Durability Assessment and Service Life Prediction of Reinforced Concrete Bridges in Coastal Areas

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Abstract

Concrete bridge structures in coastal areas generally fail to meet design expectations due to frequent heavy loads and corrosive environments. In order to further promote carbon neutrality, it is urgent to improve the service life of concrete bridge structures. Due to the limited number of existing methods for calculating and predicting service life, they cannot meet the demand. Therefore, based on the existing durability evaluation methods for concrete structures, this article proposes a service life prediction method for reinforced concrete bridge structures under the comprehensive action of load and environment based on accelerated experiments and Fick's second law. This method simulates the real working environment of bridge structures in coastal areas, and can obtain reliable evaluation results for reinforced concrete bridge structures damaged by fatigue loads and subjected to freeze-thaw cycles and seawater erosion. However, its universality still requires a large amount of reliable long-term bridge engineering service status data for verification.

Keywords

Concrete Bridge; Durability; Service Life Prediction.

1. Introduction

As an important node in the land transportation system, bridge structures have always played a crucial role in the transportation process, enduring frequent heavy loads for a long time. However, bridge structures in coastal areas, due to their highly corrosive environment, often fail to meet design expectations in terms of service life. Portland cement concrete, as the most common building material, is a stable and environmentally friendly green material. Portland cement concrete has good strength and thermal insulation performance, and does not require excessive maintenance during use. However, the energy consumption during cement production is high (4GJ/ton), and approximately 0.8 to 1 ton of CO_2 is emitted for every ton of ordinary Portland cement produced [1, 2], which has a very negative impact on the natural environment. It is urgent to achieve carbon neutrality, make more efficient use of resources, extend the service life of buildings and structures, reduce the impact of waste building materials on the environment, and lower the maintenance costs of buildings and structures. The fundamental way to fully utilize resources is to slow down the consumption rate of materials and structures. For the current stock of buildings and structures in China, it is to improve the durability of concrete structures.

For bridge structures, due to their harsher service environment compared to general buildings, long-term exposure to dynamic loads caused by vehicle passage, and generally corrosive working environments, the durability of bridge structures deteriorates faster and has significant differences. Numerous studies have shown that even in the harshest environments, the greatest threat to the durability and long-term performance of concrete bridge structures is not the weathering and erosion of the concrete itself, but rather the electrochemical corrosion of the steel bars inside the concrete [3,4]. In 1917, Wig and Ferguson [5] conducted a comprehensive investigation of concrete bridge structures in American waters and pointed out that the use of deicing salts on highway bridges posed new challenges to the durability and long-term performance of concrete bridge structures. In 1986, it was estimated that the cost value of repairing concrete bridges corroded by deicing salt in the United States was as high as $24 billion, with an annual increase of $500 million [6]. In 1998, the estimated annual cost of repairing concrete structures in Western European countries was $5 billion [7]. Internationally, the deterioration of concrete infrastructure has become one of the most serious problems.

Although the corrosion of embedded steel represents the main type of long-term performance degradation in concrete bridge structures, freeze-thaw and alkali aggregate reactions also pose challenges to the durability and long-term performance of many concrete structures. However, compared to the corrosion of embedded steel, this durability issue is easier to control in practice [8].

The large-scale construction of transportation infrastructure in China started relatively late, but many durability issues have also emerged one after another. Many concrete structural components that have been in service for many years exist on highways and railways in China, and their durability deteriorates severely, with the cracking rate further accelerating with the increase of service time. Taking Shandong Province in coastal areas as an example, a large number of highways have been built in recent years, and among these newly constructed highways, a large number of highway bridges are built in coastal areas. These highway bridges are mostly concrete structures. Due to the degradation caused by environmental erosion in coastal areas and the increase in heavy vehicle traffic brought about by economic development, they have suffered serious concrete damage, cracking, and steel corrosion after only 10 years of service [9].

Therefore, improving the durability of concrete bridge structures is an urgent problem to be solved. To improve the durability of concrete bridge structures, it is necessary to fully consider the factors that affect the durability of concrete bridge structures during design. One of the main ways to understand and master the factors that affect the durability of concrete bridge structures is to accurately evaluate the durability of existing concrete bridge structures in service. At the same time, through the durability assessment of bridge structures, technical consultation can be provided for daily management, maintenance, and reinforcement repair of bridges. Only by conducting a comprehensive and scientific evaluation of the durability of bridge structures can the service status of bridge structures be accurately determined, major safety accidents be avoided, and safe, reasonable, and economical maintenance and reinforcement plans be proposed when maintenance is needed, reducing the total life cost and providing targeted suggestions for future durability design.

