Research on the Fatigue Damage Mechanism of Corroded Steel Bar

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Abstract: Reinforced concrete bridge structures are prone to unpredictable brittle failure under fatigue loads, posing a serious threat to their safety. And its fatigue performance depends on the fatigue performance of the steel bars inside the concrete. At the same time, the corrosive environment in which the bridge structure is located can cause premature corrosion of the steel bars inside the bridge structure, and a certain degree of corrosion can significantly reduce the fatigue life of the steel bars. This article summarizes the current research status of fatigue damage mechanisms of steel bars in both non corroded and corroded states, analyzes the existing problems, and proposes suggestions for further in-depth research.

Keywords: Steel bar, fatigue Damage, corroded.

1. Introduction

The problem of fatigue was first discovered in the 19th century, when European researchers observed that bridge and railway components would crack due to repeated traffic loading during normal operation [1]. With the widespread use of metals in manufacturing machines, more and more metal components are experiencing failures under repeated loads. As the most commonly used building material today, steel bars are mainly used in reinforced concrete structures to withstand various tensile stresses. Among the bridge structures in service in China, reinforced concrete bridge structures are the most common. Bridge structures are subjected to long-term fatigue loads due to the passage of vehicles. Therefore, fatigue performance is one of the most important factors affecting the service life of bridge structures. The fatigue performance of reinforced concrete bridge structures mainly depends on the fatigue performance of the steel bars configured inside. In the American Association of State Highway and Transportation Officials(AASHTO specification) road test, fatigue fracture occurred in the overload test of concrete bridges [2]. Here, the steel bars in the outer beams of two reinforced concrete structures fractured after about 730000 cycles under different loads, and a comparison with laboratory data shows that their lifespan was shorter than expected The failure of concrete highway bridges is usually the result of multiple factors, and the impact of steel fatigue damage should not be underestimated. It is urgent to fully and effectively utilize resources, extend the service life of bridge structures, and reduce the maintenance costs of bridge structures. Therefore, it is urgent to study the fatigue performance of steel bars and better utilize their mechanical properties. The service environment of bridge structures is generally harsh, not only enduring the dynamic loads caused by vehicle passage for a long time, but also the working environment is generally corrosive, causing the durability of bridge structures to deteriorate faster and with significant differences.

2. Current Status of Research on Fatigue Damage of Steel Bars

The fatigue failure process of steel bars is as follows: during the fatigue loading process, microcracks are formed at the location with the highest relative resistance to local stress, and then as the number of loading cycles increases, microcracks develop into macroscopic cracks, ultimately leading to fatigue fracture. The fatigue failure of steel bars goes through three stages: crack formation, crack propagation, and instantaneous fracture. Unlike concrete, the crack formation stage is the longest in the fatigue life of steel bars.

The fatigue ultimate strength of steel bars is the maximum stress value of steel bars that can withstand 2 million cycles of fatigue stress without being damaged. The stress amplitude, which is the difference between the maximum and minimum stresses of steel bars, is the main factor affecting the fatigue strength of steel bars, while the magnitude of the minimum stress is a secondary factor [3]. Under fatigue load, deformed steel bars have irregular cross-sectional shapes, resulting in uneven stress distribution. The stress concentration at the inner corner of the steel rib root is the highest, and the relative resistance to the steel bar is the greatest. Under fatigue load, microcracks are prone to occur. The degree of stress concentration at the root of the steel rib depends on the ratio of the radius of the rib root to the height of the rib. The AASHTO recommends that for special-shaped steel bars used as load-bearing steel bars in reinforced concrete beams, when they are designed to withstand cyclic loads more than one million times, the maximum safe stress amplitude of the steel bars should be calculated using the following formula:

$$f_r = 21 - 0.33 f_{\min} + 8r/h \tag{1}$$

In the formula, f_r is the safe stress amplitude (*ksi*); $f_{\min}$ is the minimum stress, with positive tension and negative compression; 1*ksi*=1000 pounds force/square inch=6.895MPa; *r/h* is the ratio of rib root radius to rib height, usually taken as 0.3. But when the number of times the design can withstand cyclic loads is less than 1 million, there can be a higher stress amplitude, which can be calculated using the following formula:

$$\log N = 6.1044 - 0.0407 f_r - 0.0138 f_{min} + 0.0071 f_{su} - 0.566 A_s + 0.3233 \, {}^{D_r}/_{h} \quad (2)$$

N is the number of times the design can withstand cyclic loads. f_{su} is the static tensile strength of steel bars (*ksi*); A_s is the cross-sectional area of the steel bar (in^2); D_r is the diameter of the steel bar (*in*).

The Portland Cement Association (PCA) in the United States has provided a formula for the relationship between the maximum safe stress amplitude of deformed steel bars and the geometric dimensions of ribs through experiments:

$$f_r = 7.88 + 52.85(r/h) \quad (3)$$

The formula recommended by the American Concrete Institute (ACI) is:

$$f_r = 145 + 55(r/h) - 0.33 f_{\min} \quad (4)$$

The formula adopted by Japanese standards:

$$f_r = 160(1 - \sigma_{\min}/3)10\mu^{(6-\log N)} \quad (5)$$

μ is constants related to N.

