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Applied Mathematics

Current practices and research trends on fatigue analysis in cranes

Práticas atuais e tendências de pesquisa na análise de fadiga em guindastes

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ABSTRACT

Cranes are critical industrial systems subjected to prolonged cyclic and stochastic loading, making their metal structures prone to fatigue failure, especially at welded joints. This review systematically examines conventional and advanced methodologies for fatigue assessment in cranes. Traditional approaches based on S–N curves and Miner's rule are discussed, alongside advanced local stress methods (notch stress, hot-spot stress, equivalent structural stress) and multiaxial fatigue criteria. The role of numerical simulation, including FEM and co-simulation with Multi-Body Dynamics (MBD), is highlighted. Emerging trends such as Machine Learning (ML), Digital Twin (DT) frameworks, and Bayesian reliability updating are reviewed as transformative tools for real-time prediction and risk-based inspection. The paper emphasizes the mathematical and computational foundations of these methods, aligning with the scope of applied mathematics. Finally, a critical discussion synthesizes gaps in the literature, and future research directions are proposed.

Keywords: Cranes; Fatigue; Machine learning; Finite element method; Digital twin.

RESUMO

Guindastes são sistemas industriais críticos sujeitos a cargas cíclicas e estocásticas prolongadas, tornando suas estruturas metálicas propensas a falhas por fadiga, especialmente em juntas soldadas. Esta revisão examina sistematicamente metodologias convencionais e avançadas para avaliação de fadiga em guindastes. Abordagens tradicionais baseadas em curvas S–N e na regra de Miner são discutidas, juntamente com métodos avançados de tensão local (tensão de entalhe, tensão hot-spot, tensão estrutural equivalente) e critérios multiaxiais. O papel da simulação numérica, incluindo MEF e co-simulação com Dinâmica Multicorpos (MBD), é destacado. Tendências emergentes como Aprendizado de Máquina (ML), estruturas Gêmeas Digitais (DT) e atualização bayesiana para confiabilidade são revisadas como ferramentas transformadoras para predição em tempo real e inspeção baseada em risco. O artigo enfatiza os fundamentos matemáticos e computacionais desses métodos, alinhando-se ao escopo da matemática aplicada. Por fim, uma discussão crítica sintetiza lacunas na literatura e são propostas direções futuras de pesquisa.

Palavras-chave: Guindastes; Fadiga; Aprendizado de máquina; Método dos elementos finitos; Gêmeo digital.

1 Background and Motivation

Cranes, including large industrial types like Ship-to-Shore (STS) gantry cranes and essential mobile equipment such as loader cranes, are vital components in global logistics handling systems and industrial enterprises (Pedersen, 2011). These machines are highly susceptible to fatigue failure due to the intensive, cyclic, and stochastic loading experienced during operation. Fatigue damage manifests as progressive crack growth, initiating primarily at critical locations, notably welded joints within structures like crane runway beams, variable-section supports, or boom structures (Zhao, 2022). Failures originate from stress concentrations, defects, and geometrical discontinuities created during fabrication, necessitating immediate action when detected due to the severe consequences of structural collapse (Fisher and van de Pas, 2002). Furthermore, manufacturers often utilize ultra-high-strength steel (e.g., S700–S1300) to develop lightweight and high-performance cranes; however, the fatigue strength of welded joints generally remains independent of the base material strength, emphasizing the need for robust fatigue methods to fully exploit the materials' potential. Accurate fatigue life prediction and remaining life assessment are paramount for ensuring compliance with standards (e.g., (European Committee for Standardization, 2021c), (European Committee for Standardization (CEN), 2021)) and maintaining safe operation, particularly since many cranes continue service well beyond their original specified design fatigue life.

This review synthesizes the state-of-the-art in fatigue analysis for crane structures, with a particular focus on the integration of traditional mechanical approaches with emerging data-driven and computational methods. The paper is structured to highlight the mathematical and numerical foundations underlying fatigue assessment, aligning with the scope of applied mathematics.

1.1 Types of Cranes and Critical Fatigue Locations

Fatigue analysis of crane structures is fundamentally rooted in applied mathematics, spanning from phenomenological modeling to advanced computational algorithms. Phenomenological models of fatigue damage accumulation, such as the Palmgren-Miner rule and Paris' crack growth law, rely on differential equations and stochastic processes to describe material degradation under cyclic loading. Numerical methods, particularly the Finite Element Method (FEM) and Multi-Body Dynamics (MBD), employ discretization techniques and numerical integration to solve partial differential equations governing stress distribution and dynamic response. In the era of data-driven prognosis, machine learning algorithms, including neural networks, ensemble methods, and deep learning architectures, leverage optimization theory, linear algebra, and statistical learning to model complex, non-linear relationships between loading histories and fatigue life. Probabilistic analysis and Bayesian updating provide a rigorous mathematical framework to quantify uncertainties in loads, material properties, and inspection data, transforming deterministic assessments into reliability-based predictions. Constitutive equations of cyclic plasticity and damage mechanics formalize the material behavior under multiaxial stress states, often requiring tensor calculus and nonlinear solvers. Finally, signal processing techniques such as Rainflow counting and spectral analysis, essential for processing Structural Health Monitoring (SHM) data, are grounded in time-series analysis, cycle extraction algorithms, and frequency-domain transformations. Thus, the advancement of fatigue analysis in cranes is intrinsically tied to progress in applied mathematics, which provides the theoretical and computational tools necessary to transition from empirical practices to predictive, physics-informed digital engineering.