2. Research Status

The existing durability evaluation methods for concrete structures mainly include empirical model method, performance similarity reference method, mathematical model method, random method, and accelerated testing method. Among them, the empirical model method uses a large amount of engineering experience knowledge to discriminate and analyze laboratory sampling and testing results, as well as on-site measurement results, to obtain durability evaluation opinions for concrete structures. It is obvious that it is not suitable for structural evaluation that applies new materials or is in a new environment; The performance similarity reference method is used to predict the structural life under similar conditions by summarizing a large amount of life data of approximate environments and materials. However, the prediction accuracy depends entirely on the similarity. Due to the complexity of the environment, it is difficult to achieve the desired degree of approximation between different environments. Moreover, bridge structures with similar environments may not have similar working environment intensity, which increases the uncertainty of the prediction results; The mathematical model rule is to establish a model of materials and environmental parameters through certain mathematical formulas. Due to the complexity and correlation of material properties and environmental effects, the reliability of the predicted results is not very high; Random methods include reliability methods and methods that combine statistical and deterministic models. The limitation of random methods is that the factors and interactions that affect the service life of concrete structures still need further research. The accelerated testing method based on simulating real environment experiments is currently a more direct and reliable method, but its limitation is the long testing period and limited applicability of the results [10].

Due to the diverse working environments of bridges in coastal areas, predicting their service life also requires consideration of specific influencing factors. Many scholars [11, 12] have established a modified model of Fick's second law by considering one or more factors that affect the diffusion coefficient of chloride ions. This article will predict the service life of concrete structures based on the chloride ion concentration and diffusion coefficient obtained from seawater erosion and freeze-thaw cycle tests on fatigue damaged reinforced concrete beams completed by the author [13, 14].

3. Durability Assessment Method for Reinforced Concrete Bridge Structures under the Combined Action of Load and Environment

The durability evaluation method for reinforced concrete bridge structures under the combined effects of load and environment proposed in this article is based on accelerated testing. To establish a durability evaluation model for concrete structures based on experiments, the following issues need to be determined: 1) Durability should be analyzed based on the environment in which the structure is located: China's durability design specifications for concrete structures stipulate that the durability of concrete structures should be designed according to the category and level of environmental effects in which they are located. 2) The durability study of concrete structures should adopt a combination of Holism and Reductionism based on existing testing methods and conditions. Reduction theory can decompose the durability problem of concrete under the influence of complex factors into simple and specific factors for in-depth research; On this basis, following the holistic approach, a durability degradation model for materials, components, and structures can be proposed, which can take into account the interaction between various factors on the basis of a single factor model The durability of concrete mainly depends on its microstructure, namely the interface between cement hydration slurry, aggregates, and cement hydration slurry. The deterioration of durability of reinforced concrete bridge structures is mainly due to damage caused by cyclic loads caused by traffic, and these damages are mainly due to changes in the interface transition zone.

In concrete structures under chloride erosion environment, apart from the chloride ions contained in the concrete itself, other chloride ions entering the interior of the concrete from the environment first concentrate on the surface of the concrete and continuously accumulate, and then invade the interior of the concrete through diffusion, convection, and other means. Usually, the higher the concentration of surface chloride ions, the more chloride ions diffuse into the interior of the concrete. The variation in the concentration of chloride ions Cs on the surface of concrete is mainly related to the age of the concrete, the adsorption performance of chloride ions by the material properties of the concrete itself, and the environmental conditions in which it is located (such as the concentration of chloride salts in seawater, the position of the structure, etc.). During a certain period of time when chlorine erosion begins, the Cs value gradually increases over time. However, as the erosion time increases, the concentration of chloride ions on the surface of concrete should remain relatively constant after a certain period of time.

