10º CONFERÊNCIA SUL EM MODELAGEM COMPUTACIONAL
X SEMINÁRIO E WORKSHOP EM ENGENHARIA OCEÂNICA
10ºMCSul
CONFERÊNCIA SUL EM MODELAGEM COMPUTACIONAL
X SEMENGO
Seminário e Workshop em Engenharia Oceânica
4, 5 e 6 de dezembro de 2024 / Universidade Federal do Rio Grande - FURG/ Rio Grande - RS

A survey on fatigue analysis methods for cranes

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Abstract: Cranes operate in challenging environments, with repetitive cycles and dynamic loads, making fatigue resistance crucial for safety and reliability. About 80% of failures in metal components are related to fatigue, highlighting the importance of predicting the service life of these components. This article analyzes contemporary methods for predicting fatigue life, divided into two main categories: (i) mechanics-based methods and (ii) machine learning-based methods, which differ in the signals collected and the damage assessment methodologies. Conventional fatigue life prediction is based on theoretical and experimental research, utilizing experimentation and physical modeling to obtain approximate estimates, both quantitative and qualitative. However, variations and randomness in the data limit the accuracy of these predictions, and the use of probability statistics, although useful for dealing with uncertainties, is constrained by the limited amount of available data. Smart technologies, such as big data, present solutions to these challenges by enabling large-scale collection of signals that reflect changes in structural performance. This capability enables the use of new algorithms, such as ANNs, evolutionary algorithms, fuzzy sets and approximate set theory, which are applicable in more complex structural or environmental conditions to the prediction of life to fatigue. While current methods have demonstrated potential, they still face significant challenges in improving their effectiveness and accuracy. So, in the end, a comprehensive and up-to-date survey on the methodologies, standards and main tools used in predicting service life for fatigue in cranes is presented.

Keywords: Fatigue life prediction; FEM; machine learning methods; standards.

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1 INTRODUCTION

Cranes operate in challenging environments, characterized by repetitive operational cycles, dynamic loads, and high-impact loads. Essential for a variety of applications, these devices are typically constructed with steel structures, often composed of interconnected plates or beams welded together. However, due to the rigorous and fluctuating work-loads they endure, ensuring fatigue resistance becomes paramount in their design, aiming to ensure safety and operational reliability over time. Singh et al. (2017) indicate in their studies that approximately 80% of failures in metallic components are attributed to fatigue, highlighting the necessity of exploring precise methods for predicting the lifespan of this equipment. All structures composed of metal plates or beams connected by welding are subject to the fatigue phenomenon after repeated loading cycles, leading to crack initiation and propagation, thereby compromising the structural integrity of the equipment. Several factors influence the fatigue life of crane structures, including material properties, design considerations, operational conditions, and environmental factors.

There is a considerable amount of research related to safety and prediction of fatigue life in cranes. In this paper the articles that are being revised can be classified into articles related to case studies, maintenance and inspection, methods for fatigue assessment, and those related to design and operational conditions, that will be cited in the next section. In Brazil, the main standard governing the requirements for hydraulic articulated cranes is ABNT NBR 14768:2021. As for the main European standards, we have EN 12999:2021, EN 13001-2:2021, and EN 13001-3-1:2020, which deal with general requirements for load actions, limit states in cranes, and proof of strength of metal structures. Moreover, the DNV-RP-C203 standard is widely acknowledged for its application in fatigue analysis of offshore structures, providing essential guidelines for the design and maintenance of cranes.

A simple search in the Elsevier's Scopus database with the term "fatigue life cranes" for the last 10 years (2014-2024) resulted in 203 journal articles, 72 conference papers, which shows how important Surveys and Reviews are missing in this area. The same search using the Elsevier's Compendex platform with the same terms and for the last 10 years, resulted in 160 records, being 81 Journal articles, 60 conference papers and proceedings, being the country with more documents, China, followed by Germany and France (the same rank obtained in the Scopus database).

2 FATIGUE ANALYSIS OF CRANES

Despite the efforts of crane manufacturers to implement advanced techniques for fatigue prevention, it remains a persistent challenge in practice. Effectively monitoring fatigue-prone areas within the structure and providing accurate estimates of both initial and remaining fatigue life based on current data represent ongoing challenges in the field.

