

Applications of Finite Element Analysis in Structural Failure Investigation and Integrity Evaluation: A Review

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ABSTRACT

Engineering failures experience substantial economic losses, operational disruptions, and safety hazards across industries. This review synthesizes systematic failure investigation methodologies, integrating traditional laboratory examination with advanced Finite Element Analysis (FEA) computational techniques. Modern mechanical systems featuring multi-material assemblies, complex thermal-mechanical interactions, and demanding environmental conditions necessitate integrated investigation strategies combining empirical and numerical approaches. The review encompasses diverse failure mechanisms: fatigue fractures in pressure components (thermowells), thermal-mechanical failures in precision equipment (tool holders, spindle assemblies), contact failures in machining systems (vise jaw holders), and complex multi-physics failures involving thermal, mechanical, magnetic, and chemical coupling. FEA has become indispensable for quantitative stress analysis, identifying stress concentration regions, predicting failure behavior, and evaluating design modifications. Advanced techniques including coupled thermal-structural analysis, contact mechanics modeling, modal analysis, and optimization integration enable comprehensive failure understanding.

Future advancement depends on machine learning integration with FEA and experimental databases for enhanced pattern recognition, digital twin development combining real-time sensor data with continuously-updated FEA models, and adaptive frameworks for novel materials and operational demands.

This review provides engineers, researchers, and professionals with systematic understanding of failure investigation principles, practical FEA applications, guidance for integrating experimental-computational methodologies, and insights into emerging technologies. By synthesizing knowledge across applications and approaches, the review advances engineering capability to prevent failures, enhance reliability, improve safety, and allocate resources effectively. Systematic, integrated failure investigation remains paramount as both a reactive diagnostic tool for understanding past failures and a proactive methodology for preventing future incidents.

Keywords: -failure investigation, finite element analysis, experimental-computational integration.

1. INTRODUCTION

Traditional failure analysis has largely relied on post-failure experimental investigations such as visual inspection, metallography, fractography, and mechanical testing to identify damage mechanisms including fatigue, corrosion, creep, and overload fracture (Bhagi et al., 2013; El-Batahgy & Fathy, 2013). While these methods provide valuable insights, they are inherently reactive and offer limited capability for predicting failure or optimizing designs at early development stages. The advancement of computational mechanics, particularly FEA, has transformed failure analysis into a predictive and design-oriented discipline by enabling detailed evaluation of stress, strain, thermal behavior, and deformation under realistic operating conditions.

Recent studies demonstrate the extensive application of FEA in assessing structural integrity across diverse engineering systems, including machine tools, machining processes, and structural components (Wang et al., 2012; Verma & Pradhan, 2020; Chan et al., 2023). The method has proven effective in identifying critical stress zones, evaluating fatigue life, and understanding thermo-mechanical interactions, especially in complex assemblies such as tool holders, turbine components, and composite structures (Arslan, 2014; Chen & Lin, 2014; Xiao et al., 2014). Furthermore, advances in coupled-field simulations, damage mechanics, and digital twin frameworks have enhanced predictive capabilities, enabling real-time condition monitoring and design optimization (Armendia et al., 2019; Maziz et al., 2021). Despite these developments, challenges related to

material uncertainty, contact modeling, and multiscale behavior remain.

2. LITERATURE SURVEY

The comprehensive review of existing research related to the application of FEA in structural integrity assessment and failure analysis has been systematically compiled and summarized in Table 1. This table presents a consolidated overview of key studies reported in the literature, highlighting the application domain, analytical or experimental methodologies employed, and the major findings and contributions of each work.