The study of the diffusion behavior of chloride ions in concrete was first conducted by Collepardi in 1970. Collepardi first published the results of chloride ion diffusion based on Fick's second law in 1972 [15]. Fick's second law assumes that the pores in concrete are uniformly distributed, and the diffusion of chloride ions in concrete is one-dimensional. The concentration gradient only changes along the direction from the exposed surface to the surface of the steel reinforcement. The surface concentration of concrete is constant, and concrete is a semi infinite medium.

According to Fick's second law, the chloride ion concentration formula is shown in equation (1),

$$\frac{\partial C}{\partial t}=D\frac{\partial^2 C}{\partial x^2} \tag{1}$$

In the formula, C is the concentration of chloride ions, generally expressed as the percentage of chloride ions in the mass of the cementitious material; T is the time that the concrete structure is exposed to chlorine erosion environment; D is the diffusion coefficient of chloride ions; X is the depth of chloride ion erosion. Assuming that the concentration of chloride ions on the surface of concrete reaches a constant saturation after a certain period of time, and the diffusion coefficient of chloride ions is a certain value, the boundary and initial conditions of equation (1) can be obtained:

Boundary conditions: $C_{(x=0,t)}=C_s$

Initial conditions: $C_{(x,t=0)}=C_0$

From this, the analytical solution of equation (1) can be obtained:

$$C_{(x,t)}=C_0+\left(C_s-C_0\right)[1-erf(\frac{x}{2\sqrt{D_c t}})] \tag{2}$$

In the formula: $C_{(x,t)}$ is the chloride ion concentration, C_0 is the initial chloride ion concentration of concrete, C_S is the surface chloride ion concentration, and D_c is the diffusion coefficient of concrete during the time period t. The diffusion coefficient D_c is influenced by various factors such as time, and the predicted results based on a certain value of D become too conservative, which cannot accurately reflect the actual diffusion of chloride ions in concrete. From many research results [14,16], it can be seen that fatigue damage and freeze-thaw cycles increase the chloride ion diffusion coefficient of concrete, and these two factors have a coupled effect. Therefore, under the freeze-thaw cycle of seawater, the chloride ion diffusion coefficient of concrete in fatigue damaged reinforced concrete structures is:

$$D(t)=F_d\cdot F_t\cdot D_0\cdot\left(\frac{t_0}{t}\right)^m \tag{3}$$

In the formula, Fd is the amplification factor of chloride ion diffusion in concrete caused by fatigue damage, F_t is the amplification factor of chloride ion diffusion in concrete caused by freeze-thaw cycles, D_0 is the chloride ion diffusion coefficient of concrete at 0 exposure time to chloride erosion environment (m^2s^{-1}), t_0 is the age of concrete at the end of curing (s), m is the time factor, constant, which is related to the mix proportion of concrete and environmental temperature. The time factor m determines the rate of change of the instantaneous diffusion coefficient $D_{(t)}$ over time t. The value range of m is [0, 1].

$$\text{Let } T=\int_{t_0}^{t}D\left(x\right)\cdot dx \tag{4}$$

By replacing $D_c \cdot t$ in equation (2) with T in equation (4), we can obtain:

$$C_{(x,t)} = C_{(x,0)} + \left(C_s - C_0\right)[1 - erf(\frac{x}{2\sqrt{T}})] \tag{5}$$

When the concentration of chloride ions on the surface of the steel bar reaches the critical concentration, substituting $C_{(a_s,t)} = C_c$ into equation (5) can determine the time of corrosion occurrence. For concrete structures under the wet dry cycle environment of seawater, the diffusion model *D* (t) can be regarded as a continuous function, and the time of corrosion occurrence can be directly obtained through equation (5), thus obtaining the service life of reinforced concrete structures.

The diffusion model *D* (t) in the above methods requires a large amount of accelerated experiments and comparison and correction with actual cases for different environments, work intensities, and service life. Therefore, there is still a lot of research work that needs to be completed as soon as possible.

4. Conclusion

Due to the harsh working environment, the durability of bridge structures deteriorates severely. Most of the existing durability assessment methods for concrete bridge structures are not accurate or applicable. The durability evaluation method for reinforced concrete bridges proposed in this article simulates the real working environment of bridge structures in coastal areas. For reinforced concrete bridge structures damaged by fatigue loads and subjected to freeze-thaw cycles and seawater erosion, reliable evaluation results can be obtained. However, its universality still requires a large amount of reliable long-term bridge engineering service status data for verification.

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