Frequently, physical models are unable to encompass the majority of parameters influencing fatigue. Consequently, numerous fatigue models have been developed to describe the prediction of service life for steel structures (Dowling, N., 1993). To date, a significant body of research has been dedicated to fatigue analysis. Diverse fatigue methodologies are employed, with the predominant and extensively utilized ones including the S-N approach, Fracture Mechanics approach, and the Palmgren-Miner rule. These methodologies are applied for the estimation of fatigue life, crack propagation rate, critical crack length, and fatigue damage assessment. In this section, general fatigue life prediction models are discussed, ranging from the most classical to the most contemporary ones.

2.1 Prediction method based on mechanics

The fatigue life prediction method in cranes based on mechanics assumes a significant role and is one of the most widely used methods in engineering, including prediction-based stress, strain and fracture mechanics methods. The advantages and disadvantages of various mechanics-based life prediction methods are listed in Table 1. While numerical and analytical methods for fatigue life estimation have enhanced result accuracy, they should not be regarded as standalone tools for design decision-making, particularly in safety-critical applications. Whole product tests are always recommended to be conducted (Meggiolaro et al., 2009).

Table 1: Comparison of fatigue life prediction methods based on mechanics (Adapted from Ren et al., 2021).

Theoretical Framework	Definition	Advantage	Disadvantage
Stress	Predict fatigue life based on S-N curve.	High-cycle fatigue. Extensive experimental data available. Total life models.	Empirical. No plasticity models. No low-cycle fatigue.
Strain	Predict fatigue life based on ε-N curve.	Plasticity models. Includes residual stress.	Low-cycle fatigue. Complicated to apply.
Fatigue Crack Propagation	Based on fracture mechanics models. It is assumed that there is a defect in the material or component.	Approach of crack growth, linear elastic fracture, plastic fracture and microstructural fracture mechanics.	Ignore the crack initiation phase. Difficult to calculate for complex structures.

The literature abounds with studies investigating the fatigue characteristics of cranes and their individual components. Presented below are study examples of research pertaining to each of the aforementioned theoretical frameworks.

2.1.1 Stress

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 Basquin Law, which describes the behavior of materials subjected to high-tension cyclic loading, is given by the formula: $\sigma_a = \sigma'_f \cdot (2\mathrm{N})^{\mathrm{b}}$.

Palmgren and Miner advanced the study of fatigue by introducing the linear summation rule to predict fatigue life under variable loading conditions. Palmgren initially presented this concept in 1924, and Miner further developed it in 1945. Known as the Palmgren-Miner rule: $D = \sum(n_i/N_i)$, this method enables the assessment of accumulated damage from varying load amplitudes and has since become a fundamental tool in the field of fatigue engineering (Miner, 1945).

M. Matsuishi and Tatsuo Endo developed a counting algorithm that, when combined with the Palmgren-Miner rule, enables the estimation of fatigue life in structures subjected to cyclic loads with variable amplitudes, such as those encountered in random loads in automobiles, aircraft, and ships. This algorithm is now known as the Rainflow Counting Method or simply the Rainflow Method (Schütz, 1996).

Verschoof (2002) outlines critical parameters for calculating fatigue in cranes: the conventional number of cycles and the stress spectrum to which the component is subjected; the material used and the effect of notches at specific points; the maximum extreme stress the component can withstand; and the ratio between minimum and maximum stress. According to Hobbacher (2016), methodologies for assessing fatigue in welded joints include nominal stress, critical structural stress (hot-spot), effective notch stress, fracture mechanics, and component testing. The evaluation process depends on data related to fatigue action, such as the type of stress and fatigue resistance, represented by S-N curves.

A comparative study of post-weld treatment for high-strength steel welded joints in medium-cycle fatigue was conducted by Pedersen (2010). The primary goal of his research was to provide methods for developing durable, robust, and lightweight load-bearing cranes. Through fatigue tests on specimens made from S700 material and welded using T-joint methods, it was observed that all samples failed from the weld root, with fatigue cracks initiating at the center of the specimen. Furthermore, investigations using the notch stress approach also indicated the center as the most critical point of the samples. The research results demonstrate that the use of high-strength steel, combined with local post-weld treatment, can be highly advantageous in medium-cycle fatigue regimes.

Buczkowski and Żyliński (2021) developed a finite element analysis model to estimate the fatigue life of cranes. Their fatigue analysis relies on the S-N curve (stress versus number of cycles to failure) and the Goodman formula, which incorporates the effects of mean stress. The Goodman formula was applied to account for mean stress by considering a zero-pulsating fatigue cycle and calculating the fatigue resistance factor. Miner's rule was used to determine cumulative damage, allowing for the estimation of the crane's structural lifespan based on the calculated number of fatigue cycles.

