Durability evaluation and reinforcement design method of municipal bridges under extreme climate

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Abstract: Under the background of global climate change, extreme weather events occur frequently, and municipal bridges are facing increasingly severe durability challenges. Focusing on the durability evaluation and reinforcement design of municipal bridges in extreme climate, this paper constructs a dynamic evaluation system integrating multi-source data perception, climate-structure coupling deterioration modeling and intelligent early warning, and puts forward an adaptive reinforcement design method based on the concept of "toughness reinforcement". Through the integration of sensor network and BIM technology, the digital twin of bridge is established to realize real-time monitoring and evaluation of environmental action and structural response; By introducing machine learning algorithm, the early warning model of durability grade is constructed, and the intelligent classification and life prediction of bridge service state are realized. Propose differentiated reinforcement strategies for different climate threats, and combine technologies such as carbon fiber reinforced plastic (CFRP) wrapping, cathodic protection, and expansion joint upgrades to enhance the disaster resistance and repairability of bridges in extreme weather conditions. Engineering case analysis shows that this method can effectively identify the trend of structural durability degradation, significantly improve the service life and resilience level of bridges, and provide technical support for smart bridge maintenance and resilient urban construction.

1. Introduction

With the intensification of global climate change, the frequency and intensity of extreme climate events have increased significantly. As the key node of urban traffic network, municipal bridge has been exposed to complex climate environment for a long time, and its structural safety and durability are facing severe challenges. For example, the torrential rain in Zhengzhou in 2021 caused many municipal bridges to suffer from diseases such as bearing void and beam displacement; Concrete spalling and steel corrosion are common problems in bridges in northern cold areas due to freeze-thaw cycles. However, the life span of coastal bridges is greatly shortened due to chloride ion erosion [1]. These cases show that the traditional bridge design code has been difficult to adapt to the dynamic role of extreme climate, and it is urgent to build a durability evaluation and reinforcement system with stronger climate adaptability.

The durability of municipal bridges is directly related to the toughness of urban transportation system. Extreme weather can significantly shorten the service life of bridges by accelerating material deterioration, changing structural mechanical properties and inducing chain disasters [2]. If effective measures are not taken in time, extreme weather may lead to sudden failure of bridges, resulting in significant economic losses and casualties [3]. Therefore, it is not only an urgent need to ensure the safety of urban infrastructure, but also an important way to promote the construction of resilient cities and achieve the goal of "double carbon" to study the evaluation and reinforcement methods of bridge durability under extreme climate.

In order to solve the above problems, this paper takes municipal bridges as the research object, constructs a method system of durability evaluation and reinforcement design for extreme climate adaptability, and reveals the coupling mechanism of extreme climate, material deterioration and structural response. A dynamic evaluation model based on multi-source data fusion is proposed to

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realize real-time early warning of bridge durability grade. Develop economical and efficient reinforcement technology to improve the disaster resistance of bridges in extreme climate.

2. Evaluation method of bridge durability under extreme climate

2.1 Multi-source information perception and data fusion

By laying sensor networks in key parts of the bridge, multi-dimensional environmental data such as temperature, humidity, wind speed, chloride ion concentration and structural mechanical response data such as displacement, strain, vibration frequency and crack development are collected in real time, and the service state of the bridge under extreme climate load is fully captured. With the help of the Internet of Things (IoT) and BIM technology, and by integrating multi-source information such as environmental monitoring, structural response, design drawings, historical inspection records and manual inspection, the digital twin of the bridge is constructed by using data fusion algorithms such as Kalman filtering and machine learning, and the bridge health database covering the whole life cycle is integrated to realize accurate perception and dynamic evaluation of the bridge state [4].

2.2 Climate-structure coupling deterioration model and dynamic analysis

According to different extreme climatic conditions, the coupling mechanism model of "climate action-material degradation-performance degradation" is constructed, and the internal relationship between environmental factors and structural performance degradation is deeply revealed. In the scene of rainstorm or flood, the foundation hollowing caused by water scouring, bearing failure and steel bar corrosion caused by water infiltration are mainly simulated. In the freeze-thaw cycle environment, a frost heaving damage model considering the pore saturation of concrete is established to predict the degradation trend of surface peeling depth and structural stiffness [5]; In view of the high temperature and drought conditions, the effects of concrete creep intensification, expansion joint function failure and material thermal fatigue accumulation are analyzed. In salt fog or high chloride ion concentration area, based on Fick's second law and its modified model, the diffusion and enrichment process of chloride ion in concrete is simulated, and the failure time of passive film on steel bar surface is dynamically predicted [6].

