FATIGUE LIFE ASSESSMENT OF STEEL STRUCTURE, A STATE-OF-THE-ART REVIEW

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ABSTRACT

Engineering structures undergo deterioration, primarily fatigue and corrosion, impacting structural reliability. Shared materials and environmental conditions create spatial links among components, fostering dependencies that influence system safety. Recognizing structures as interconnected systems is crucial, necessitating consideration of spatial correlation in structural reliability analysis. Valuating fatigue damage and predicting the remaining life of steel structures is a persistent challenge. Progressive collapse, tied to safety assessment ambiguities, garners attention, emphasizing the need for comprehensive evaluation. Old, rusted steel structures face heightened vulnerability to wind loads due to potentially extreme wind speeds. Over time, steel constructions weaken due to cycling loads, wind, seismic activity, usage, and environmental factors. Structural degradation may result from design flaws, construction errors, poor materials, and use. The issue of progressive collapse, linked to potential ambiguities affecting safety assessments, has gained attention. Calculating the likelihood of a structure remaining safe under excessive stress involves probability analysis. Factors such as service environment, duration, and fatigue loading inform the forecast of fatigue life. Steel structural members often fail due to pitting corrosion under chloride attack and fatigue. Numerous studies using deterministic or probabilistic techniques have explored fatigue damage evaluation and steel structural life prediction. Decisions about a structure's safety under cyclic stress, considering the remaining fatigue life, emerge from a fatigue evaluation.

This review aims to offer a concise overview of the field's evolution and the current state of fatigue state assessment for steel structures. It covers fundamental fatigue concepts, conventional analysis methods, data-driven approaches for fatigue life evaluation, and reliability-based techniques for assessing fatigue conditions.

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Keywords: *Fatigue failure, structural collapse, steel structure, structural deterioration, structural reliability.*