Cranes subjected to cyclic loading frequently experience fatigue failure, making the identification of critical locations crucial for safety assessment (Qi et al., 2013). The sources cover a diverse range of lifting equipment, including large industrial machines such as Ship-to-Shore (STS) gantry cranes used in ports (van Jole, 2016), travelling gantry cranes (e.g., the LT51B used in the forest industry), portal cranes, bridge cranes, and tower cranes used in construction. Also examined are specialized structures like lattice boom cranes (Cai et al., 2014) and loader cranes (truck-mounted, using mobile hydraulics). Failures typically initiate as cracks in welded joints, which possess lower fatigue strength than the base material due to stress concentrations, notches, and high tensile residual stresses introduced during fabrication. For example, studies confirm frequent fatigue failures in travelling gantry cranes, where cracks initiate and propagate in the welded joints of the crane bridge and supports (Kopnov, 1999). In mobile cranes, fatigue resistance is governed by these critical welded joints. Several components across these different crane types are identified as being highly susceptible to fatigue damage due to high or fluctuating loads. For STS gantry cranes, structural integrity is frequently compromised at the welds (van Jole, 2016). Highly sensitive locations, often due to accessibility limitations during welding and large load fluctuations, include the connections at the forestay and backstay, the connections between the crane boom and the portal beams, the connections at the legs, and the base of the A-frame. In tower cranes, the boom structure is generally cited as the most vulnerable component, potentially accounting for about 95% of structural fatigue issues, with critical points located at the connections of the drawbars and lifting arms (Tawjoeram, 2016). Crane runway girders, essential for supporting traveling cranes, are notoriously prone to fatigue cracking, especially at the connection of the top flanges to the webs and in specialized components like variable-section supports used in industrial buildings (Zhao, 2022). In box-girder bridge-cranes, failure points typically occur at the weld joints connecting the lower cover plate to the web tension flange and the transverse diaphragm to the web lower end. For lattice boom cranes, concentrated failures occur at numerous K-type welded joints and in the chord near variable cross-sections on the bottom segments. Furthermore, even non-structural failures, such as those involving turret bolts in mobile cranes, can be attributed to crack initiation and propagation due to fluctuating tensile loads (Alam et al., 2018).

The academic literature about crane safety and fatigue is substantial and can be broadly classified into several research streams, including case studies, maintenance and inspection protocols, fatigue assessment techniques, and analyses of design and operational parameters (Associação Brasileira de Normas Técnicas, 2021), which will be elaborated upon in subsequent sections. The regulatory framework governing crane design is well established. In Brazil, the (Associação Brasileira de Normas Técnicas, 2021) and (Associação Brasileira de Normas Técnicas, 2019) standards specify requirements for hydraulic articulated cranes, and (Associação Brasileira de

Normas Técnicas, 2020) specifies the corresponding loads and nondestructive tests. In Europe, a comprehensive suite of standards, including (European Committee for Standardization, 2021a), (European Committee for Standardization, 2021b), and (European Committee for Standardization, 2021c), provides detailed guidelines on general safety, load actions, and strength verification. Furthermore, the DNV-RP-C203 standard is widely recognized for its application in fatigue analysis, particularly for offshore structures, offering valuable insights for crane design. A preliminary bibliometric analysis highlights the significance of this review. A search in the Scopus database for "fatigue life cranes" over the past decade (2014-2024) returned 203 journal articles and 72 conference papers, indicating a vibrant field of study. A similar query on the Compendex platform yielded 160 records, with China, Germany, and France being the most prolific contributing nations. This volume of research underscores the necessity of a synthesizing review to consolidate existing knowledge and identify future directions.

1.2 Survey Organization and Contributions

The subsequent sections provide a comprehensive survey organized into seven main parts. Section 2 establishes the fundamental prerequisite for fatigue assessment, reviewing the characterization of fatigue loading in cranes. Section 3 details the traditional fatigue assessment methodologies, focusing on the widespread use of the Stress-Life (S-N) approach. Section 4 reviews advanced local stress methods tailored for intricate structural details like welded joints and variable-section supports. Section 5 examines the role of modern modeling techniques, specifically the application of Finite Element Method (FEM) and coupled dynamics simulations (MBD/FEM) for accurate stress history acquisition. Finally, Section 6 addresses practical structural integrity management for existing cranes, outlining established practices for remaining life assessment. The paper concludes in Section 8 with a summary of key findings and an outlook on future research directions. From the bibliographical survey performed starting from 1988, it can be observed main trends in methods applied to the study of fatigue analysis in main crane components. Table 1 shows these main strategies applied to the mechanical problem.

