WHIOCE PUBLISHING PTE. LTD.
PROVIDING FIRST-CLASS SCIENTIFIC INFORMATION FOR TOP SCHOLARS

2025 Volume 3, Issue 6
Lecture Notes in Education, Arts, Management and Social Science
ISSN(Online): 2705-053X

Fatigue Damage Mechanism and Life Prediction of Steel Structure Joints in Super High-Rise Buildings

Yuan Li
Zhengzhou University of Industrial Technology, Zhengzhou 451199, Henan, China

Abstract: With the acceleration of urbanization, super high-rise buildings have increasingly become iconic structures of modern cities. The fatigue damage of their steel structure joints directly affects the safety and durability of the building structures. This paper systematically studies the fatigue damage mechanism and life prediction methods of steel structure joints in super high-rise buildings. By combining theoretical analysis, experimental research, and numerical simulation, it deeply analyzes the fatigue damage mechanism from both microscopic and macroscopic perspectives, and explores the influence mechanisms of factors such as materials, structures, loads, and environments on fatigue damage. In terms of fatigue life prediction, it comprehensively compares and analyzes prediction methods based on S-N curves, fracture mechanics, damage mechanics, numerical simulation, and intelligent algorithms, and expounds the principles, application processes, and applicable scenarios of each method.

Keywords: Super high-rise buildings; Steel structure joints; Fatigue damage mechanism; Life prediction; Stress concentration

Online publication: July 26, 2025

1. Introduction

In recent years, with the rapid advancement of global urbanization, super high-rise buildings, with their significant advantages of efficiently utilizing land resources and demonstrating the modern style of cities, have become a key area for development in major cities. According to statistics, by the end of 2024, more than 300 super high-rise buildings over 300 meters had been completed worldwide, with China accounting for more than half. Among them, steel structures have become the mainstream choice for super high-rise building structures due to their characteristics of light weight, high strength, convenient construction, and excellent seismic performance. However, during the full life cycle of super high-rise buildings, steel structure joints, as key parts for component connection and load transmission, are subject to long-term cyclic loads such as wind loads, seismic actions, temperature changes, and crowd activities, leading to the gradual emergence of fatigue damage problems.

From the perspective of research status, scholars at home and abroad have carried out extensive research on the fatigue performance of steel structures. Early studies mostly focused on fields such as bridges and machinery, while systematic research on the fatigue problems of steel structure joints in super high-rise buildings under special service environments is relatively lagging. In terms of fatigue damage mechanism, existing studies have not fully clarified the crack initiation and propagation mechanisms under the coupling effect of multiple factors (such as the synergy of high stress amplitude, complex stress state, and corrosive environment). In the field of life prediction, traditional methods based on S-N curves are difficult to accurately describe the randomness and complexity of dynamic loads in super high-rise buildings, while the reliability verification of emerging intelligent prediction technologies in engineering applications is still insufficient.

In view of this, in-depth exploration of the fatigue damage mechanism of steel structure joints in super high-rise buildings and the construction of accurate life prediction models are of great significance for ensuring the safety of building structures and reducing operation and maintenance costs. This paper will systematically reveal the microscopic and macroscopic mechanisms of joint fatigue damage through the combination of theoretical analysis, experimental research, and numerical simulation, compare and evaluate the applicability of various life prediction methods, and verify relevant theories and methods with typical engineering cases. It aims to provide a scientific basis for the design, inspection, and maintenance of steel structure joints in super high-rise buildings, and promote the sustainable development of the super high-rise building field[1].

2. Fatigue damage mechanism of steel structure joints in super high-rise buildings

2.1. Basic concepts of fatigue damage

Fatigue damage refers to the process in which the performance of materials, structures, or components gradually degrades until failure occurs under long-term repeated loads. It is a cumulative damage phenomenon. During their service life, steel structure joints in super high-rise buildings are subjected to dynamic and cyclic loads caused by wind loads, seismic actions, mechanical vibrations, and temperature changes. These loads cause repeated stress variations in the joint areas, thereby inducing fatigue damage. Unlike failure under static loads, fatigue failure usually occurs when the stress is far below the yield strength of the material, and it is highly sudden and concealed.

The characteristics of fatigue damage show certain regularity. In the early stage of damage, cracks usually initiate at micro-defects inside the material or in surface stress concentration areas. Since these initial cracks are extremely small, they are difficult to detect visually, making fatigue damage concealed and hard to identify in the early stage. As the number of load cycles increases, the cracks gradually propagate. The crack propagation process is generally slow, but after reaching a certain stage, the propagation speed accelerates. During the fatigue crack propagation process, fatigue striations are formed, which record the traces of crack propagation in each cycle of loading and are one of the important microscopic characteristics of fatigue damage. When the crack propagates to a certain extent, the load-bearing capacity of the structure is severely reduced, eventually leading to sudden fracture, which reflects the suddenness of fatigue failure.