By inputting the real-time collected environmental and structural response data into the coupling deterioration model, the driving system carries out real-time or periodic simulation analysis, and dynamically updates the durability state of the bridge components and the overall system. This method can quantitatively evaluate the current remaining life, reliability index and other key parameters, realize the intelligent transformation from the traditional mode of "regular inspection and post-event maintenance" to "real-time diagnosis and predictive maintenance", and significantly improve the safety management level and maintenance efficiency of bridges in complex climate environment.

2.3 Early warning of durability grade based on intelligent algorithm

Based on the three levels of materials, components and systems, a bridge durability evaluation system with multi-dimensional indexes is constructed, and the state quantification is realized by determining the threshold and weight of each index. On this basis, the real-time monitoring data and simulation analysis results are combined, and the durability classification model is trained by machine learning or deep learning algorithm, so as to realize automatic identification of the deterioration mode and development trend of bridges, grade the current state as "good, slightly damaged, moderately damaged and dangerous", and predict the performance evolution path in combination with future climate scenarios, and dynamically issue grading warnings such as blue, yellow, orange and red, so as to provide scientific and forward-looking decision support for bridge management and maintenance [7].

3. Design method of adaptive reinforcement in extreme climate

3.1 Design concept and principle of toughness reinforcement

The design of ductile reinforcement adheres to the concept of changing from "resisting conventional loads" to "adapting to extreme weather events", emphasizing that the structure can still maintain overall stability, prevent collapse and have the ability of rapid repair after encountering extreme weather; Based on the weak links and dominant climate threats identified by durability assessment, the differentiated and customized reinforcement strategy of "one bridge, one policy" is implemented, and the initial investment, operation and maintenance expenses and social costs caused by traffic interruption are comprehensively considered in the scheme comparison, so as to achieve the optimal balance of safety, functionality and economy in the whole life cycle.

3.2 Adaptive reinforcement technology for different climate threats

3.2.1 Anti-rainstorm/flood erosion

In view of the erosion risk caused by rainstorm and flood, reinforcement measures focusing on foundation protection and structural stability improvement are adopted [8]. Strengthen the anti-scouring ability of riverbed by riprap, gabion and anti-scouring blanket, or set diversion facilities to adjust the direction of water flow to reduce the direct impact on pier foundation; At the same time, anti-falling beam systems such as dampers, beam coupling devices and anti-falling beam stops are installed to effectively limit the abnormal displacement of the superstructure under flood impact, prevent the beam from falling off and ensure the overall stability of the bridge.

3.2.2 Freeze-thaw and chloride ion erosion

To address the combined threats of freeze-thaw cycles and chloride ion erosion, the focus is on implementing durability improvement technologies that combine concrete protection with steel reinforcement corrosion prevention. Using high-performance fiber-reinforced polymer (FRP) to wrap the pier column, spraying waterproof and weather resistant coating or applying silane impregnating agent to block the path of moisture and chloride ion penetration [9]; Implement cathodic protection on corroded steel structures to suppress the process of electrochemical corrosion; Using new toughness materials such as ECC (high ductility cement-based composite material) for local repair, improving the crack resistance and self-healing ability of components, and delaying the development of deterioration.

3.2.3 Adapt to extreme temperature changes

In the extreme temperature change environment, the structural structure is optimized to adapt to the frequent thermal expansion and cold contraction effects. Focus on replacing or upgrading expansion joints with large displacement to ensure their normal expansion and contraction under the condition of alternating high and low temperatures, and avoid excessive temperature stress inside the structure; The bearings are updated, and seismic bearings or damping bearings with strong weather resistance and excellent horizontal deformation ability are adopted, which not only meet the daily temperature deformation requirements, but also provide additional energy consumption and restraint capacity under sudden loads such as floods and earthquakes, and improve the overall adaptability and safety of the bridge.