Table 1. Summary of literature on finite element analysis applications

Author(s) & Year	Application Area	Methodology / Approach	Key Findings	Major Contributions / Outcomes
Chan et al. (2023)	Gantry-type high-precision machine tools	FEA-based structural and topology optimization	Achieved lightweight yet rigid structural configuration with improved stiffness	Demonstrated effectiveness of topology optimization for improving precision and reducing material usage
Chan et al. (2023)	Machine tool structural design	Finite Element Analysis	Identified optimal structural configuration for enhanced rigidity and machining accuracy	Improved performance and reliability of high-precision machine tools
Chen & Lin (2014)	High-speed tool holder systems	Contact element-based FEA	Analyzed clamping force distribution and deformation under high rotational speeds	Provided guidelines for improved tool holder design and enhanced machining stability
Chinnuraj et al. (2020)	CNC lathe bed (steel–epoxy granite composite)	Static and dynamic FEA	Demonstrated improved vibration damping and stiffness due to composite reinforcement	Established epoxy–granite as an effective alternative to cast iron for machine tool beds
Verma & Pradhan (2020)	CNC turning operations	Experimental analysis and FEA	Evaluated influence of tool–workpiece combinations on cutting performance	Enabled optimization of machining parameters for improved surface quality
Wang et al. (2012)	Tool holder–spindle assembly	Modal analysis using FEA	Identified natural frequencies and vibration modes affecting machining accuracy	Provided basis for minimizing chatter and enhancing dynamic stability
Xiao et al. (2014)	Spindle–holder taper joint	Zero-thickness interface finite element modeling	Accurately captured contact stiffness and deformation behavior	Introduced improved modeling approach for precision joint analysis
Ortiz et al. (2013)	Spark plug failure analysis	Experimental investigation and material characterization	Identified magnetic field interaction and fuel additives as failure causes	Highlighted influence of electromagnetic effects and fuel quality on component life
Bhagi et al. (2013)	Low-pressure Steam turbine blade	Fractography, SEM, material testing	Identified corrosion–fatigue as primary failure mechanism	Emphasized need for corrosion-resistant materials and improved operational control
El-Batahy & Fathy (2013)	Thermowell failure in gas pipelines	Experimental analysis and vibration assessment	Demonstrated resonance-induced fatigue due to vortex shedding	Recommended design modification using tapered thermowells
Park & Park (2006)	Martensitic stainless steel	Heat treatment and corrosion testing	Found strong influence of austenitizing temperature on corrosion resistance	Provided guidance for optimizing heat treatment processes
Al-Bahkali & Abbas (2018)	Hacksaw machine vise jaw	Finite element-based stress analysis	Identified stress concentration zones causing premature failure	Recommended geometric redesign and material improvement
Armendia et al. (2019)	Digital twin for machine tools	Integration of real-time data with FEA models	Enabled predictive monitoring and process optimization	Demonstrated feasibility of digital twin frameworks in manufacturing
Arsilan (2014)	Shrink-fit tool holders	Coupled thermal–structural FEA	Evaluated thermal expansion effects on clamping force and stiffness	Provided design guidelines for thermally stable tool holders

3. INTERFERENCES FROM LITERATURE SURVEY

3.1 Paradigm shift in failure analysis: from reactive to predictive approaches

Early failure analysis relied primarily on post-failure investigations such as visual inspection, metallography, fractography, and mechanical testing to identify damage mechanisms including fatigue, corrosion, and overload

fracture (Bhagi et al., 2013; El-Batahgy & Fathy, 2013). While effective for root-cause identification, these approaches were inherently reactive and offered limited predictive capability. The emergence of Finite Element Analysis (FEA) has transformed failure analysis into a proactive and design-integrated discipline by enabling prediction of stress distributions, deformation patterns, and critical failure locations under realistic loading conditions (Wang et al., 2012; Arslan, 2014; Chan et al., 2023). The cause and effect diagram of the components is shown in Fig. 1.

FEA-based methodologies allow early identification of structural vulnerabilities, enabling design optimization prior to fabrication. Studies on machine tool systems demonstrate that vibration-induced failures and resonance phenomena can be predicted through modal and harmonic analyses, thereby preventing performance degradation and structural damage (Wang et al., 2012). The integration of numerical simulations with experimental validation has established a robust framework where computational predictions guide experimental investigation and vice versa, leading to more reliable and efficient failure assessment practices (Xiao et al., 2014).