1. INTRODUCTION

When structures are repeatedly exposed to external loadings like traffic for steel bridges, wind for tall structures, waves for offshore platforms, and temperature for turbine apparatuses, structural damage gradually builds up over time. This is still true even if the forces being applied may be substantially lower than the structural scuffle aptitude. This method is highly unsafe because a sole presentation of the load would not produce any odd results, unlike a traditional structural stress assessment, which can lull one into thinking they are safe. In-depth research has been done on the asset and serviceability mechanisms of failure over time by specialist engineering departments. Although fatigue is the most serious type of destruction and the main catastrophe mode for steel structures, little is known about its production process and failure mode. Because steel bridges are essential components of a nation's transportation infrastructure, it is imperative to find novel strategies and develop cutting-edge technology to capture the fatigue facts and perform precise evaluations of the fatigue damage condition of steel structures. Two methodologies are typically employed for the valuation of lassitude failure and life assessment of steel constructions. The standard S-N curve approach establishes a connection between the continuous generosity stress assortment, S, and the number of cycles to disaster, N, which is then depicted as an S-N curve. This methodology is expanded to loadings with variable amplitudes by the Palmgren-Miner rectilinear destruction theory, also referred to as Miner's rule (Milton, 1945). The study of the structures and conditions of crack commencement and development while taking into account the stress field at the break tip is the main goal of another method known as fracture mechanics. The fracture mechanics approach is typically used for a more accurate crack-based residual lassitude life assessment or effective decision-making on inspection and maintenance tactics. In contrast, the S-N curve method is typically used at the structure strategy phase or for a preliminary assessment of fatigue lifespan (Chryssanthopoulos and Timothy, 2006). Research and implementations of the conventional S-N method or the fracture mechanics methodology have been conducted on the evaluation of lassitude damage and the life prediction of bridge projects. In some specifications, the conventional nominal S-N technique serves as the basis for the design or assessment of bridge fatigue (BSI, 1980) (AASHTO, 1990) (CEN, 1992). These requirements are ceremonial, and the association between the stress scale and factual endurance should be developed in instruction to forecast the lassitude life of stochastically loaded constructions. S-N curves typically show the material endurance for loadings with constant amplitude. Because it is frequently unknown, the stress spectrum must be assessed using experiments or computer models. The stress spectrum is obtained during the fatigue life prediction process by separating the strain sequences from a restrained or simulated stress time history using an appropriate cycle-including manner. Using the selected fatigue effect accumulative rule, calculated the fatigue damage brought on by each stress cycle. The numerous damages for each stress cycle are added up to create the overall fatigue damage. The Miner's rule is one of the most often used damages accumulative rules, and the rain flow cycle estimating method is frequently used to derive stress sequences from stress time antiquities (Matsuichi and Sutomu, 1968). Field assessment is a crucial technique for locating and reducing fatigue damage due to the nature of the fatigue process, ambiguity surrounding historical load antiquities, and estimates of forthcoming loads. Then, using statistics and evidence obtained from monotonous field reviews, it is determined how much fatigue damage has occurred and whether fatigue fractures have developed in bridge components. An assessment may include visual inspection of structural elements as well as the application of a number of nondestructive evaluation (NDE) procedures, such as dye penetration, dynamic testing, radiographic inspection, electric inspection, sonic and ultrasonic processes, and sonic emission (Achenbach, 2000). Large bridges are frequently costly and labour-intensive to complete. They are usually carried out after wearing, and destruction, including fatigue cracking, is discovered in nearby digging areas. When visual inspections without the use of NDE procedures are utilized, the technician's involvement and the sort of destruction seen in general classes of inspected structures are the two key criteria that affect the effectiveness of the inspection program. The accuracy of the inspection process is significantly impacted by the viability of the chosen strategy for identifying fatigue damage when NDE methods are applied. These tests may enable the evaluation of the lassitude life at fatigue-sensitive (particularly at fracture-critical) details by providing a polaroid of the functioning masses and the bridge's consistent retorts. However, some of the tests won't allow for the normal operation of bridges. One of the main themes of attention for academics and engineers in the material, computer science, mechanical, and civil departments is long-term structural health monitoring (SHM) of structures (Daniel et al., 2006). Analytical abilities and instrumentation technologies are combined with expertise in structure design, erection, assessment, preservation, and administration during the system's design and implementation. A bridge's reliability, toughness, and integrity can be evaluated using an online SHM system. In order to improve design standards, specifications, codes, and recommendations, as well as to streamline maintenance procedures, data can then be uploaded to the bridge management and maintenance system (BMMS). Since SHM makes use of cutting-edge technologies in detecting, statistics attainment, calculating, communication, and statistics and evidence oversight, as well as through the successful integration of these innovations into a sophisticated system, it is actually an improvement rather than a replacement of the current practices in structure upkeep and supervision. The correct calculation of the vital components' present state of fatigue and remaining life using the continuously monitored data on dynamic strain is a crucial challenge for the overtime SHM system. The fatigue performance of steel bridges is influenced by a number of variables, including material properties, stress antiquity, and atmosphere, all of which exhibit unpredictability and volatility during a bridge's service life. The uncertainties associated with the data and the errors caused by data processing methods, on the other hand, are permanent and essentially avoidable when the field measurement data are employed to assess the condition of fatigue. Given these characteristics, probabilistic techniques rather than predictable ones should be employed to gauge damage lifespan.

2. FUNDAMENTAL MECHANISM OF FATIGUE

Wilhem Albert first discovered the fatigue phenomenon in 1837; in 1842, William John discovered the fundamental mechanism of fatigue failure (Aprianur et al., 2021). Mikkel Melters states that fatigue can be termed as “the process of progressive localized permanent structural change occurring in a material subjected to conditions that produce fluctuating stresses and strains at some point or points and that may culminate in cracks or complete fracture after a sufficient number of fluctuations” (Ralph et al., 2000). Wohler et al. conducted multiple research laboratory lassitude assessments underneath recurring pressures to launch the first systematic investigation of fatigue in response to the failure of railway axles after prolonged durations of operation at loads much below the motionless strong point of the structures (Ralph et al., 2000).