Jiang and Jiang (2023) present a study on the fatigue life prediction of tower cranes under the influence of moving loads, focusing on the dynamic response and fatigue life of key components of the boom under luffing and lifting conditions. The study establishes a moving load model and uses transient dynamic analysis to simulate and analyze the vibration characteristics of the boom. Linear fatigue damage accumulation is used along with actual S-N curves for the material. The results show that the luffing speed and lifting speed significantly impact the vibration amplitude and frequency of the boom, affecting the fatigue life of key components. The study concludes that the damage degree of key components is greater during luffing than during lifting, resulting in a shorter service life.

A recent study by Liu (2024) provides an effective and precise evaluation of the fatigue life of lifting machinery structures. Utilizing the Palmgren-Miner linear cumulative damage theory and the S-N curve from the British standard BS 7608, the study calculates the fatigue life of welded metal structures. Using the large-scale bridge crane at the hydroelectric station as a case study, nominal stresses of corresponding key components are determined by applying real loads to the finite element model. Subsequently, the stress history over time is computed, enabling estimation of the structure's safe life.

2.1.2 Strain

The Strain-Based Method, or ε-N Method, is especially suited for analyzing low-cycle fatigue, where cyclic plastic deformations occur in localized regions of a component. This approach is particularly valuable when stresses exceed the material's yield strength, with failure often occurring within a range of $1 \leq N \leq 10^3$ cycles. It is designed for scenarios where deformation behavior is crucial to understanding fatigue failure, as it accounts for plastic deformations that stress-based methods may not fully capture (Dowling, 1993).

Working independently on thermal fatigue issues, Louis F. Coffin and Samuel Stanford Manson introduced a groundbreaking concept in fatigue analysis. Instead of relying on stress values as proposed by A. Wöhler, they recommended using cyclic strain values to estimate fatigue life. This novel approach necessitates the development of ε-N curves for the material in question. The equation that describes these curves is known as the Coffin-Manson Equation: $\Delta\varepsilon_p = \varepsilon_f'(2N_f)^c$ (Coffin, 1954a, b; Manson, 1953).

Cai et al. (2014) conducted a study delving into the fatigue life analysis of K-type crane welded joints, employing the theory of nonlinear cumulative damage. The cumulative damage at each stage is computed using an algorithm and constant amplitude strain-life data. Their approach hinges on the Basquin-Manson-Coffin equation, acknowledged as the predominant method for analyzing constant amplitude strain-life. The calculation results indicated that the accuracy of the non-linear damage accumulation was higher than that of the Miner's rule, although the calculation result based on the non-linear damage accumulation method was slightly unconservative when the initial damage was not considered in the calculation.

Mourão et al. (2019) present a study on the fatigue damage analysis of offshore structures using both hot-spot stress and notch strain approaches. The research focuses on jacket-type platforms, examining fatigue damage accumulation due to cyclic environmental and operational loads. The study employs the notch strain (local) approach, incorporating the Neuber rule, Ramberg-Osgood description, and Coffin-Manson relationship to assess strain amplitude and cycle count. The findings reveal that in both methodologies, the fatigue damage estimated using the Palmgren-Miner linear damage rule is below 0.1. However, the notch strain approach indicates a significantly higher level of damage compared to the hot-spot stress approach.

2.1.3 Fatigue crack propagation

Fatigue crack propagation theories are based on fracture mechanics-based models, this approach assumes that a crack has already been detected within the component. It is used to estimate the time required for this initial crack to propagate to a size that will ultimately lead to the component's failure.

During the 1960s, the systematic study of crack propagation due to fatigue gained significant attention with the introduction of the model proposed by Bilby et al. in 1963. The concept of linear defects in the crystalline structure was integrated into fracture mechanics theory, demonstrating how the movement of dislocation bands contributes to crack growth. The introduction of the stress intensity factor (K) in the model allowed for the quantification of stress concentration at the crack tip, providing a robust theoretical foundation for predicting crack propagation. This fundamental advance laid the groundwork for the subsequent development of more sophisticated theories and models in fatigue analysis, including the Paris' Law: $dN/da = C(\Delta K)^m$ (Dowling, 1993).