Table 1 – Main strategies used for fatigue analysis in crane-related structures

Technique	Description	References
Stress-Life (S-N) Curve Approach (Nominal Stress Method)	The fundamental method for predicting fatigue life (crack initiation life) is used during the design phase. It uses standard S-N curves, derived from material testing, to relate nominal stress ranges to the number of cycles to failure (N). This method is generally used for structures operating under the yield strength.	Dong et al. (2021);Wei et al. (2025);Liu et al. (2024); Tawjoeram (2016);Gbagba et al. (2024); Zhu et al. (2025); Xiong and Wang (2012);Fisher and van de Pas (2002);Caglayan et al. (2010); Romanowicz (2017)
Cumulative Damage Theory of Miner's Rule	Applied in conjunction with the S-N approach to assess damage under the crane's characteristic variable amplitude loading. Palmgren-Miner's linear (Miner, 1945) accumulation theory is the standard, although non-linear models (e.g., Huffman non-linear cumulative damage theory) are proposed to improve accuracy and reduce dispersion, particularly for welded joints.	Caglayan et al. (2010);Cai et al. (2014); Lehner et al. (2019); Hectors et al. (2020); Euler and Taylor (2021); Zhao et al. (2024)
Fracture Mechanics (FM)	Used primarily for predicting crack propagation life and remaining service life in structures where initial defects or cracks are present. This approach models the growth rate of cracks (often using Forman's formula or Paris' Law) from an assumed initial size(α_0) to a critical size (α_c). Essential for aging cranes operating beyond their design life.	Hu and Chen (2025); Dong et al. (2021); Li et al. (2023a); van Jole (2016); Zhao (2022); Cai et al. (2014); Qi et al. (2013); Zhu et al. (2025); Buczkowski and Zylinski (2021); Avila et al. (2017)
Local Stress Approaches	Methods that move beyond nominal stress to assess local stress concentrations, especially critical for welded joints, where fatigue failures typically initiate. This category includes the Notch Stress Approach (NSA), the Hot-Spot Stress Method (HSM), and the Peak Stress Method (PSM).	Radaj et al. (2009);Cai et al. (2014);Zhao et al. (2024); Zhao (2022); Hectors et al. (2020); Liu et al. (2024); Zhao et al. (2023); Pedersen (2011); Tawjoeram (2016);Zhao (2022);Wei et al. (2025)
Integrated Simulation (FEM/MBD)	The combination of Finite Element Method (FEM) for calculating local stresses with Multi-Body Dynamics (MBD) simulations (e.g., using ADAMS) is used to accurately model the transient dynamic response. This technique is critical for obtaining realistic stress time histories that account for complex operational loads (multidirectional principal axis), like moving loads and the lifting impact effect.	Xiong and Wang (2012); Tawjoeram (2016); Li et al. (2023b); Jiang and Jiang (2023); Li et al. (2023a); Zhao et al. (2024)
Probabilistic and Data-Driven Methods	Advanced methods aimed at improving efficiency and reliability using statistical or learning models. This includes: Artificial Neural Networks (ANN) and Stacking Ensemble Learning Models (SELM) for rapid stress spectrum analysis and life prediction; Monte Carlo Simulation for stochastic load modeling and reliability analysis; and Bayesian Updating to refine reliability estimates using inspection data.	Zhao et al. (2024); Yu et al. (2023); Kopnov (1999);Li et al. (2023a);Dong et al. (2021); Bucas et al. (2013); Xu et al. (2014); Xiong and Wang (2012); Palczyński et al. (2023)

2 Operational Load Classification and Standards

Crane safety and fatigue design are governed by comprehensive standards that classify the severity of operation based on usage frequency and load magnitude, requiring the crane owner to specify the real usage profile (Tawjoeram, 2016). The prevailing standard in Europe is (European Committee for Standardization, 2021b), which applies to all EU countries and is considered more accurate than previous standards, such as (Deutsches Institut für Normung, 1984), in terms of fatigue calculations. This standard mandates a systematic design process that starts with Crane Classification. Classification involves determining the total number of working cycles during the specified useful life (utilization level, designated as classes U0 to U9, where U4-U6 are typical for lattice boom cranes as indicated by Cai et al. (2014)), and defining the Load Spectra (load state level, designated as classes Q0 to Q5, as indicated by Euler and Taylor (2021)). These classes quantify the frequency of use and the relative magnitude of loads handled, ranging from cranes that ”rarely lift rated loads” (Q1) to those that ”normally lift loads close to rated loads” (Q6). The standard also requires specification of the Position Spectrum, which describes the loading and unloading method. For crane runway systems in the US, the AISC LRFD Specification defines Loading Conditions based on the expected number of cycles (for instance, 20k to over 2M cycles). It correlates this with the Crane Manufacturers Association of America (CMAA) Specifications, which use designations A through F to estimate the number of cycles of full uniform amplitude load over a service life, such as 40 years (Fisher and van de Pas, 2002).

When defining the type of load to be handled, its weight, geometry, and specific features, such as fragility or hazardous properties, play a key role in selecting the appropriate crane type and capacity, thus minimizing the likelihood of overloading. The conditions of the worksite where the equipment will operate must also be evaluated (Associação Brasileira de Normas Técnicas, 2025). The loads themselves are categorized and factored into the assessment. Vertical crane loads are primarily considered wheel loads, reaching their maximum magnitude when the crane lifts its rated capacity with the trolley adjacent to the girder. These quasi-static loads, including the crane’s self-weight (Qc1), trolley weight (Qc2), and hoist load (Qh), are amplified by dynamic factors (impact factors) to account for effects like acceleration in hoisting, sudden braking, or wheels rolling over rail irregularities. In US codes, these dynamic factors typically increase loads by 25% for cab/radio-operated cranes and 10% for pendant-operated cranes (Fisher and van de Pas, 2002). Horizontal crane loads (lateral and longitudinal forces), caused by trolley/bridge acceleration/deceleration, non-vertical lifting, or skewed travel, are also specified. Under (European Committee for Standardization, 2021c), loads are classified into Regular Loads (which occur frequently under normal operation and are key for fatigue analysis), Occasional Loads (infrequent, usually neglected in fatigue), and Exceptional Loads (excluded from fatigue assessment). The combination of these loads (Load Combinations A, B, and C) and their multiplication by partial safety factors form the basis for structural checks using methods like the Limit State Method. For offshore cranes, regulatory bodies like DNV and Germanischer Lloyd (GL) classify structural analysis conditions into crane operating conditions and boom rest conditions. Fatigue analysis for offshore cranes may require a linear combination of damages calculated under normal operating conditions and seagoing conditions (Shin, 2021).