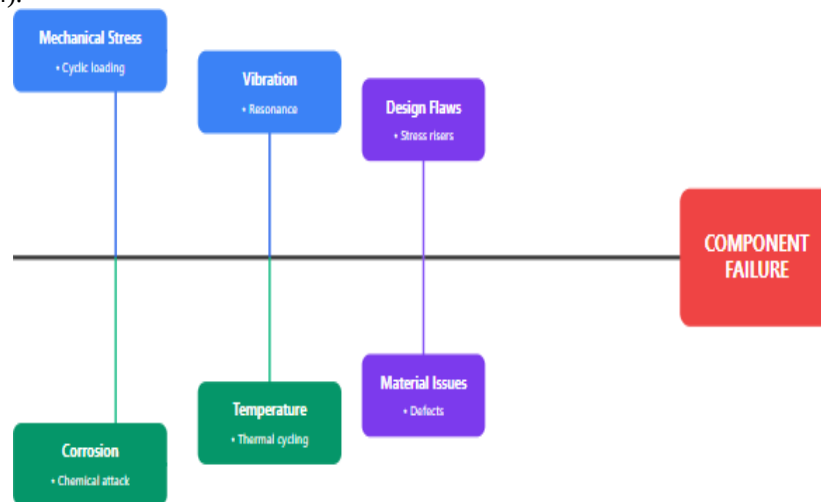


Fig. 1 Failure mechanism cause and effect

3.2 Multi-physics nature of modern failure mechanisms

Contemporary engineering failures rarely result from isolated physical phenomena; instead, they arise from complex interactions among thermal, mechanical, chemical, and electromagnetic effects. Multi-physics coupling has therefore become essential for accurate failure prediction. Arslan (2014) demonstrated that coupled thermal–mechanical analysis of shrink-fit tool holders reveals stress evolution patterns unattainable through single-physics simulations. Similarly, Bhagi et al. (2013) showed that corrosion fatigue interactions in turbine blades significantly accelerate crack initiation compared to purely mechanical fatigue.

Further illustrating this complexity, Ortiz et al. (2013) reported spark plug failures caused by combined electromagnetic effects and chemical degradation from fuel additives, emphasizing that failure mechanisms often emerge from interacting physical domains rather than isolated factors. These studies collectively establish that reliable failure prediction necessitates integrated multi-physics modelling frameworks capable of capturing such coupled interactions. Fig. 2. Detailed the process of integrated failure analysis methodology applied in industries.

3.3 Role of contact mechanics and interface behavior

Contact interfaces represent critical locations for stress concentration and failure initiation. Numerous studies have demonstrated that inaccurate representation of contact behaviour leads to significant underestimation of localized stresses. Chen and Lin (2014) showed that non-uniform contact pressure in high-speed tool holders' results in localized deformation and reduced machining accuracy. Similarly, Xiao et al. (2014) developed specialized finite element formulations for taper joints, demonstrating that interface deformation significantly influences system stiffness and positional accuracy. Al-Bahkali and Abbas (2018) further highlighted the importance of contact mechanics through failure analysis of hacksaw machine vise jaws, where stress concentrations at contact regions led to premature fracture. These findings emphasize the necessity of advanced contact modeling techniques such as nonlinear contact algorithms and refined mesh strategies to accurately predict failure initiation in jointed structures.

3.4 Industry-specific failure characteristics

Distinct industrial sectors exhibit characteristic failure patterns governed by operational environments and loading conditions. In machine tools, vibration-induced failures and thermal distortion dominate, as evidenced

by studies on spindle–tool assemblies and optimized gantry structures (Wang et al., 2012; Chan et al., 2023). In power generation systems, corrosion-fatigue mechanisms govern component degradation, particularly in steam turbine blades operating under aggressive thermal and chemical environments (Bhagi et al., 2013).

Process industries exhibit failure modes driven by fluid–structure interactions. El-Batahgy and Fathy (2013) demonstrated that flow-induced resonance in thermowells led to catastrophic fatigue failure, requiring geometric redesign for mitigation. Composite and hybrid material systems introduce additional complexity, where damage evolves through coupled mechanisms such as matrix cracking, delamination, and fiber fracture, as reported by Maziz et al. (2021). These findings underscore the necessity for industry-specific failure modeling approaches rather than generic analytical frameworks.

3.5 Material selection and heat treatment optimization

Material properties and processing routes play a decisive role in determining component durability. Park and Park (2006) demonstrated that variations in austenitizing temperature significantly influence the corrosion resistance of martensitic stainless steels by altering grain structure and carbide distribution. Such studies highlight the importance of tailoring heat treatment parameters to enhance resistance against environmental degradation. Similarly, Chinnuraj et al. (2020) showed that steel epoxy granite composites provide superior damping and vibration control compared to conventional metallic structures, offering improved structural performance in machine tool applications. These findings emphasize that strategic material selection and processing optimization can effectively mitigate failure risks, often outperforming purely geometric design modifications.

