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Research status of fatigue damage of reinforced concrete structures under erosion environment

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Abstract

Due to the influence of the working environment, the durability of reinforced concrete structures will continuously deteriorate. The reinforced concrete bridge structure is subjected to long-term fatigue loads, and its fatigue damage accumulates over time. The erosion and freeze-thaw environment will accelerate the development of fatigue damage and reduce the service life of bridge structures. This article summarizes the current research status of fatigue performance of reinforced concrete structures in ordinary working and erosion environments, analyzes the existing problems, and proposes suggestions for further in-depth research.

Keywords

Durability, fatigue damage, erosion environment.

1. Introduction

Reinforced concrete structures are formed by combining concrete and steel bars, as the two materials complement each other well in terms of mechanical properties, durability, and price, and have similar coefficients of thermal expansion [1]. Therefore, they are widely used in buildings, bridges, dams, and some infrastructure. Due to the widespread presence of reinforced concrete structures in various working environments, their durability performance is affected by various factors, including carbonation, chloride erosion, freeze-thaw cycle damage, and sulfate corrosion. Among them, freeze-thaw cycle damage and sulfate corrosion mainly damage the concrete itself, leading to cracking and microstructure loosening, while the strength and stiffness of the structure deteriorate [2, 3]. However, carbonation and chloride erosion have little effect on the performance of concrete itself, especially during the carbonation process, carbon dioxide promotes the hydration of cement, increases the volume of hydration products, and makes the microstructure denser. The strength and compactness of carbonated concrete can even be improved [4, 5]. However, due to the entry of carbonates, the internal alkalinity of concrete decreases, leading to the destruction of the passive film on the surface of steel bars [6]. Then, under the combined action of external moisture, oxygen, or chloride ions, the steel bars undergo corrosion, and when the corrosion continues to develop, it will seriously threaten the service life of the structure [7]. The slight structural damage caused by long-term loading on reinforced concrete structures, mainly cracks, also exacerbates the entry of external corrosive substances and accelerates the deterioration of durability [8]. Therefore, concrete structures that bear loads and corrosion will produce a comprehensive effect, and these two effects will intensify each other, leading to structural failure.

Reinforced concrete bridges in coastal areas are in a complex and constantly changing working environment, including environmental changes that are different from the original design (such as typhoons, acid rain, road de icing salts, etc.), changes in load intensity (overloading of vehicles on the original bridge, increased traffic flow), and the continuous deterioration of the

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bridge's own bearing capacity in harsh working environments. This requires us to study the impact of different environmental and fatigue load coupling on the bearing capacity of components in order to accurately evaluate the condition of the bridge in service. Bridges mainly bear high-frequency fatigue loads caused by vehicles or trains, rather than static loads. Compared to static loads, the stress level of fatigue loads is usually lower. However, repeated fatigue loads can lead to the continuous accumulation and development of microcracks and pores inside concrete, accelerating the entry of external corrosive substances [9,10]. Due to the complexity of designing load testing devices to measure the coupling effects of corrosion and fatigue loads, there is currently relatively less research in this area compared to the study of the coupling effects of static loads and corrosion. Moreover, in the actual working environment of bridges, the erosion of corrosive substances and fatigue loads do not always occur simultaneously. Therefore, most studies use alternating test methods to investigate the combined effects of fatigue loading and corrosion. Therefore, Section 2 also briefly introduces the development of fatigue performance research and strength degradation models for reinforced concrete structures.

2. Fatigue Study of Reinforced Concrete Structures

The fatigue bending failure of reinforced concrete beams is generally caused by the fatigue fracture of tensile steel bars inside the beam. Only when there is excessive longitudinal reinforcement configuration, will the phenomenon of concrete failure in the compression zone under fatigue bending and compression loads occur. This is because in general, under the condition of consistent fatigue stress levels, the compressive fatigue performance of concrete is better than the tensile fatigue performance of threaded steel bars arranged in general beams. The fatigue fracture of tensile steel bars inside the beam is often caused by the uneven distribution and development of internal stress in the concrete section. After one tensile steel bar breaks and unloads, the stress shared by the other steel bars suddenly increases, and the deflection of the beam rapidly increases, causing the neutral axis to move upward until it loses its load-bearing capacity.