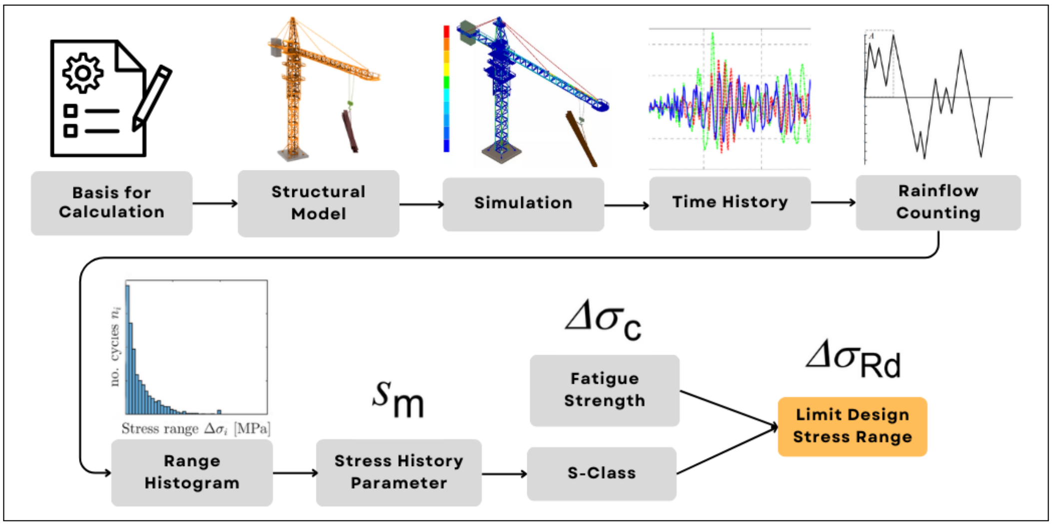
2.1 Stress Time-History Acquisition and Cycle Counting Techniques

Accurate determination of the forces acting on a crane requires sophisticated methods for Stress Time-History Acquisition to obtain representative random stress spectra of critical components (Xiong and Wang (2012), and Li et al. (2023a)). The traditional and highly reliable approach involves field strain measurements, where strain gauges or specialized sensors like Fiber Bragg Grating (FBG) sensors are bonded to critical locations of the metal structure, such as welded joints or supports, to monitor the strain time history. These measurements help determine the range of stresses and capture the dynamic fluctuations during operation. However, obtaining long-term, reliable stress spectra through continuous field measurement is often costly, time-consuming, and limited by the difficulty of covering all potential fatigue locations on large structures. Consequently, simulation models, particularly those based on FEM, are widely used to predict stress distribution under specified conditions. To enhance accuracy, a combined simulation and testing strategy is frequently adopted, sometimes formalized as a measured /simulated /compared /statistics integrated strategy. This approach often includes conducting quasi-static load tests, such as having a crane travel at a crawling speed, to collect calibration data for refining and verifying the FEM models.

Once the stress time history is obtained, whether through measurement or simulation, the rainflow cycle counting method is the standard and widely utilized technique for processing the resulting random stress signal (Kopnov, 1999). The primary function of this technique is to analyze the variable amplitude-loading characteristic of crane operation by effectively reducing the complex stress-time history into a series of identifiable, closed "loading cycles" (or mini-cycles). This process is crucial because it extracts the stress amplitude and the corresponding number of occurrences, which are essential inputs for cumulative damage calculations like the Palmgren-Miner rule (Cai et al., 2014). The method accounts for two key parameters (stress amplitude and mean stress), aligning with the inherent mechanical characteristics required for robust fatigue assessment. It is important to distinguish the singular "loading cycle" from the "loading block," which represents the total set of stress cycles accumulated during one overall crane operation sequence (e.g., clamping, hoisting, transferring, lowering). Furthermore, for handling the enormous volumes of monitoring data collected by modern Structural Health Monitoring (SHM) systems, fast rainflow counting methods based on stack data structure have been developed to quickly process "big data" and generate stress amplitude-mean-frequency matrices, laying an essential foundation for rapid health diagnosis and remaining life analysis (Yu et al., 2023).

According to Cai et al. (2014), variables such as load spectrum, cycle number, weld quality, and material properties are decisive for crane fatigue reliability. The European Committee for Standardization (2021b) guidelines represent a significant advance in fatigue assessment compared with earlier regulations, as they incorporate variable load histories more effectively through Rainflow counting. Additionally, crane owners must provide operational usage profiles of their equipment. Figure 1 illustrates the project flow according to European Committee for Standardization (2021c).

Figure 1 – EN13001 design flowchart



Source: Authors, 2025

2.2 Traditional Fatigue Assessment Methodologies

As outlined by Xu et al. (2014), various fatigue methodologies are employed, with the predominant and extensively utilized ones including the S-N approach, the fracture mechanics approach, and the Palmgren-Miner rule.

The foundational and widely utilized methodologies for assessing fatigue life in cranes, such as travelling gantry cranes and other lifting machinery, primarily rely on the Stress-Life (S-N) approach combined with Miner's linear cumulative damage theory (Fisher and van de Pas, 2002). The S-N approach, derived from cyclic constant amplitude loading tests and documented in standards like the AISC Specification and Eurocode 3, uses S-N curves to define allowable stress ranges for specific structural details or categories. Since cranes are subjected to variable amplitude loadings, the design criteria are applied using Miner's principle, which linearly accumulates fatigue damage based on the ratio of actual stress cycles (n_i) to the total cycles to failure (N_i) at each stress level. This traditional approach is suitable for predicting the number of cycles required to initiate a crack, particularly in high-cycle fatigue structures like cranes (Hussain et al., 2024). When assessing existing or aged cranes where initial cracks may already exist, or when the structure has exceeded its design life, the methodology shifts to Fracture Mechanics (FM), specifically Linear Elastic Fracture Mechanics (LEFM). LEFM models the fatigue-crack growth rate from an assumed or measured initial crack size using formulas like Paris' Law, allowing for the reliable prediction of the remaining service life until the crack reaches a critical length. These two approaches (S-N and FM) are often viewed as complementary tools in a comprehensive fatigue analysis of welded crane structures.

2.3 Stress-Life (S-N) Approach, Cumulative Damage Theory, and Remaining Life Assessment

In 1870, August Wöhler published the results of a systematic scientific study that took 10 years to complete. Wöhler aimed to address the frequent failures in railway axles of his time. To achieve this, he conducted a series of tests to understand how these axles failed under cyclic loading conditions. His research revealed that a simple monotonic load, below the material's elastic limit, did not cause significant damage. However, when such a load was applied repeatedly, it could lead to complete failure. This led Wöhler to introduce the S-N curve concepts, which relate the number of cycles to the applied stress amplitude and the fatigue limit, thereby establishing a foundational principle in materials engineering (Zenner, 2015).