The Paris' Law, formulated by Paul C. Paris and J. Walter in the 1960s, is a fundamental contribution to fracture mechanics and fatigue analysis. This law provides an empirical relationship between the crack growth rate and the amplitude of the stress intensity factor, enabling the prediction of the service life of components subjected to cyclic loading. The Paris Law presents the crack growth rate per cycle (da/dN) and highlights the importance of the stress intensity factor amplitude (ΔK) in controlling the crack growth rate. While it is widely used to predict the life of components under high-cycle fatigue conditions, the law has limitations, such as reduced applicability in low-cycle conditions and for very small cracks (Dowling, 1993).

Qi et al. (2013) conducted a study to assess the safety and analyze the fatigue life of aged crane structures. Based on the results of stress tests and non-destructive examinations, a framework is constructed to evaluate the remaining fatigue life of crane metal structures, based on crack propagation theory. The method relies on Linear Elastic Fracture Mechanics (LEFM), and several key items are required to estimate or predict the remaining life: stress intensity factor, maximum and minimum stresses, fracture toughness (K_{IC}), and initial crack size. Naturally, environmental conditions, load history, statistical aspects, and safety factors should be incorporated into this methodology for assessing remaining fatigue life. This methodology is most suitable for cranes that may have some cracks or structural defects.

Over the past decade, researchers have developed a variety of other methods for crack detection. One approach relied on dynamic properties (Rajiv and Peng, 2018), another was based on finite element analysis (Barski and Stawiarski, 2018), and thermoelastic stress analysis (Chen et al., 2018), while a third direction was guided by non-destructive tests, such as ultrasonic testing (Wang et al., 2019), guided ultrasonic waves (Delrue et al., 2015), computerized tomography (Makino et al., 2016), and acoustic emission tests (Xu and Wu, 2020).

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).

2.2 Prediction method based on machine learning

Traditional methodologies, such as strain-life analysis, linear elastic fracture mechanics, and stress-based procedures, have long been valuable for diagnosing fatigue failures. However, these techniques are often limited by geometry, require significant computational resources, lack self-learning capabilities, and offer limited automation. With advancements in computational technology, combining intelligent optimization algorithms with machine learning has emerged as a powerful new approach for damage prediction. This combination enables rapid identification of failure patterns, enhances cost and time efficiency, and facilitates improved automation.

According to Di Fatta (2018) and Gbagba et al. (2023), the main algorithms of machine learning used in prediction of fatigue life in welded structures include several techniques such as Regression (R)-based methods, Monte Carlo (MC)-based methods, Numerical

(N)-based methods, Neural network (NN)-based methods, and Random/hybrid (RH)-based methods. Specifically for Machine Learning techniques used in fatigue life also involve the use of various algorithms such as random forests, factor analysis, deep learning, uplift modeling, rule induction, link analysis, genetic and revolutionary algorithms, multivariate adaptive regression splines (MARS), ensemble methods, survival analysis and association rules. As stated by Gbagba et al. (2023), these methods and algorithms have been applied to analyze input parameters in the welding process, such as arc voltage and welding speed, as well as their effects on output parameters, including residual stress and stress concentration factors.

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 the 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 (Tech in Trend, 2022). A flowchart of the machine learning process is presented in Figure 1.

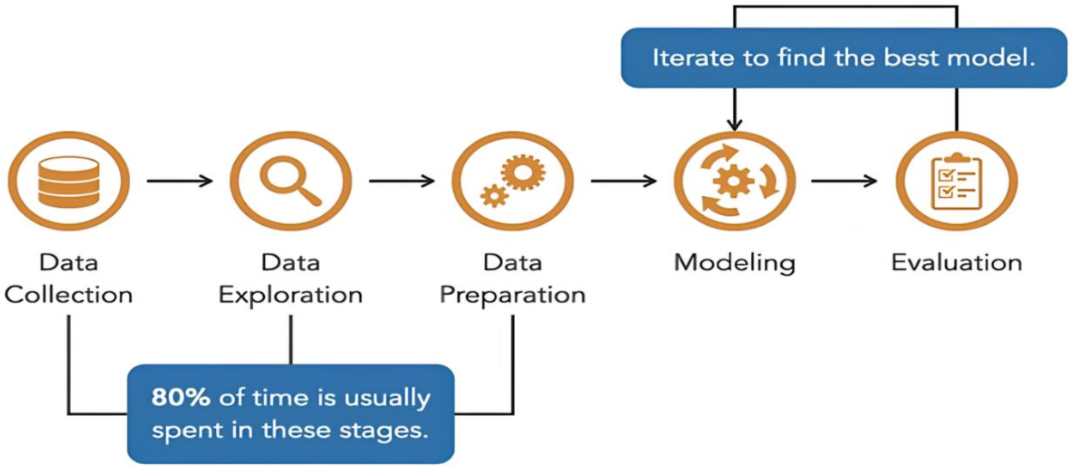

Figure 1: Machine learning process (Tech in Trend, 2022).