The Chinese Code for Design of Concrete Structures provides the limit values of fatigue strength indicators for structures subjected to fatigue loads. For concrete, the fatigue strength design value and fatigue deformation modulus are given, while for steel, the fatigue stress amplitude limit considering the fatigue stress ratio is given. The upper limit values refer to the fatigue life of 2 million cycles under equal amplitude fatigue loads.

Similar to the current research status of concrete fatigue, the existing research results on steel fatigue mainly focus on the S-N curve equation (S is the maximum stress under fatigue loading, N is the number of fatigue loading cycles), which can only be used for engineering design. There is still a lack of basis for evaluating and detecting the bearing capacity of existing structures. Talreja and Weibull [4] studied the residual strength of metal specimens after fatigue loading, providing new ideas for the study of fatigue failure. They proposed that the residual strength of the material decreases continuously with the increase of fatigue loading cycles. When the residual strength drops to the maximum stress of fatigue loading, fatigue failure occurs, and proposed a formula:

$$R_0 = S + (R - S)/(1 - n(1+m)S^m N)^{1/(1+m)} \quad (6)$$

In the formula, R_0 is the static tensile strength, R is the residual strength after fatigue loading, S is the maximum stress under fatigue loading, and N is the number of fatigue loading cycles. The test results can only reflect the fatigue performance of the material, and there are significant differences in shape and dimensional accuracy between the steel bars in the actual structure, making it difficult to accurately reflect the actual fatigue performance of the steel bars.

Ling [5] tested the residual strength of steel bars with different diameters after fatigue loading at different times and stresses, and confirmed that the residual strength of steel bars decreases continuously with increasing fatigue loading times. Ling proposed the formula based on equation (6):

$$R = S \cdot \exp\left[\frac{\beta}{2}\left(N_f - N\right)\right] \quad (7)$$

From the above research, it can be seen that most studies on the fatigue performance of steel bars focus on fatigue strength and fatigue life, and there is relatively little research on the strength attenuation law of steel bars during fatigue loading. The existing strength attenuation models cannot be applied to engineering practice at present due to limited experimental data. There is no problem with the mechanical testing of ordinary steel bars under static loads, but there are some difficulties in the testing of steel bars under varying loads, because fatigue cracks usually occur in the area where the specimen is fixed to the jaws of the testing machine, that is, in areas with obvious notches. So, the results of these tests cannot be considered reliable and should be rejected. When testing steel bars, it is not possible to make classic shrinkage specimens of metal specimens, such as those used to test other metals, because these specimens must be tested in their factory state without any intervention in their cross-section to reflect their working performance [6, 7]. In addition, the fatigue performance of round steel bars is relatively stable, and the experimental results have little dispersion. However, the fatigue life test results of deformed steel bars have a large dispersion. Due to poor anchoring performance in concrete, round steel bars are difficult to fully exert their performance when subjected to fatigue loads in components. The anchoring performance of deformed steel bars is good, but their fatigue performance is unstable, which is a dilemma that urgently needs to be solved.

3. Static Properties of Corroded Steel Bars

The steel bars in concrete structures are prone to rusting in corrosive environments, and after rusting, their mechanical properties will undergo significant changes, bringing uncertainty to the structural performance. Therefore, many scholars have conducted research on the changes in the mechanical properties of steel bars after rusting.

In terms of statics, Hui Yunling et al. [8] conducted tensile tests on corroded steel bars extracted from concrete structures that have been in service for more than 20 years, and compared them with steel bars of different diameters and sections with different corrosion rates from other batches. The following conclusions were drawn: when the steel bar section loss rate is less than 1%, it has no effect on the various properties of the steel bars; When the loss rate of the steel bar section is between 1% and 5%, the mechanical properties of the steel bar do not change much, only the ductility decreases significantly, but still meets the requirements of the specifications; When the cross-sectional loss rate of steel bars is between 5% and 10%, the mechanical properties of the steel bars significantly decrease; When the loss rate of corroded steel bars exceeds 10%, the mechanical properties of the steel bars severely deteriorate.

Yuan Yingshu[9] obtained corroded steel bar specimens through on-site sampling, accelerated simulation of corrosion in the laboratory, and simulation production methods. Then, the specimens were subjected to tensile tests. Through comparative research and analysis, the results showed that the strength and elongation of the steel bars decreased with the increase of steel bar corrosion rate. Anlin et al. [10] used electrochemical accelerated corrosion method to produce HRB335 hot-rolled steel bars with different degrees of corrosion (quality loss rate 0-55%). Afterwards, through measurement, a functional relationship between the quality loss rate and the maximum cross-sectional loss rate was regressed. Finally, the nominal strength and elongation of the specimen were obtained through static tensile testing. The experimental results show that the nominal strength ratio of corroded steel bars to uncorroded steel bars is approximately equal to the minimum residual area ratio of corroded steel bars, and the influence of stress concentration in corrosion pits is negligible; The elongation rate of corroded steel bars decreases exponentially with the increase of maximum cross-sectional loss rate, and is significantly affected by stress concentration in the corrosion pit.