The Stress-Life (S-N) curve approach is the most common and widely used methodology for predicting the fatigue life of crane structures, often assuming linear damage accumulation (Tawjoeram, 2016). It relates applied stress ranges ($\Delta\sigma$) to the number of cycles to failure (N).

$$D = \sum (N_i/n_i) \tag{1}$$

where n_i is the number of cycles at stress range $\Delta\sigma_i$, and N_i is the fatigue life at that range. Failure is assumed when D=1. Although simple and codified, this approach does not account for load sequence effects or nonlinear damage accumulation.

For variable-amplitude loading, Palmgren–Miner's linear cumulative damage rule is applied: This method is fundamental to the design process, defining allowable stress ranges as a function of the number of load cycles for different connection classes, typically using nominal stress calculations. When dealing with the variable amplitude-loading characteristic of crane operation—such as in travelling gantry cranes or crane runway girders—the S-N approach is combined with Palmgren-Miner's linear cumulative damage theory. Miner's rule linearly sums the damage (D) caused by various stress ranges ($\Delta\sigma_i$) and their corresponding number of applied cycles (n_i) until failure is assumed to occur when the accumulated damage equals one ($D = \Sigma(n_i/N_i) = 1$), as reported in (Caglayan et al., 2010). For cranes that have accumulated fatigue damage or are operating beyond their design life, the assessment transitions to remaining life prediction. This is often achieved using linear fracture mechanics:

$$da/dN = C(\Delta K)^m, \tag{2}$$

where ΔK is the stress intensity factor range, and C, m are material constants. This approach allows estimation of residual life from an initial crack size a_0 to a critical size a_c. It focuses on the crack propagation life using models like Forman's formula or Paris' Law. This combined strategy allows for the estimation of total fatigue life and remaining service life, ensuring the structural integrity of components like crane runway girders and other welded metal elements.

Based on theoretical analysis and acoustic emission testing, a novel method for analyzing crack propagation in in-service gantry cranes has been proposed. This non-destructive acoustic emission technique detects cracks within a material by monitoring and analyzing high-frequency elastic waves generated during the fracture process. A two-parameter base function was utilized to assess crack propagation in Q235B steel, and a response surface model was developed to predict the fatigue life of the steel sample. Comparisons with theoretical analysis demonstrate that this method is both accurate and practical for real-world applications (Xu and Wu, 2020).

2.4 Fracture Mechanics for Residual Life Assessment

For existing cranes with known or assumed cracks, Linear Elastic Fracture Mechanics (LEFM) is used to model crack propagation. Paris' law describes the crack growth rate:

$$da/dN = C(\Delta K)^m, \tag{3}$$

where ΔK is the stress intensity factor range, and C, m are material constants. This approach allows estimation of residual life from an initial crack size a_0 to a critical size a_c.

3 Advanced Local Stress Approaches for Welded Joints

While traditional fatigue analysis, relying on the nominal stress approach and Palmgren-Miner's linear cumulative damage theory, provides a foundation for crane design and assessment of structures like crane runway girders, its reliability diminishes when evaluating complex geometries and critical areas, especially welded joints in high-performance machinery such as loader cranes (Zhao et al., 2023). Fatigue failures predominantly initiate in these welded joints due to inherent stress concentrations and high tensile residual stresses. Furthermore, as crane manufacturers increasingly utilize ultra-high strength steels to minimize self-weight and maximize lifting capacity, the gap between the material's static strength and the low fatigue strength of its welded details widens significantly. Consequently, advanced local stress approaches have become indispensable for achieving accurate fatigue life assessment, allowing designers to quantify local damage phenomena (including the influence of complex weld shapes and geometric irregularities) which are poorly accounted for by the conventional nominal stress approach. These local methods aim to improve the fatigue performance of welded joints through sophisticated analysis and design optimization, sometimes alongside mitigation techniques like Post-Weld Treatment (PWT).

Advanced local stress approaches have been developed to improve the fatigue assessment of welded joints in crane structures, where complex geometries and high stress concentrations prevail. The structural hot-spot stress (HSS) method evaluates the stress at critical weld toes by extrapolating surface stresses at specific distances from the weld, effectively capturing geometric effects while excluding local notch stresses. The effective notch stress (ENS) approach, in turn, explicitly models the weld geometry using a fictitious notch radius, typically 1 mm, allowing direct evaluation of the elastic stress concentration and improved correlation with experimental fatigue data. The equivalent structural stress (ESS) or Dong's method (Dong, 2001) further advances fatigue evaluation by combining membrane and bending stresses into a single mesh-insensitive parameter, providing consistent results even for complex finite element models of crane girders and attachments. For existing or aging cranes, the notch stress intensity factor (NSIF) or local fracture mechanics approach enables the characterization of stress singularities and fatigue crack propagation at weld toes (Lazzarin and Tovo, 1998). Moreover, modern studies increasingly incorporate multiaxial fatigue and critical-plane criteria, such as the Fatemi–Socie (Fatemi and Socie, 1988) or Findley models (Findley, 1959), to address the combined effects of bending, torsion, and axial stresses inherent in crane operations under variable and stochastic loading conditions.