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.

Fatigue assessment is crucial not only during the initial design phase but also while the crane is in operation. Structural health monitoring has emerged as a pivotal tool in automated damage diagnosis, merging damage detection algorithms with structural monitoring systems (Loh et al., 2006). Recent years have witnessed remarkable strides in monitoring, gathering, and processing extensive data, including stress spectrum, acceleration, environmental, and operational data pertinent to crane equipment. This data, sourced from structural health monitoring systems, falls under the category of 'big data' due to its diverse, huge amount and high rate of acquisition (Huang et al., 2013; Li and Ou, 2015; Cremona et al., 2018). Analyzing and deciphering trends in this data necessitates robust and efficient algorithms, primarily due to the substantial volume of information.

Ding et al. (2021) present the traditional Rainflow counting method applied to the rapid big data analysis of the random stress spectrum of a crane, adopting a linear data structure (Stack Data Structure). The method is utilized to analyze and compute stress monitoring data collected by the crane's structural health monitoring system, thus evaluating fatigue damage on the main beam. Shen et al. (2023) evaluate an online damage prediction framework for wheeled crane booms. Time/frequency domain features and fatigue characteristics from finite accelerometers are captured. The Gaussian process regression model is applied to achieve more satisfactory point and interval prediction results, thus improving model accuracy. Additionally, the model's transfer potential is also verified through real boom damage data, demonstrating its usefulness in real engineering applications.

As recently demonstrated by Yo et al. (2023), while some algorithms exhibit high computational capacity, they all come with their own limitations that need addressing. For instance, the Genetic Algorithm used for optimization can easily spent a large number of computational resources or fall into a local optimum, while the Ant Colony Algorithm struggles with continuous optimization problems. Therefore, when selecting the most suitable optimization algorithm to tackle a problem, it is crucial to consider the intrinsic characteristics of the problem. This careful analysis ensures an effective and efficient approach to solving the challenge at hand.

According to Gbagba et al. (2023), the random/hybrid taxonomy appears to be the most promising candidate for predicting fatigue life in most cases, as it combines the advantages of individual algorithms. For instance, data-driven Long Short-Term Memory (LSTM) would be suitable for applications requiring long-term monitoring and updating of parameters. However, authentication and validation of advanced algorithms cannot be complete without comparing machine learning results with experimental and computational outcomes, taking into account in-service scenarios.

The literature surveyed suggests that future research should also adopt a probabilistic or dual (probabilistic and deterministic) approach to fatigue life prediction, as well as the application of a Digital Twin framework to study the lifecycle of components and structures concerning uncertainties, fatigue load axiality, and fatigue evolution. Additionally, the integration of computer vision techniques could assist in the efficient analysis of fatigue crack images.

3 LOADER CRANE DESIGN

In the crane industry, prioritizing safety and operational efficiency is crucial. To ensure proper standards for manufacturing, operation, and maintenance of these equipment, governmental regulations and standards are established globally. In Brazil, the Brazilian Association of Technical Standards (ABNT) issues standards such as NBR 14768:2021, which outlines specific requirements for hydraulic articulated cranes. Similarly, in the European Union, standards like EN 12999:2021, EN 13001-2:2021, and EN 13001-3-1:2020 are enforced to ensure crane compliance with rigorous safety and performance standards. Additionally, the DNV-RP-C203 standard is widely recognized for its application in fatigue analysis of offshore structures, providing essential guidelines for the design and maintenance of cranes.