Matarov[11]. elaborated in detail on the mechanical properties of reinforced concrete bending members under reciprocating loads: the influence of steel reinforcement structure on the strength, crack formation, and stiffness of reinforced concrete bending members under reciprocating loads; Several issues regarding fatigue calculation methods for reinforced concrete structures. In reference [12], it is believed that the mechanical properties of beams exhibit three-stage characteristics under fatigue loading, and a relationship between the deflection of beams during fatigue loading and the number of loading cycles is proposed:

$$f_N = f_1\left(1.5 - 0.5e^{-0.03N^{0.25}}\right) \tag{1}$$

Where f_1 is the maximum deflection in the first cycle under cyclic loading, including shear strain effects. Lambotte and Baus [13] concluded through fatigue loading tests on reinforced concrete beams that the fatigue failure model of reinforced concrete beams differs from the static loading failure model. Meanwhile, Lambotte also believes that the fatigue strength of the concrete in the compression zone during bending of the beam is higher than the axial compression fatigue strength of the same proportioned concrete prism. Chang and Kesler [14] conducted fatigue bending tests on reinforced concrete beams at different load levels, and the test results showed that there are two different models of fatigue failure of reinforced concrete beams when the load level of fatigue loading changes from low to high. Tepfers [15] studied the effects of the duration and waveform of pulsating loads on the fatigue performance of concrete. The results indicate that the fatigue load of rectangular waves is more detrimental to the structure than that of sine waves.

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Li et al. [16] conducted static load and equal amplitude fatigue load tests on high-strength concrete beams with steel bars on the tensile side (maximum fatigue load ratio of 0.3~0.6), analyzed and studied the fatigue characteristics of reinforced concrete bending members, proposed calculation methods for concrete stress and tensile steel stress in the compression zone of the beam section during fatigue loading, and determined the design value of the fatigue strength of the steel bars. Finally, a fatigue design method for the normal section of reinforced concrete bending members under equal amplitude fatigue load was proposed. In the study of fatigue strength of reinforced concrete beams, it is generally believed that the level of fatigue stress is the main factor affecting the fatigue strength of reinforced concrete beams, while the frequency of fatigue loading and the waveform of load changes have little effect. The difference between the maximum and minimum stresses during fatigue loading - the stress amplitude - has a significant impact on the fatigue life of materials or components. When the loading frequency of fatigue loading is in the range of 0.17-5Hz, it has little effect on the anti fatigue bearing capacity of beams in air, and there is no need to distinguish and consider [17].

Many achievements have been made in the flexural fatigue performance of reinforced concrete components, but research has focused on their fatigue strength and fatigue life, and there is relatively little research on the degradation of mechanical properties during the fatigue process. There is relatively little research on the degradation mechanism of component fatigue performance based on material fatigue performance, and the analysis of degradation mechanism is not comprehensive enough.

3. The influence of load and damage on the bearing capacity of reinforced concrete components under erosion, freeze-thaw environment

Huiyunling [18] conducted a study on the static properties of steel bars in corroded concrete components and believed that at a certain corrosion rate, the mechanical properties of steel bars will deteriorate, manifested as a decrease in yield strength, a decrease in ductility, an increase in brittleness, and a decrease in nominal ultimate strength. According to research reports [19], the bending capacity of reinforced concrete beams in marine environments decreases to 81% of their original design in the short term due to the corrosion degradation caused by chloride salts. However, if this trend continues, after 50 years, their bending capacity will only remain at 20%.

Mircea D. [20] conducted experimental research on the bearing capacity of reinforced concrete subjected to long-term loads (10-12 years) and in different erosion environments (urban and offshore), and established a durability and safety model for concrete considering factors such as long-term erosion and concrete cracking. Capozuca Robert. [21] studied the effect of the expansion stress generated by the volume expansion of corroded steel bars on the bending, shear, and torsional properties of reinforced concrete components.