4. Fatigue Performance of Corroded Steel Bars

In terms of fatigue performance, Cao Jian'an et al. [11] collected corroded steel bar samples from the Meiji railway line for fatigue testing. The samples were taken from replaced reinforced concrete beams made in 1936. The results show that after the corrosion of steel bars, their fatigue strength is significantly reduced due to the loss of effective cross-section; The fatigue limit of corroded steel bars tends to disappear, that is, no matter how small the stress is, as long as the number of fatigue loading cycles is large enough, the corroded steel bars will be destroyed. Apostolopoulos et al. [12-14] conducted salt spray accelerated corrosion tests on S400 grade and BSt500s grade steel bars, and then conducted tensile and low cycle fatigue tests on steel bars with different degrees of corrosion. The results showed that the effective energy, fatigue life, and ductility of both types of steel bars decreased with increasing degree of corrosion.

Zhang Weiping [15] conducted fatigue tensile tests on 28 naturally corroded steel bars extracted from aged concrete components with a stress ratio of 0.1. The results showed that as corrosion developed, the logarithm of the nominal stress range of the steel bars could be approximately linearly related to the logarithm of the fatigue life. However, the fatigue life of corroded steel bars decreased significantly, and the magnitude of the decrease increased with the stress range. As the corrosion rate or stress level of steel bars increases, the number of fatigue crack sources gradually increases, and the instantaneous fracture zone area ratio increases, which explains the reasons and laws of the degradation of fatigue performance of corroded steel bars from a microscopic perspective.

Li Shibin et al. [16] conducted fatigue axial tensile tests on 7 specimens of uncorroded steel bars and 34 specimens of corroded steel bars accelerated by applied current to analyze the effects of stress amplitude and average section corrosion rate on the fatigue life of steel bars. The steel bar specimens are divided into 5 groups based on the average section corrosion rate, with a corrosion rate range of 0-20%. The research results indicate that the fatigue life of corroded steel bars significantly decreases; Compared with the steel bar specimens with an average section corrosion rate of 5%, 10%, 15%, and 20%, the fatigue life of the steel bar specimens with an average section corrosion rate of 0 decreased by 70%, 80%, 90%, and 95%; The fatigue life of corroded steel specimens approximately decays according to the law of corrosion rate index.

Hawileh [17] accelerated the corrosion of BS4449/2005 grade B500B steel bars using an acid solution, and then divided the steel bars into three groups according to different mass losses, and conducted low cycle tensile tests on each group. The results show that the yield strength, ultimate tensile strength, and ductility of steel bars all decrease with the increase of steel corrosion degree.

Fernandez [18] studied the mechanical properties of corroded or uncorroded steel bars using monotonic tensile tests and cyclic loading fatigue tests. In order to determine the main mechanical properties of artificially corroded steel bars with diameters of 10mm and 12mm, two experimental stages were conducted. The first stage includes monotonic testing, while the second stage includes high cyclic load testing. By comparing the results with the test results of uncorroded steel bars, the changes in mechanical properties are related to the degree of corrosion. In the monotonic test, 40 specimens with corrosion levels ranging from 8% to 22% were measured. In the second stage, 140 specimens with lengths ranging from 310 to 320 millimeters and corrosion levels of 8% to 28% were tested under several cyclic loads. Three different stress amplitudes (D_S=150 MPa, 200 MPa, and 300 MPa) were defined to evaluate the effect of stress amplitudes on the fatigue life of corroded steel bars. The results indicate that the depth of corrosion pits on the surface of steel bars has a greater impact on fatigue life behavior than the length of pits. When the pit length is greater than twice the pit depth, it has no effect on the fatigue life. Compared with uncorroded steel bars, the fatigue life of corroded steel bars is greatly reduced. For very small degrees of corrosion, their impact can be ignored. For high levels of corrosion, there is an exponential decrease in the number of resistance cycles. In addition, a very high degree of corrosion can significantly reduce fatigue life, regardless of the range of applied stress.

5. Conclusion

In order to achieve better anchoring performance, reinforced concrete structures generally use deformed steel bars as load-bearing steel bars, and concrete bridge structures are no exception. However, when subjected to fatigue loads, the concave convex structure on the surface of deformed steel bars will inevitably accelerate the generation and development of fatigue cracks, thereby shortening their fatigue life. Moreover, due to the processing accuracy of deformed steel bars, the consistency of their concave convex structure at the microscopic level cannot be guaranteed, resulting in significant variability in the fatigue life of deformed steel bars under high stress amplitudes, which poses difficulties for design work. When evaluating the safety and durability of concrete bridge structures, this uncertainty greatly reduces the reliability of the evaluation results. Meanwhile, if the steel bars corrode in an erosive environment, this uncertainty will be further amplified. Therefore, in the design of concrete bridge structures, efforts should be made to control the growth of fatigue stress in steel bars, and methods such as increasing the safety reserve of the bridge structure or applying prestress should be adopted to reduce the accumulation of plastic deformation of steel bars under fatigue loading.

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