3.1 Multiaxial Fatigue Criteria

In multiaxial fatigue analysis, the objective is to predict the fatigue life of materials or structural components subjected to complex stress states involving simultaneous normal and shear stresses that vary over time. Unlike uniaxial fatigue, where the stress or strain acts along a single direction, multiaxial fatigue considers that the local stress tensor (**t**) varies in both magnitude and orientation. At any given material point, the state of stress can be represented by a combination of principal stresses σ_1, σ_2, σ_3, or equivalently, by shear and normal components on a specific plane. The general formulation of multiaxial fatigue is based on the critical plane approach, which identifies a plane within the material where damage is most likely to initiate. On this plane, the combined effects of shear and normal stresses or strains govern fatigue life. The Fatemi and Socie (1988) criterion, for example, defines fatigue damage as:

$$(\Delta\gamma_{max}/2)(1 + k(\sigma_{n,max}/\sigma_y) = const \tag{4}$$

where $(\Delta\gamma_{max}/2)$ is the maximum shear strain amplitude, $\sigma_{n,max}$ is the maximum normal stress on the critical plane, σ_y is the yield stress, and k is a material parameter accounting for the influence of mean stress. Similarly, the (Findley, 1959) criterion relates the amplitude of shear stress and the maximum normal stress on the critical plane through:

$$\tau_a + k\sigma_{n,max} = \tau_f \tag{5}$$

where τ_a is the shear stress amplitude, k is a material constant describing the sensitivity to normal stress, and τ_f is the material fatigue limit under pure shear.

The complexity of stress states in crane components, particularly in structures like loader cranes and crane wheels, necessitates the application of multiaxial high-cycle fatigue (MHCF) criteria (Romanowicz, 2017). Traditional S-N approaches based on uniaxial (nominal) stress are often inadequate for accurately assessing structures subjected to combined and non-proportional loading. In loading cranes, such as the jib elements of tower cranes, models sometimes utilize a fatigue criterion inspired by the Dang Van criterion under the assumption of a proportional stress state to calculate an equivalent local stress (Bucas et al., 2013). However, analyzing components working in rolling contact fatigue problems, like cylindrical crane wheels, involves complex, non-proportional stress states characterized by three normal compressive and three shear stresses. For these critical parts, various MHCF hypotheses, which may be based on the critical plane approach, stress invariants (like the Crossland criterion), or energy formulations (like the Papadopoulos P2, or Lagoda E criteria), are employed to estimate the equivalent fatigue stress. Research indicates that for hard materials used in RCF, criteria based on the integral approach, such as P1 (Papadopoulos' integral formulation), or modified critical plane approaches that account for the harmful influence of compressive stress and shift in phase between stresses (like DV2mod), are typically required to provide appropriate estimations (Romanowicz, 2017), as criteria assuming profitable in-phase shifts can be contradictory to experimental results. Furthermore, multiaxial criteria are also explored for fatigue strength analysis in complex welded frames (Dong, 2001).

These formulations capture the effect of non-proportional loading, when principal stress directions rotate during a cycle, which often accelerates damage. The fatigue life prediction is then obtained by correlating the equivalent damage parameter with material S–N or ϵ–N curves derived from multiaxial fatigue tests. In structural applications such as crane welded joints, where bending, torsion, and axial loads coexist, such multiaxial criteria are essential for estimating realistic fatigue lives under service-like complex loading paths.

4 Modeling and Simulation Techniques

The Finite Element Method (FEM) is fundamental for obtaining the accurate stress states required for the fatigue analysis of cranes, especially in complex areas like welded structures (Xiong and Wang, 2012). FEM models are established based on actual geometric specifications and material properties to analyze structural performance under various working conditions, including the loader crane's quasi-static analysis. The goal of FEM stress calculation is to predict stress distribution and locate critical regions, such as the bottom chord angle, I-beam of the top chord, the mid-span and end-span of main beams, and fatigue-prone welds in loader cranes (Zhao et al., 2024). For precise analysis, especially of existing cranes, FEM models of components like crane runway girders are prepared using shell and beam elements and subsequently refined and calibrated using strain data collected from quasi-static load tests. The use of FEM is often integrated into a multi-stage approach, where a global rough model (composed of beam or shell elements) is developed to simulate overall deformations and nominal stresses, which then provides boundary conditions for a local fine model used to accurately evaluate complex welded joints at critical locations, thereby improving efficiency and accuracy.

To accurately capture the impact of the operation, the Integrated Dynamics Analysis method couples FEM with Multi-Body Dynamics (MBD) simulation software, such as MSC.ADAMS, which is crucial for modeling the dynamic, cyclic, and stochastic nature of crane loading. This co-simulation technique is necessary because dynamic effects (like starting, stopping, and lifting impact effects) significantly increase stress amplitude and the number of stress cycles, negatively impacting fatigue life. For instance, loader cranes require a holistic approach where the hydraulic control system, which governs the fatigue loading, is considered alongside the structural fatigue resistance. The joint FEM and MBD simulation allows for the transient dynamic simulation of the lifting process, where the trolley and cargo can be modeled as a moving concentrated force or mass, extracting the dynamic load-time history and corresponding nominal stress spectrum with multiple degrees of freedom at connection points, which is then used for fatigue life assessment. This integration, sometimes framed as a "measured & simulated & compared & statistics" integrated strategy, allows for the acquisition of stress-time spectra that are accurate when compared to actual measured data.

5 Structural Integrity Management for Existing Cranes

Management (SIM) for existing cranes is a critical and multifaceted endeavor, driven by the need to ensure continued safe and economical operation, often extending service life beyond the original design limits. This management involves a hybrid approach combining inspection, advanced computational analysis, life prediction methods, and explicit maintenance and repair decision frameworks. Effective SIM relies on a combination of assessment methods, data acquisition, and proactive intervention strategies. Structural Integrity Management (SIM) for existing cranes is a systematic framework aimed at ensuring the safe and reliable operation of aging lifting structures that are frequently subjected to repetitive, cyclic, and impact loading. Many cranes, especially ship-to-shore (STS) and gantry types, continue operating well beyond their original design fatigue life (van Jole, 2016), in some cases reaching twice the intended service duration. Similarly, failures of gantry crane metalwork have been observed frequently after just three to four years of operation (Kopnov, 1999). This extended operation increases the likelihood of fatigue-related failures, which can lead to catastrophic outcomes involving both human and economic losses. Traditional design and inspection approaches, based on fixed intervals and deterministic safety margins, are inadequate to capture the real and evolving condition of such structures, necessitating a shift toward more data-driven and reliability-based methods.