Thus, a crack instigation phase (N_{i}) and a crack proliferation stage (N_{ρ}) make up the total fatigue life (N_{f}) (Mikkel Melter Pedersen, 2018).

$$N_{\mathrm{f}} = N_{\mathrm{i}} + N_{\rho} \quad (1)$$

The ASCE panel on Fatigue and Fracture Durability claims that fatigue fracture accounts for about 80–90% of fractures in metallic structures (ASCE, 1982). The conclusions of a comprehensive study conducted by Battelle Columbus Labs and "The National Bureau of Standards" (currently NIST, "The National Institute of Standards" and Technology), which was released in 1983 (Reed et al., 1983) also attest to the fact that fatigue is a common cause of mechanical failures. According to reports, fatigue was a factor in 141 of 230 failures (almost 61%) and has three leading causes: poor maintenance, fabrication flaws, and poor design. The fatigue process is typically seen as the beginning of a crack, followed by a period of fracture propagation. Phase I, known as crack initiation, begins lassitude impairment as minuscule shear fractures on crystallographic error planes as interferences and extrusions. The constant presentation of insufficient stress triggers lassitude cracks to cause failure. During stage II of the crack propagation procedure, the crack grows from the confined flexible distortion to a macroscopic extent in a way upright to the functional force. The component may crack as well when the crack ultimately becomes unstable. The evolution among the two stages of the lassitude procedure is frequently challenging to identify since it depends on various variables, including the component's size, substance, and fracture methods for identification. The conclusions of a comprehensive study conducted by Battelle Columbus Labs and "The National Bureau of Standards" (now NIST, "The National Institute of Standards" and Technology), which was released in 1983 (Reed et al., 1983) also attest to the fact that fatigue is a common cause of mechanical failures. According to reports, fatigue was a factor in 141 of 230 failures (almost 61%) and has three leading causes: poor maintenance, fabrication flaws, and poor design. The examination also made clear that by employing the proper fatigue analysis techniques and tools, the expense of fatigue-induced fracture may be significantly decreased.

Nevertheless, due to the complexity of the fatigue mechanism, designers and engineers need help forecasting and understanding how metal materials, components, and structures may fail from fatigue. The majority of the fatigue life is typically accounted for by the (HCF) regime (about more than ten thousand cycles). The majority of the lassitude lifecycle in the stumpy sequence fatigue (LCF) command (less than ten thousand cycles) is consumed by fracture progression. Each stage of the weary process is separated in modern theories of fatigue. According to theories on crack initiation, indigenous stresses and pressures that concentrate on the shallowness of a structural section as a result of geometrical features like holes, gaps, and fillet radii lead to stress failures. The mechanics of fractures are used to link crack growth to element stresses, allowing for the investigation of crack propagation and final failure phases.

3. CONTEMPORARY FATIGUE ANALYSIS TECHNIQUES

Morrow Socie and JoDean discovered two main criteria that have historically promoted techniques for fatigue analysis (Socie and JoDean, 1980). The first has been the requirement for realistic, user-friendly, and economical approaches to be offered to designers and engineers. The second factor is the requirement to make these analytical methods and physical observations compatible. The fact that fatigue can frequently be divided into two separate segments—instigation life and proliferation life—is one of the most significant physical realities. Three exhaustion investigation approaches are covered in this work: the strain-life (e-N) method, the cracked mechanical strategy, and the stress-life (S-N) process. Although there is some overlap between these strategies, each has a specific use.

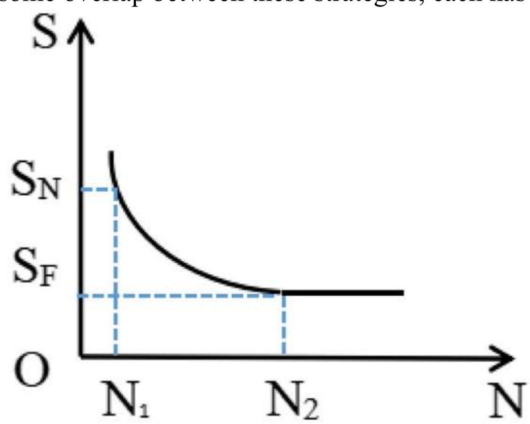

Figure 1: Example of S-N Curve (Zhang, 2020)

The S–N curve of material is the relationship between stress and fatigue life, which a fatigue test can measure. A complete S–N curve can be divided into the low-cycle fatigue zone, high-cycle fatigue zone, and sub-cycle fatigue zone. Figure 1 shows the S-N curve proposed by Yq Zhang (Zhang, 2020).