NBR 14768:2021 outlines the essential requirements for the design, calculation, inspections, and testing of hydraulic articulated cranes, as well as their installation on vehicles or fixed bases. This standard incorporates fatigue stress analysis, which involves assessing failure risks due to alternating and cyclic mechanical stress. This analysis encompasses all load-bearing components and connections, identifying critical fatigue points. Construction details, stress amplitude, and stress cycle count, which may be a multiple of the load cycles, must be carefully considered. The standard also delineates load groups categorized by stress cycle count and resultant stress, specifying ideal resultant stresses, permissible stresses, and combined stresses.

In addition to the Brazilian standard, the European Standard EN 12999:2021 also sets forth minimum quality and safety requirements for hydraulically powered loading cranes and their installations on vehicles or static foundations.

The EN 13001-2:2021 standard specifies load actions and their combinations for calculating effects, serving as the basis for demonstrating the competence of a crane and its major components. This standard is utilized alongside other parts of the EN 13001 series of standards. It delineates design conditions and requirements aimed at preventing mechanical hazards associated with cranes and provides a method for verifying compliance. Additionally, it provides a list of significant hazardous situations and events that could pose risks to individuals during normal and reasonably foreseeable misuse.

a) rigid body instability of the crane or its parts (tilting);

b) exceeding the limits of strength (yield, ultimate, fatigue);

c) elastic instability of the crane or its parts or components (buckling, bulging).

The EN 13001-3-1:2020 standard establishes the limit states and proof competence of the metal structure. This standard should be used in conjunction with EN 13001-1 and EN 13001-2, which specify general conditions, requirements, and methods to prevent mechanical hazards of cranes through design and theoretical verification, as previously discussed.

According to Cai et al. (2014), the key parameters that have a significant impact on crane fatigue reliability include load, number of cycles, weld classification, and material properties. The EN 13001 standards demonstrate an improvement in fatigue calculation accuracy compared to previous standards, as they are more proficient in handling the variable load spectrum through the Rainflow counting method. Additionally, crane owners are required to provide information about the equipment usage profile. Figure 2 shows the project flowchart according to EN 13001.

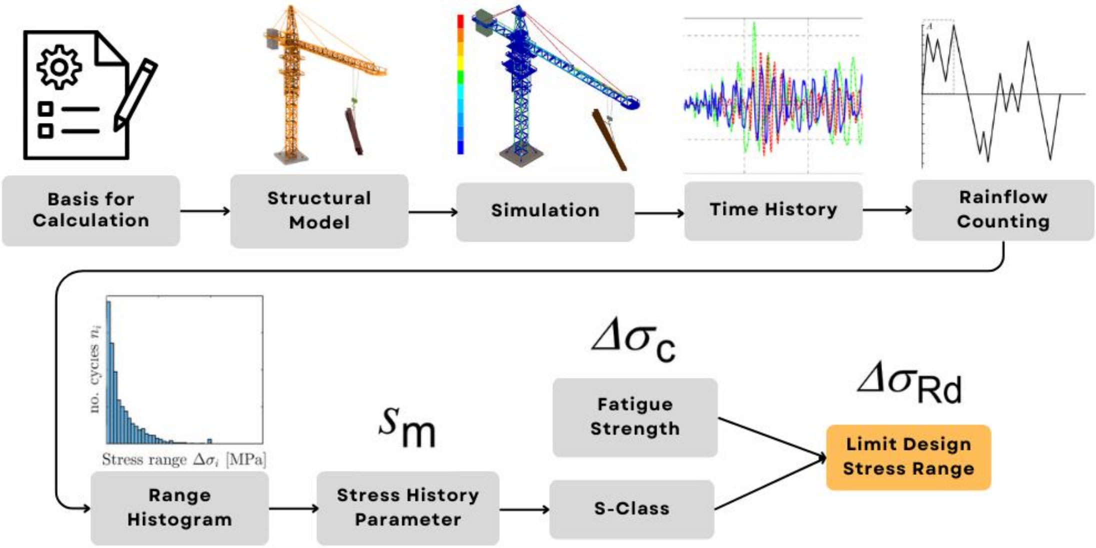

Figure 2: EN13001 design flowchart.

When determining the type of load to be lifted, its weight, dimensions, and special characteristics, such as brittleness or hazard, will help determine the type and capacity of crane required, thereby reducing the risk of exceeding its capacity. Site conditions where the crane will be used must also be taken into account, including available space, obstacles in the path, terrain slope, and equipment access, all of which impact the stress levels experienced by mechanical parts.