The process of fatigue failure can generally be divided into three stages: the crack initiation stage, the stable crack propagation stage, and the unstable fracture stage. In the crack initiation stage, due to the inhomogeneity of the internal microstructure of the material and the existence of stress concentration, dislocations inside the material start to move and gradually accumulate under cyclic loads, forming microscopic slip bands[2]. As the number of cycles increases, the slip bands continue to expand and intersect with each other, forming microcracks. In this stage, the crack size is small and the propagation speed is relatively slow, which is the initial stage of fatigue damage.

2.2. Analysis of fatigue damage mechanism

2.2.1. Microscopic mechanism

From the microscopic perspective, the fatigue damage of steel structure joints in super high-rise buildings is closely related to the changes in the internal microstructure of materials. Dislocation slip is one of the important microscopic mechanisms for the initiation of fatigue cracks. Under cyclic loading, dislocations inside the material will slip and move. Due to the existence of microscopic defects in the material, such as inclusions and pores, these defects will hinder the movement of dislocations, causing dislocations to accumulate at the defects and form dislocation cells or dislocation walls. As the number of cycles increases, the accumulation of dislocations becomes more and more serious, leading to local stress concentration. When the stress exceeds the local strength of the material, microcracks will be generated in these areas. For example, through observation of fatigue-damaged steel using a Transmission Electron Microscope (TEM), the distribution and accumulation of dislocations, as well as the correlation between microcracks and dislocation accumulation areas, can be clearly seen.

Grain boundary cracking is also an important microscopic mechanism leading to the initiation and propagation of fatigue cracks. Grain boundaries are regions in the material where the atomic arrangement is irregular, and the atomic bonding force there is relatively weak. Under cyclic loading, stress concentration is prone to occur at grain boundaries, causing the atomic bonds at grain boundaries to gradually break, thereby initiating grain boundary cracking. In addition, segregation of impurity atoms may exist at grain boundaries, which further reduces the strength of grain boundaries and increases the possibility of grain boundary cracking. Studies have shown that refining grains can increase the area of grain boundaries, thereby dispersing stress and improving the fatigue resistance of materials. Because in a fine-grained structure, the size of each grain is small, the hindering effect of grain boundaries on crack propagation is more significant, making it more difficult for cracks to propagate at grain boundaries and requiring more energy consumption.

2.2.2. Macroscopic mechanism

At the macroscopic level, stress concentration and deformation accumulation are important factors leading to fatigue damage of steel structure joints in super high-rise buildings under cyclic loading. Stress concentration refers to the phenomenon that in local areas of the structure, due to sudden changes in geometric shape, material discontinuity, or uneven load distribution, the stress in these areas is much higher than the average stress. In steel structure joints, stress concentration is a common phenomenon. The stress concentration in these parts will lead to a significant increase in local stress levels, thereby accelerating the initiation and propagation of fatigue cracks. Taking welded joints as an example, welding residual stress will be generated during the welding process. At the same time, the geometric shape and material properties of the welded joint are different from those of the base metal. These factors will lead to stress concentration at the welded joint. Through finite element analysis, the stress distribution at the welded joint can be intuitively seen, and it is found that the stress concentration areas are mainly concentrated near the weld, where the stress value is significantly higher than that in other parts.

Deformation accumulation is also a key factor affecting fatigue damage at the macroscopic level. Under cyclic loading, steel structure joints will undergo repeated elastic and plastic deformations. Although the amount of plastic deformation in each cycle may be small, with the increase in the number of cycles, plastic deformation will gradually accumulate, leading to a decrease in the stiffness of the joint and an increase in deformation. This deformation accumulation will further aggravate stress concentration, making fatigue cracks more likely to initiate and propagate. For example, in the simulation analysis of steel structure joints in super high-rise buildings, it is found that with the increase in the number of load cycles, the deformation of the joints gradually increases, especially in the stress concentration areas, where the deformation accumulation is more obvious. At the same time, deformation accumulation will also lead to loosening of the joint connections, reducing the integrity and stability of the structure, thereby further accelerating the development of fatigue damage.

3. Fatigue life prediction methods for steel structure joints in super high-rise buildings

3.1. Life prediction method based on S-N curve

The S-N curve, i.e., stress-life curve, is an important tool for describing the fatigue life of materials under different stress levels. It takes the fatigue strength of standard material specimens as the ordinate and the logarithm of fatigue life (lgN) as the abscissa, intuitively showing the relationship between the fatigue strength and fatigue life of standard specimens under a certain cyclic characteristic. In the fatigue life prediction of steel structure joints in super high-rise buildings, the S-N curve has important application value.

The S-N curve can be obtained mainly through two methods: experimental determination and empirical estimation. Experimental determination is the most direct and reliable method to obtain the S-N curve. By conducting fatigue tests on standard specimens under different stress levels, the number of cycles before the specimen fractures at each stress level is recorded, so as to obtain a series of data points of stress levels and fatigue lives. By sorting out and fitting these data points, the S-N curve can be drawn. The experimental determination process requires strict control of test conditions, including specimen preparation, loading mode, loading frequency, environmental conditions, etc., to ensure the accuracy and reliability of the test results. For example, during specimen preparation, it is necessary to ensure that the material properties, geometric dimensions, surface quality of the specimens meet the standard requirements; in the loading process, precise loading equipment should be used to ensure the stability and accuracy of loading[3].