3.3 Integrated intelligent reinforcement and long-term monitoring

In the process of bridge toughness reinforcement, the integrated design of "reinforcement-monitoring" is implemented, and the sensor network is embedded or integrated at the same time of structural reinforcement, so as to realize real-time tracking and data acquisition of the long-term performance of the reinforced parts, effectively verify the reinforcement effect and provide scientific basis for subsequent maintenance decisions; Modular and standardized design is adopted for vulnerable components such as bearings and expansion joints, so as to improve the detectability and replaceable of components, ensure that the detection and replacement can be completed quickly after extreme events, shorten the maintenance cycle, minimize traffic interruption, and realize the coordinated improvement of bridge safety performance and operation and maintenance efficiency.

4. Engineering case analysis

Taking the "Binhai Avenue Overpass", a prestressed concrete continuous box girder bridge in a coastal city in eastern China, as an example, this paper analyzes it. Built in 2005, the bridge has been eroded by ocean salt fog all the year round and has been hit by storm surges caused by typhoons many times. In recent years, routine inspection has found that there are longitudinal cracks in the bottom plate of the main girder, local concrete peeling off in the pier area, and obvious signs of steel corrosion. In this study, it was specially monitored and evaluated for one year, and targeted reinforcement was implemented.

Firstly, a sensor network is set up to monitor the chloride ion concentration, concrete humidity, temperature and steel bar potential in the pier area. Based on the chloride ion erosion model, the chloride ion concentration distribution in the pier protective layer is predicted to evaluate the corrosion risk of steel bars. Through core sampling and testing, the measured data of chloride ion concentration in concrete at different depths are obtained to verify and calibrate the model. Table 1 below shows the comparison between the measured values of chloride ion concentration at different depths from the surface of pier No.3 and the predicted values of the model. The calibrated model can well reflect the chloride ion invasion.

Table 1 Comparison table of chloride ion concentration (mass percentage, accounting for cement content) of pier No.3

Depth (mm)	Measured value (%)	Model Initial Predicted Value (%)	Predicted value after model calibration (%)
10	0.45	0.38	0.44
20	0.28	0.21	0.27
30	0.15	0.11	0.14
40	0.08	0.05	0.07

Based on the calibrated model, it is predicted that the reinforcement in the pier column will reach the critical corrosion chloride ion concentration threshold (0.05%) within two years, and the early warning of durability level will be upgraded from yellow (general) to orange (poor), so reinforcement measures are urgently needed (see Figure 1).

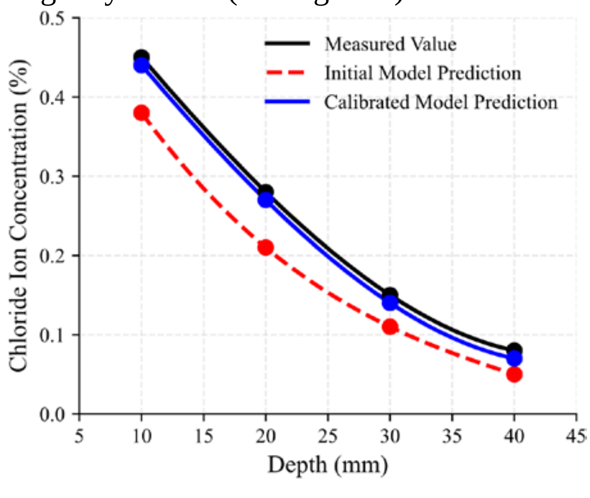

Figure 1 Chloride ion concentration distribution curve

Aiming at the main durability problem of chloride ion erosion and steel corrosion, according to the differentiated reinforcement strategy, a comprehensive reinforcement scheme with "blocking erosion and controlling corrosion" as the core is formulated. Firstly, the surface treatment of the structure is carried out, including pressure grouting of cracks, chiseling of deteriorated concrete and rust removal and corrosion prevention of steel bars; Subsequently, the pier is strengthened with CFRP, and the bearing capacity of the structure is improved by using the high tensile strength of CFRP, while its dense structure effectively blocks the further invasion of chloride ions and moisture. Finally, a weather resistant protective coating is applied to the outer surface of CFRP to enhance the overall reinforcement layer's resistance to UV aging, improve long-term durability, and form a long-term protection system that integrates structural enhancement and environmental protection. Fiber Bragg Grating (FBG) strain sensors are pre embedded in the reinforcement area for long-term monitoring of strain changes in CFRP and evaluation of reinforcement effectiveness.

