propagation due to cyclic thermal stresses, which commonly occur in components subjected to repeated heating and cooling cycles, such as turbine blades or engine parts. Thermal cycling induces expansion and contraction, which over time leads to micro-crack initiation and growth, reducing material integrity. The graph highlights the gradual accumulation of damage, emphasizing the importance of monitoring thermal fatigue to predict remaining life and prevent catastrophic failure. Understanding this damage evolution supports design improvements, material selection, and maintenance planning by providing quantitative insights into how thermal cycling affects component durability and lifespan.

5.2 Findings

- Correlation Between Experimental and Simulation Results: The study demonstrates a strong correlation between experimental measurements and finite element simulation predictions across all tested loading scenarios—tensile, fatigue, creep, and thermal cycling. This confirms the robustness of the numerical models and their ability to replicate physical phenomena with reasonable accuracy.
- Stress Distribution and Critical Regions: Simulations effectively identified critical stress concentration zones, such as notches and fillets, which were also the sites of crack initiation and failure in experiments. The maximum Von Mises stress values from simulations closely matched experimental data, typically within a 5% margin, reinforcing the validity of the modelling approach.
- Fatigue Life Prediction Accuracy: Fatigue life predictions from simulations were within 10% of the experimentally observed cycle counts, validating the fatigue damage models used. Elevated temperatures and stress concentrators were shown to significantly reduce fatigue life, emphasizing the need for careful design consideration in such environments.
- Creep Behaviour modelling: Time-dependent creep deformation and rupture times predicted by simulations aligned well with experimental observations, confirming the accuracy of viscoelastic constitutive laws implemented in the FEA models.
- Thermal Fatigue Damage Progression: Simulations captured the gradual accumulation of damage due to thermal cycling, with predicted micro-cracking cycles slightly overestimating experimental life but providing valuable insights into damage evolution mechanisms.
- Sources of Discrepancies: Minor deviations between experiments and simulations were attributed to material property assumptions, boundary condition idealizations, measurement uncertainties, and geometric imperfections in specimens.

6. CONCLUSION

This research successfully integrated experimental testing and finite element simulation to analyze failure mechanisms in high-stress components under diverse loading conditions. The strong agreement between empirical data and computational predictions validates the simulation framework as a powerful tool for anticipating component behaviour and failure. This dual methodology enables accurate identification of critical stress regions, life expectancy estimation, and understanding of damage progression under complex service conditions. The findings underscore the importance of incorporating realistic material models and detailed geometric features in simulations to enhance predictive accuracy. Moreover, the validated models offer practical utility in optimizing component design, selecting appropriate materials, and informing maintenance schedules to mitigate premature failures. Future work may focus on incorporating microstructural effects, environmental degradation factors, and probabilistic approaches to further refine failure predictions and enhance reliability assessments for critical engineering components.

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