Abdullah A. Almusallam [22] obtained unidirectional concrete slabs with steel bars of different degrees of corrosion by accelerating corrosion with electricity, and then conducted experimental research on the flexural strength of the concrete slabs, obtaining the relationship between the deterioration of the bearing capacity of unidirectional slabs and the corrosion rate of steel bars.

4. Study on fatigue damage of reinforced concrete components under erosion, freeze-thaw environment

With the deepening of research on the fatigue problem of reinforced concrete structures, people have realized that different working environments have a significant impact on the fatigue performance of reinforced concrete structures. The corrosive environment causes severe corrosion of steel bars in reinforced concrete structures, greatly shortening the fatigue life of the structure [23]. Radian [17] conducted experimental studies on the fatigue life of RC beams in air environment, saltwater environment, and saltwater freeze-thaw environment. The results showed that under different environments, as the fatigue load level increased, the fatigue life of RC beams showed an approximately linear decreasing trend; The environment has a significant impact on the fatigue life of RC beams, and the fatigue life is significantly reduced in saltwater and saltwater freeze-thaw environments. However, the fatigue load level of the experiment was 0.41~0.92, which is higher than the fatigue stress state of ordinary RC beams during normal use. At the same time, the failure mode of the beam under different fatigue load levels also varies greatly, indicating that there are certain deficiencies in the experimental design.

Al Hammoud et al. [24] conducted monotonic and fatigue loading tests on electrically corroded reinforced concrete beams, and the results showed that the corrosion rate had a significant impact on the fatigue life of RC beams. However, the corrosion morphology of electrically corroded steel bars differed greatly from that of steel bars in RC beams in natural environments.

Wang Haichao et al. [25] conducted fatigue tests on RC beams in air, freshwater, and saltwater environments, studying the deformation and fatigue life of RC beams in these three environments. The results indicate that the fatigue process of RC beams is similar in different environments, with the shortest fatigue life of RC beams in saltwater and the longest in air. When the fatigue stress ratio is 0.55, the fatigue life of beams in air, freshwater, and saltwater environments is 2 million cycles (undamaged), 910000 cycles, and 330000 cycles, respectively.

At present, research on achieving simultaneous testing of fatigue load and corrosion is very limited. For chlorides and sulfates, as the corrosive medium is a salt solution, simultaneous testing can be achieved by fatigue loading concrete specimens in a salt solution container. But adding the influence of environmental temperature changes is very difficult. Currently, only Qiao et al. [26] and Li et al. [27] have achieved simultaneous testing of freeze-thaw cycles and fatigue loads by combining a fatigue testing machine with a temperature chamber. However, the freeze-thaw environment is a closed air environment that does not allow moisture to enter, so it cannot simulate the harshest working environment in reality.

In addition, it is generally believed that corrosion is a long-term slow development process, and the fatigue loads generated by transportation are intermittent. Therefore, some studies [28-30] suggest conducting multiple alternating simulation tests, including alternating tests of fatigue loads and freeze-thaw cycles or sulfate corrosion. However, current research on multiple alternating simulation tests using fatigue loads in corrosive environments is limited. Compared with synchronous testing, this testing method is more flexible and suitable for different corrosive environments, and even for the coupling of multiple environmental factors and fatigue loads.

5. Conclusions

At present, there have been many achievements in the research on the fatigue life of RC beams under the coupling effect of erosion environment and fatigue loading at home and abroad. However, corrosion fatigue is only one aspect of the durability problem of reinforced concrete structures under fatigue loading. In practical engineering, there are more complex comprehensive effects of erosion environment and fatigue damage, which need further research.

The research on the fatigue problem of reinforced concrete structures under erosive environment mainly focuses on the influence of environment on the fatigue life of structures, and there is relatively little research on the degradation of structural bearing capacity and durability caused by the combined effect of environment and fatigue load. Therefore, in order

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to better identify the bearing capacity and durability status of in-service reinforced concrete bridge structures, it is necessary to strengthen research in this area.

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