After the reinforcement is completed and a typhoon season passes, it is verified by sensor data and retest, and the effect is remarkable. The internal humidity of pier concrete remained stable and did not increase. The monitoring of reinforcement potential shows that the corrosion activity has been effectively suppressed. As shown in Table 2 below, the natural frequency of the strengthened structure has been improved, indicating that the overall stiffness has been restored to some extent and the reinforcement effect is good.

Table 2 Comparison of dynamic characteristics of bridges before and after reinforcement

Parameter	Before reinforcement	After reinforcement (3 months)	Rate of change
First-order vertical frequency (Hz)	2.15	2.23	+3.7%
First-order transverse frequency (Hz)	1.88	1.93	+2.7%

The dynamic evaluation method based on multi-source data fusion can accurately identify the weak links of bridge durability in extreme climate and realize effective early warning. According to this, the targeted reinforcement design scheme has correct technical route and remarkable effect, which significantly improves the ability of the bridge to resist the harsh coastal climate environment and provides a useful reference for the management and reinforcement of similar bridges.

5. Conclusion

Through multi-source information perception and data fusion technology, the response data of environment and structure are collected in real time, and the digital twin of bridge is constructed, which realizes accurate perception and dynamic evaluation of bridge state. Based on the coupling mechanism model of "climate action-material degradation-performance degradation", the degradation mechanism of bridges under different extreme weather conditions is deeply analyzed, and the automatic early warning of durability grade is realized by using intelligent algorithm. In terms of reinforcement design, different reinforcement strategies are put forward according to different climate threats, including technical measures such as resisting rainstorm/flood erosion, freezing and thawing and chloride ion erosion, and adapting to extreme temperature changes, and the integrated design of "reinforcement-monitoring" is implemented to ensure the long-term and maintainability of reinforcement effect. The engineering case analysis shows that this method can effectively identify the weak links of bridge durability, and the resistance of the bridge is significantly improved after the targeted reinforcement, which provides a useful reference for the management and reinforcement of similar bridges. This study provides scientific and forward-looking decision support for the safe operation and maintenance of municipal bridges in extreme climate, and is of great significance to promoting the construction of resilient cities.

References

[1] Fan Zhenhuan. Analysis of the Causes of Beam Displacement in a Bridge and Countermeasures for Correction and Reinforcement[J]. Science and Technology Innovation, 2025, (17): 175-178.

[2] An Pinghe, Li Zhaoqi. Stress Analysis and Reinforcement Scheme Study of Fenghe Bridge Based on Riverbed Erosion[J]. Transportation Science and Management, 2025, 6(16): 56-58.

[3] Zhang Maogang. Seismic Performance and Reinforcement Techniques of Reinforced Concrete Bridges[J]. Popular Standardization, 2025, (15): 40-42.

[4] Sun Weirong, Tian Hui, Wang Chong. Research on New Prestressing Technology in Emergency Reinforcement of Highway Bridge Engineering[J]. Transportation Science and Management, 2025, 6(15): 67-69.

[5] Li Wanjun. A Brief Discussion on the Cost Compilation of Bridge Strengthening and Maintenance Projects[J]. Transportation Science and Management, 2025, 6(15): 171-173.

[6] Chen Minggui, Hou Zhifeng. Preparation and Performance Study of Dual-Mixed Modified Epoxy Structural Adhesive for Bridge Structure Strengthening[J]. Adhesion, 2025, 52(08): 12-15.

[7] Wang Shuo, Hou Jinde. Preparation and Performance of a New Modified Epoxy Adhesive for Bridge Strengthening[J]. Adhesion, 2025, 52(08): 32-35.

[8] Lu Haitao. Practical Discussion of Prestressing Construction Technology in Municipal Bridge Engineering[J]. Sichuan Building Materials, 2025, 51(02): 116-118.

[9] Meng Fanta, Zhang Xiuling. Study on Anti-Overturning Verification and Reinforcement Design of Single-Pier Bridge[J]. Jiangxi Building Materials, 2024, (12): 204-206.