Environmental factors such as wind, temperature, and other weather conditions can also affect the final stresses to which the crane will be subjected in its use. While many modern cranes are equipped with automated systems to ensure structural stability, operating in different conditions can still significantly affect the stress levels to which mechanical components are subjected. It is essential to account for dynamic amplification factors in the analysis of live loads or situations where the loads may induce vibrations in the system, as they can significantly amplify stresses or, depending on the conditions, create resonance effects that could have catastrophic consequences for the operation.

The DNV-RP-C203 standard provides comprehensive guidelines for the design of offshore steel structures with a focus on fatigue analysis. It emphasizes the use of S-N curves and correction factors to accurately estimate the lifespan of structural components under cyclic loading. The standard requires that fatigue analysis be based on S-N data specific to the welded detail in question. If the estimated fatigue life is deemed insufficient for components with significant safety implications, a more thorough evaluation using fracture mechanics may be necessary. In such cases, it is crucial to document and ensure an adequate time interval between the detection of cracks during service inspections and the onset of unstable fracture.

Dynamic effects must be considered when defining the stress history. Fatigue analysis can use an expected stress history, which represents the predicted number of cycles at each stress level in the projected service life. It is important to establish a long-term stress history that ensures safety and to evaluate the portion that most significantly contributes to fatigue damage. The DNV-RP-C203 emphasizes the need to use realistic stress spectra in design and recommends detailed analyses to assess variability in loading conditions, such as waves and wind. The standard provides methods for determining stress in welded joints and suggests using safety factors to address uncertainties, variations in manufacturing, and potential inspection failures throughout the structure's service life.

Regarding inspection and maintenance, the standard recommends implementing regular monitoring and inspection programs to detect cracks and other forms of fatigue damage early. It also provides guidance on repair and reinforcement techniques to extend the service life of structures and mitigate risks associated with fatigue failure. Together, these guidelines offer a robust technical foundation for the design, assessment, and management of offshore steel structures, ensuring compliance with the highest safety and performance standards in harsh marine environments.

4 CONCLUSIONS

The prediction of fatigue life for cranes is a fundamental aspect of structural engineering, ensuring the safety and operational reliability of these equipment. In this study, two main categories of prediction methods were presented: those based on mechanics and those based on machine learning. Additionally, regulatory standards guiding the design of cranes are discussed.

While the S-N method has traditionally been considered comprehensive and reliable, there is a growing adoption of advanced algorithms to accelerate calculations and improve prediction accuracy. The random/hybrid taxonomy emerges as a promising approach for fatigue prediction, as it combines the advantages of individual algorithms. However, the validation of these advanced methods is essential, requiring comparison of their results with experimental and computational data, considering real-world operating scenarios.

The incorporation of probabilistic techniques and digital twins was also found in the literature as also important for accurately predicting fatigue life, taking into account inherent uncertainties and the evolution of fatigue over the equipment's lifespan. By adopting a multidisciplinary and integrative approach that combines traditional methods with emerging technologies, we can significantly advance the prediction and management of fatigue in cranes, thus ensuring their safety and operational performance over time.

In summary, this literature review made it possible to map the main lines of research related to fatigue life prediction of loading cranes as being those related to: (i) understanding the fatigue behavior of new and existing materials used in crane construction; (ii) accurately assessing the loads scenarios that cranes experience during operation including the study of static and dynamic loads imposed by lifting and moving heavy loads, wind forces and/or other environmental factors; (iii) investigating new modelling approaches by finite element analysis (FEA) to simulate the stress distribution within crane structures under various loading conditions; (iv) proposing and validating new fatigue life prediction models specific to crane components that take into account factors such as load spectra, stress concentrations, and material properties; (v) studies on how fatigue damage accumulates over time in crane components, considering factors such as cyclic loading frequency, stress amplitude, number of load cycles, and principal stress orientation; (vi) research on methods to mitigate fatigue damage by surface treatments, and maintenance practices aimed at reducing stress concentrations; (vii) the analysis of real-world performance data and case histories of crane failures to improve understanding the fatigue failure mechanisms.

This literature survey on fatigue life prediction on loading cranes represents the state of the art articles and research in the area till this date and may be useful for starting point of new research ideas and improvements based on investigations lines already developed in the theme. This work was not intended to be an exhaustive review of the subject, especially with regard to Theses and Dissertations, which are more difficult to access than international journal articles.

ACKNOWLEDGMENTS

We would like to express our gratitude to CAPES for the support and funding provided, which made the completion of this work possible.

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