Effective SIM programs integrate three main components: comprehensive structural assessment, data acquisition and monitoring, and maintenance decision-making (Tawjoeram, 2016). The assessment process often employs a hybrid approach combining classical stress-life (S–N) fatigue methods—used during the original design phase—with Fracture Mechanics (FM)-based crack propagation models for the post-design-life phase, defining the remaining life as the time between crack initiation and critical failure. Finite Element Models (FEM) are refined or calibrated using measured strain data from quasi-static load tests, while probabilistic reliability analyses quantify fatigue damage likelihood and safety margins more rigorously than conventional deterministic approaches.

A key element of SIM is the acquisition of field data through Structural Health Monitoring (SHM) systems, which record real stress histories, load spectra, and environmental parameters. These data are essential for accurately reflecting real operational conditions and improving fatigue life predictions. Advanced SHM frameworks (often incorporating machine learning or Digital Twin (DT) technologies) combine measured responses with simulated models to continuously update the structure's health status and predict residual life or degradation of lifting capacity (Dong, 2001).

Finally, SIM provides a quantitative foundation for maintenance, inspection, and repair decisions. Risk-Based Inspection (RBI) strategies, informed by Bayesian updating, optimize inspection intervals by accounting for uncertainties in fatigue data, inspection quality, and deterioration models (Tawjoeram, 2016). The approach includes determining critical crack sizes, performing Non-Destructive Inspection (NDI), and applying appropriate repairs or strengthening actions. These may include modifications to improve fatigue detail performance, continuous welding of girders, or reducing the Safe Working Load to extend service life. Through this integrated and adaptive methodology, SIM enables crane operators to ensure structural reliability, minimize downtime, and prevent failures throughout extended service periods.

6 Emerging Trends:Machine Learning,Data-Driven and Digital Prognosis

ML techniques are emerging as powerful alternatives or supplements to traditional, physics-based fatigue models, primarily because they can handle nonlinearity, large data volumes, and complexity that often limit classical methods (Ren et al., 2020). ML, particularly Artificial Neural Networks (ANNs), is used to find the nonlinear relationship between fatigue damage and dynamic load in structures like gantry cranes. This capability allows for accurate and rapid acquisition of damage or life data when inputting random load data, overcoming limitations of linear regression models (Caglayan et al., 2010).

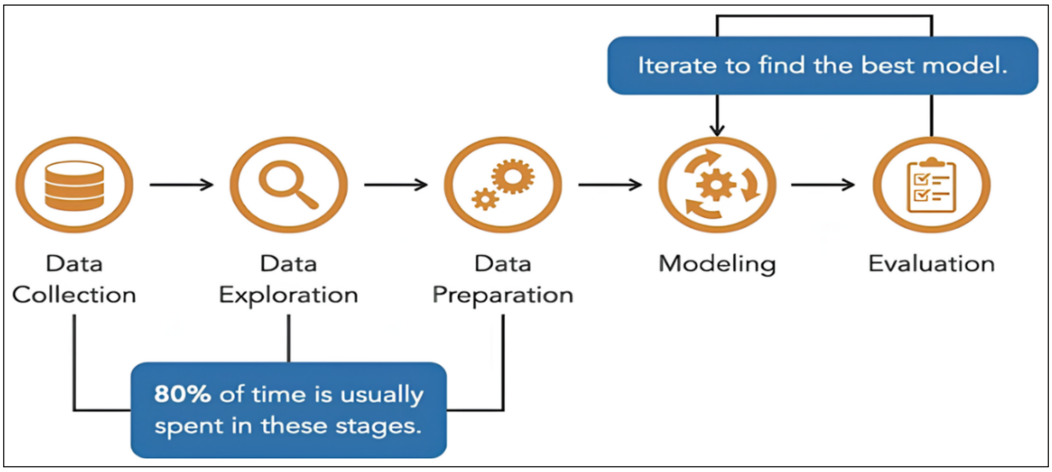
ANNs have been utilized to acquire the equivalent load spectrum for crane remaining fatigue life evaluation. More advanced deep learning models, such as the Convolutional Neural Network (CNN) combined with Bidirectional Long Short-Term Memory (BiLSTM) networks, are proposed to predict crane load sequences by exploring the intrinsic connections of the load time series, addressing the difficulty of obtaining accurate load spectra due to uncertain loads (Hu and Chen, 2025).

6.1 Digital Twin (DT) Frameworks

ML models like Dense Neural Networks (DNNs), Random Forest (RF), Support Vector Regression (SVR), Decision Tree (DT), and XGBoost are used for life prediction, showing results comparable to classical fatigue models (e.g., Ellyin–Gołoś, Fatemi–Socie). DNNs, in particular, often achieve the best and slightly more accurate results in multiaxial fatigue life estimation (Palczyński et al., 2023). Moreover, advanced hybrid models, such as the Stacking ensemble learning model (combining Gradient Boosting, Ridge Regression, Extra Trees, and Linear models), have been proposed for the fast prediction of fatigue life in metal structures (like those in bridge cranes). This ensemble model achieved accuracy improvements ranging from 6.3% to 49.2% compared to single learning models in life prediction (Zhao et al., 2024). The life prediction method based on intelligent technology (including neural networks, fuzzy calculation, and expert systems) is identified as the future development trend. It is suitable for more complex environmental conditions or structures and can address issues of variation and randomness that limit prediction accuracy in traditional methods (Ren et al., 2020).

The Machine Learning process typically begins with data acquisition (analytical, experimental, or numerical), followed by the exploration and preparation of this data. These steps, together, often consume the majority of the time, representing approximately 80% of the process. There is a definition of features that will be associated with classes and are defined by an expert, such as failure and non-failure. Subsequently, these features must be extracted from the data, which are usually separated into training, validation, and test sets. Finally, the model is applied and evaluated for its performance (Dietrich and Schilders, 2025). A flowchart of the machine learning process is presented in Figure 2.