3.1 Analysis of Fatigue Using the Stress-Life Method.

When stresses and strains are elastic, the stress-life method can forecast the prolonged fatigue life of HCF. Instead of focusing on the overall lifespan or the lifecycle until the collapse of a structural element, it deals with the life until fracture initiation and propagation. When test specimens are repeatedly cycled under constant amplitude loads until observable cracking appears, the stress-life method produces S-N curves that show the link between the strain variety and fatigue catastrophe. Basquin depicted the Wohler curve's finite life zone as log N on the abscissa, and log S scheduled the direction (Basquin, 1910). The mathematical formulation of the Basquin function is as follows:

$$NS^m = A \quad (2)$$

$$\log N = -mlog\, S + logA \quad (3)$$

The constructive experimental substantial coefficients m and A. Log A and m are (3)'s constant slope and catch on the log N axis. To account for the fatigue ceiling, Stromeyer (Stromeyer, 1914) amended (3) by including an additional constraint F_l as

$$\log N = -m \log(S - F_1 + \log A \quad (4)$$

Since F_l reflects the fatigue limit stress, it should be ignored when the parameter's optimal value is negative or negligible.

Walker presents a similar stress Sq model to show how the strain proportion Rs or mean stress Sm affects the duration of lassitude (Walker, 1970).

$$\log N = -m \log(S_q - F_l) + \log\ A \quad (5)$$

Where,

$$S_q = S(1 - R_s)^C \quad (6)$$

Consider

$$S_m = \frac{S}{2}(1 + R_s) \quad (7)$$

Exchanging R_s in (6) through S_m, then.

$$S_q = S(2 - \frac{2S_m}{S})^C \quad (8)$$

In this case, C is a variable. The most-viewed stress management techniques include the minimal stress technique, hot spot pressure process, and operative indentation stress approach. This depends on evaluating the structure's specific specifics under stress (Wolfgang, 2003).

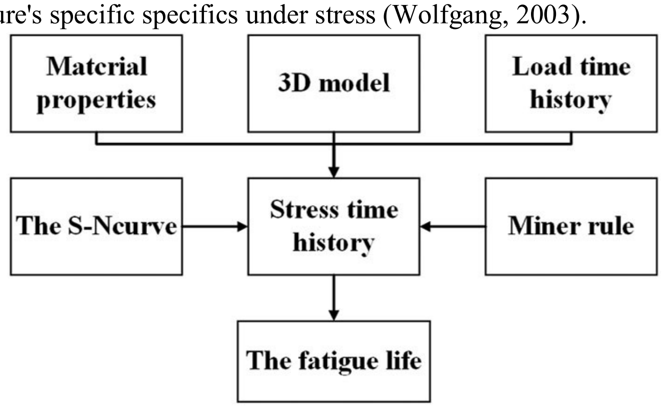

Figure 2: Stress-fatigue analysis process (Zhang, 2020)

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3.2 Fracture Mechanics-based Fatigue Analysis and the Strain-Life Procedure

The crack introduction phase is the main focus of the strain life technique, which was created in the 1960s. When the strain has a plastic component rather than being entirely elastic, it is employed. Under these circumstances, LCF regime fatigue lifetimes tend to be short. There have been various studies evaluating the fatigue performance of steel bridges using theoretical strain-life methods and low-cycle fatigue testing (David, 1982). The cracking mechanics process is frequently used to anticipate how long a crack or defect will last once it first appears. The production of cracks due to fatigue is commonly described by Paris and Erdogan's "N. Paris's rule," which is connected to the number of fatigue periods in the linear elastic fracture mechanics (LEFM) method (P Paris and F Erdogan, 1963).

$$\frac{da}{dN} = C(\Delta K)^m \quad (9)$$

Where C and m are characteristics relating to the substantial, and Broek (David, 1982) has defined the ΔK stress intensity factor's range.

$$\Delta K = SY\,(a)\sqrt{\pi a} \quad (10)$$

S is the stress series, and Y(a) is the purpose of the fracture geometry. The assessment of bridge fatigue state using a break mechanism approach has been the subject of numerous works. The crack introduction phase is the main focus of the strain life technique, which was created in the 1960s. It is employed when the strain has a plastic component rather than being entirely elastic. Under these circumstances, LCF regime fatigue lifetimes tend to be short. Various studies have evaluated the fatigue performance of steel bridges using theoretical strain-life methods and low-cycle fatigue testing (Hanbin et al., 2012). The crack spread fatigue data was obtained from five old metallic bolted bridges in Portugal, employing deterministic and probabilistic models; the strain life fatigue data were associated.