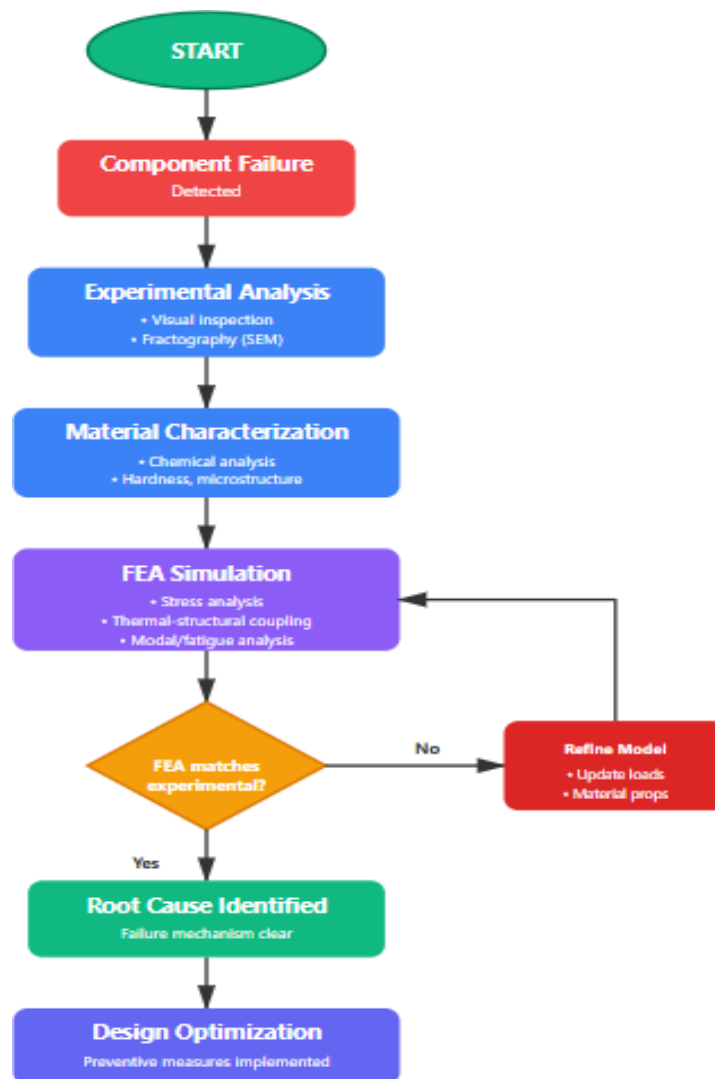


Fig. 2. Integrated failure analysis methodology

3.6 Emerging directions: AI, digital twins, and multi-scale modelling

Recent advancements increasingly integrate artificial intelligence and machine learning with FEA to enhance predictive capability. Machine learning algorithms enable surrogate modeling, rapid evaluation of design

alternatives, and automated identification of failure-prone regions from simulation datasets (Nath et al., 2024). Digital twin frameworks extend this capability by continuously updating numerical models using real-time sensor data, enabling predictive maintenance and life-cycle optimization (Armendia et al., 2019).

Multi-scale modelling represents another critical frontier, linking microstructural evolution with macroscopic structural behavior. Studies on composite and metallic materials demonstrate that microstructural features such as grain morphology, phase distribution, and defect populations significantly influence macroscopic failure behavior (Maziz et al., 2021). Integrating these effects through hierarchical modelling frameworks remains a key research challenge.

3.7 Uncertainty quantification and reliability-based design

Traditional deterministic analyses inadequately capture variability arising from material heterogeneity, manufacturing tolerances, and uncertain loading conditions. Probabilistic methods, incorporating statistical distributions of material properties and loads, enable reliability-based failure assessment and risk-informed design. Such approaches allow quantification of failure probability rather than binary safety judgments, supporting more rational engineering decisions.

Uncertainty quantification techniques including stochastic finite element methods, Monte Carlo simulation, and reliability index evaluation are increasingly adopted to address these challenges. Their integration with FEA facilitates robust design optimization and enhances confidence in predicted service life, particularly for safety-critical components.

4. CONCLUSIONS

In summary, contemporary failure analysis has evolved into a multidisciplinary, predictive science integrating experimental investigation, advanced numerical simulation, and data-driven methodologies. The convergence of FEA, multi-physics modelling, material science, and emerging digital technologies provides a comprehensive framework for understanding and mitigating failure mechanisms. Continued advancements in multi-scale modelling, AI integration, and probabilistic analysis are essential for developing resilient, efficient, and reliable engineering systems across diverse industrial domains.

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