The principle of predicting the fatigue life of steel structure joints in super high-rise buildings using the S-N curve is based on the theory of cumulative fatigue damage of materials. This theory holds that the fatigue damage of materials under cyclic loads accumulates linearly, and when the cumulative damage reaches a certain level, the material will undergo fatigue failure. The specific steps are as follows: First, calculate the stress level of the steel structure joint under actual loads through methods such as finite element analysis. When establishing the finite element model, it is necessary to accurately simulate the geometric shape, connection mode, material properties and load conditions of the joint to ensure the accuracy of the calculation results. Second, according to the calculated stress level, find the corresponding fatigue life on the S-N curve. If the S-N curve is obtained through experimental determination, the corresponding fatigue life can be directly read from the curve; if it is obtained through empirical estimation, the fatigue life is calculated according to the empirical relationship. Finally, considering various uncertain factors in actual engineering (such as the dispersion of material properties, the randomness of loads, the influence of environmental factors, etc.), the prediction results are corrected and evaluated to improve the accuracy and reliability of the prediction[4]. Probability and statistics methods can be used to quantitatively analyze the uncertain factors and obtain the probability distribution of fatigue life, so as to more accurately evaluate the fatigue reliability of the joint.

4. Conclusions and prospects

4.1. Summary of research results

This study conducted in-depth research on the fatigue damage mechanism and life prediction of steel structure joints in super high-rise buildings, achieving a series of results with important theoretical and practical value[5].

In terms of the research on fatigue damage mechanisms, the essential causes and evolution laws of fatigue damage in steel structure joints of super high-rise buildings were revealed from both microscopic and macroscopic perspectives. Microscopically, the key roles of microscopic mechanisms such as dislocation slip, grain boundary cracking, and changes in microstructure in the initiation and propagation of fatigue cracks were clarified. The movement and accumulation of dislocations under cyclic loading lead to local stress concentration, triggering the generation of microcracks; grain boundaries, as regions with irregular atomic arrangement, have relatively low strength and are prone to cracking under cyclic loading, thereby promoting the propagation of fatigue cracks. Changes in second-phase particles in the material's microstructure also have a significant impact on fatigue performance. Macroscopically, the influences of factors such as stress concentration, deformation accumulation, and structural vibration characteristics on fatigue damage were analyzed. Mutations in the geometric shape of joints, welding residual stress, and connection methods can cause stress concentration, accelerating the initiation and propagation of fatigue cracks; deformation accumulation under cyclic loading will reduce the stiffness of joints, further exacerbating stress concentration and promoting the development of fatigue damage; the vibration of structures under dynamic loads such as wind loads and seismic actions, especially resonance phenomena, will significantly increase the stress and deformation of joints, accelerating the process of fatigue damage. Meanwhile, a comprehensive analysis of the influences of materials, structures, loads, environment, and other factors on the fatigue performance of joints was conducted, providing a solid theoretical foundation for subsequent life prediction and engineering applications.

4.2. Research limitations and prospects

Although this study has achieved certain results in the fatigue damage mechanism and life prediction of steel structure joints in super high-rise buildings, there are still some limitations that need to be further improved and expanded in future research.

Although the current research has considered the influences of multiple factors on fatigue damage and life, the research on fatigue performance under the coupling effect of multiple factors is not in-depth enough. In actual engineering, factors such as material performance degradation, environmental corrosion, and temperature changes often interact and influence each other, collectively leading to fatigue damage of steel structure joints. However, most existing studies consider the influence of one or several factors individually, and the complex coupling relationships and synergistic mechanisms between various factors have not been fully clarified. Under the combined action of temperature and corrosive media, the corrosion rate of steel and the propagation rate of fatigue cracks will change significantly, but there are still certain difficulties in the quantitative description and prediction of such changes. Therefore, it is necessary to carry out more systematic research on fatigue performance under the coupling effect of multiple factors in the future, and establish more accurate multi-factor coupled fatigue damage models and life prediction models.

Disclosure statement

The author declares no conflict of interest.

References

[1] Li W, 2021, Multi-scale simulation and experimental study on fatigue degradation of weld details in high-rise and tall steel structures. Gansu Province: Lanzhou University of Technology, 2021-05-23.

[2] Li A, Qu W, Ding Y, 2016, et al. Review on fatigue degradation mechanism and life prediction of welds in high-rise and tall steel structures. Journal of Beijing University of Civil Engineering and Architecture, 32 (03): 29-35.

[3] Fang Z, 2019, Research on Wind Induced Fatigue Life Prediction of Welded Joints in High rise Steel Structures. Southeast University, 2019

[4] Zheng X, Lv H, Li H, 2022, etc Steel strength degradation model in wind-induced fatigue analysis of high-rise buildings. Journal of Disaster Prevention and Reduction Engineering, 42 (02): 276-282

[5] Fan Z, Tang J, Luo L, 2025, Fatigue crack detection of beam column joints in building steel structures. Weapon Materials Science and Engineering, 48 (01): 121-126