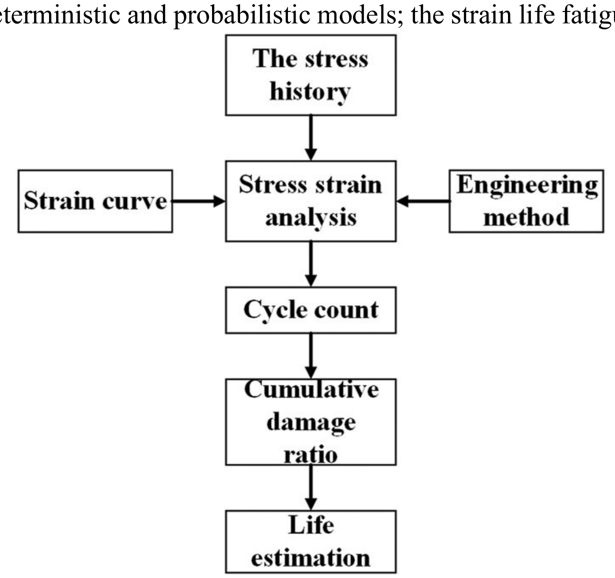

Figure 3: Strain-fatigue analysis process (Zhang, 2020)

The usefulness of the strain-life process in determining the fatigue development of steel structures has received little attention up to this point because many fatigue issues in steel bridges are associated with the HCF regime.

3.3 Fatigue Life Evaluation Based on the SHM.

A growing number of countries, including the USA, Europe, Japan, Korea, Hong Kong, the Chinese mainland, and Canada, have realized the value of deploying enduring SHM systems for steel structures (Feng, 2009) (Brownjohn, 2007). This is done to keep the bridges structurally and operationally safe for the duration of their useful lives and to give early indications of any deterioration or damage so that they can be repaired economically or even prevented entirely. In light of their significant economic contributions, high initial costs, and innovative construction and design methods, long-span bridges, in particular, are increasingly being equipped with workstations and sensor-based long-term health checking schemes. In addition to monitoring structural health and performance, SHM systems are essential for precisely estimating the proper amount of fatigue and the residual lifecycle of the structure (Tommy et al., 2001). With the expansion of SHM schemes for immense, intricate structures, it has emerged as a fundamental research interest. There has been little advancement in the last ten years in terms of fatigue investigation and complaint valuation of structures based on longstanding observing statistics, despite the fact that SHM is a moderately innovative skill for applications in the civil engineering sectors. In reality, a thorough description of SHM and the guiding principles for system design have yet to be codified.

4. CONCLUSIONS

This paper provides a concise overview of developments in fatigue life assessment for steel structures. Concluding a comprehensive review of theories, methods, technologies, and applications, it highlights that while the nominal stress-life method is widely used in fatigue-related design for steel bridges, the hot spot stress method proves more accurate and effective in estimating fatigue life (i). Emphasizing the importance of field measurement data, the paragraph underscores the need to develop data-driven methods for accurate fatigue life assessment of steel structures, as this source provides the most precise information for deriving key physical parameters in fatigue condition assessment (ii). Furthermore, recognizing the uncertainties and randomness in fatigue phenomena and measurement data, the paragraph advocates for investigations into probabilistic fatigue life assessment for steel structures, enabling reliable fatigue condition assessment and guiding rational strategies in structural inspection and maintenance based on the correlation between reliability indices and predefined actions (iii). The paper explores methodologies for analyzing and predicting fatigue life, suggesting future directions for fatigue investigation. The current analysis, focused on individual tool components, is prone to errors due to obligatory boundary requirements. This leads to inaccuracies in life predictions. To enhance precision, it is crucial to consider the essential parts of a structure and their minimum life within the total working environment when predicting fatigue life. The field has significant potential for growth in this direction, especially with the introduction of new technology, promising more precise and practical approaches. The primary development path involves integrating novel technologies with fatigue analysis expanding the correctness and applicability of fatigue-lifespan expectation techniques by identifying and utilizing unknown constituents. It emphasizes that developing new technologies for fatigue analysis requires a shift from conventional thinking, highlighting the need for innovative approaches beyond the integration of current methodologies with state-of-the-art technology to address issues and provide more dependable answers.

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