Figure 2 – Machine learning process



Source: adapted from Dietrich, 2025

Zuo et al. (2021) developed a method based on radial basis neural networks to quickly obtain the stress spectrum and calculate the remaining lifespan of cranes. The remaining lifespan was assessed based on fracture mechanics methods. The results demonstrate that this method can significantly save investment in crane field measurement and also provide a reliable basis for long-term safe use and subsequent maintenance of the crane. The Digital Twin (DT) approach integrates physical models, sensor data, and operating history to create a virtual replica capable of real-time safety monitoring and prognosis. A DT framework is proposed for the real-time prediction of the fatigue life of bridge crane structures. The framework uses multi-theoretical calculation models (load, strength, defect, and fatigue life analytical models) encapsulated within the DT and modified by the current service status information. The DT approach enables real-time prediction, unlike many non-DT models (Dong et al., 2021). A Digital Twin-Driven (DTD) framework and model are introduced to predict the degraded lifting capacity (LC) of aging tower cranes. This DTD model integrates numerical analysis of fatigue accumulation with real-time vibration data from the physical crane. The prediction relies on fusing cumulative residual stress values (as ”damage indices” from virtual simulation) with real-time sensory data (vibrations and load) (Hussain et al., 2024). Implementing a complete digital model of a large structure like a ladle crane is currently difficult due to limited computing power, but local digital twin models for specific critical details can be realized to capture real fatigue damage evolution characteristics. Furthermore, DT models, while high in calculation accuracy, are typically high in complexity.

6.2 Reliability and Probabilistic Methods using Bayesian Updating

Probabilistic methods address the inherent uncertainties (in loads, material properties, and defect sizes) that traditional deterministic fatigue models ignore (Bucas et al., 2013). Bayesian updating is the key emerging trend for refining these probabilistic predictions based on evidence. Fatigue assessment and prediction are properly performed in a reliability context because both loadings and resistances contain large uncertainty. The application of probability theory and statistical theory helps solve problems of discreteness and uncertainty, improving the reliability of traditional mechanical methods (Ren et al., 2020). MCS is commonly employed to evaluate reliability. It was used to develop a fatigue resistance model for tower crane steel structures (such as jib elements) to quantify and optimize safety margins. MCS can also be used to simulate fatigue reliabilities and initial cracks for welded box girders of cranes (Cai et al., 2014).

While the Bayesian approach is widely used in general engineering applications, particularly in the maritime industry for structural fatigue problems (e.g., inspection planning coupled with Palmgren–Miner’s rule and Fracture Mechanics), the sources conclude that ”currently there is no cutting-edge framework” specifically for the deployment of the Bayesian approach to update crane fatigue reliability. The Bayesian approach is foundational to Risk-Based Inspection (RBI) planning frameworks for steel structures, which can be adapted to analyze the fatigue risk of crane components. RBI procedures for cranes are ideally quantitative, accounting for data and inspection quality using probabilistic deterioration and inspection models (Tawjoeram, 2016).

7 Conclusion and Future Research Outlook

This review has delineated the two predominant paradigms for fatigue life prediction in cranes: mechanics-based and machine learning-based methods. While traditional S-N approaches remain widely used and codified, the integration of advanced algorithms offers significant potential for enhancing the speed and accuracy of predictions, especially when leveraging data from structural health monitoring systems. The validation of these sophisticated data-driven models against experimental and field data is essential for their adoption. Future research should focus on several key areas:

- The development and application of probabilistic and hybrid models to better quantify uncertainties;
- The implementation of Digital Twin technology for real-time, holistic lifecycle management of crane structures;
- The refinement of material models for new high-strength steels and advanced composites on composite materials in cranes;
- The enhancement of inspection technologies through automation and advanced signal processing.

7.1 Critical discussion and research gaps

This review identifies several persistent challenges and research opportunities. While advanced local stress and multiaxial criteria exist, their practical application in crane design remains limited. Further work is needed to harmonize these methods with industry standards in order to integrate methods. Besides, ML and DT models require extensive validation against experimental and field data. Open datasets and benchmark problems would accelerate adoption and the validation of Data-Driven models.

Probabilistic fatigue analysis is not yet routine in crane engineering. Developing user-friendly tools for reliability updating and RBI is a priority allowing for Uncertainty Quantification. With new material advances, new high-strength steels and composites offer weight savings but pose challenges for weld fatigue. Research is needed to characterize their fatigue behavior and develop appropriate design curves. Finally, in the Mathematical and Computational Foundations point fo view, many fatigue methods rely on numerical approximations and phenomenological and heuristic corrections. There is room for more rigorous mathematical formulations, particularly in multiaxial fatigue and damage accumulation.

In summary, this review has mapped the current research landscape, which encompasses studies on material behavior, load scenario assessment, advanced FEA modeling, novel life prediction algorithms, damage accumulation mechanisms, and failure case analyses. By adopting a multidisciplinary approach that synergizes traditional engineering principles with emerging digital technologies, significant strides can be made in ensuring the long-term safety and reliability of crane structures. This survey serves as a foundation for identifying research gaps and inspiring future innovations in the field. Further research is explicitly demanded to develop a specific framework for a fatigue Bayesian updating model for cranes, starting with one fatigue detail and gradually extending to the whole structure, often requiring collaboration with statisticians due to the complexity (Tawjoeram, 2016).

APPENDIX - NOTATION

$\Delta\sigma$ - Stress range

N_i - Number of cycles to failure

n_i - Number of cycles at stress level

D - Cumulative damage

a - Crack length

ΔK - Stress intensity factor range

τ_a - Shear stress amplitude

$\sigma_{n,max}$ - Maximum normal stress on critical plane

σ_y - Yield strength

k - Material constant

m - Material constant

t - Stress tensor

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