Durability evaluation for existing railway engineering: a review

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Abstract

Purpose – This study aims to analyze the factors, evaluation techniques of the durability of existing railway engineering.

Design/methodology/approach – China has built a railway network of over 150,000 km. Ensuring the safety of the existing railway engineering is of great significance for maintaining normal railway operation order. However, railway engineering is a strip structure that crosses multiple complex environments. And railway engineering will withstand high-frequency impact loads from trains. The above factors have led to differences in the deterioration characteristics and maintenance strategies of railway engineering compared to conventional concrete structures. Therefore, it is very important to analyze the key factors that affect the durability of railway structures and propose technologies for durability evaluation.

Findings – The factors that affect the durability and reliability of railway engineering are mainly divided into three categories: material factors, environmental factors and load factors. Among them, material factors also include influencing factors, such as raw materials, mix proportions and so on. Environmental factors vary depending on the service environment of railway engineering, and the durability and deterioration of concrete have different failure mechanisms. Load factors include static load and train dynamic load. The on-site rapid detection methods for five common diseases in railway engineering are also proposed in this paper. These methods can quickly evaluate the durability of existing railway engineering concrete.

Originality/value – The research can provide some new evaluation techniques and methods for the durability of existing railway engineering.

Keywords Durability assessment, Existing railway engineering, Evaluation techniques

Paper type Research paper

1. Introduction

Railway engineering is a key transportation infrastructure that affects the development of China's national economy and the quality of people's lives. As of 2021, the operating mileage of railways in China has exceeded 150,000 kilometers, including over 40,000 kilometers of high-speed railways, accounting for more than 70% of the world's total. The "four vertical and four horizontal" high-speed rail network has been fully completed, and the "eight vertical and eight horizontal" high-speed rail network has been densified. The Beijing-Shanghai high-speed railway, Beijing-Tianjin intercity railway and Beijing-Zhangjiakou high-speed railway have achieved normalized operation at a high standard speed of 350 km/h. China has become the only country in the world to achieve commercial operation of high-speed railways at a speed of 350 km/h (Lu, 2013; Gao, 2010; Zhao, Xiao, & Xiao, 2016).

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With the continuous advancement of infrastructure construction in China, the stock of railway engineering is still increasing. Among them, the early railway structures that have reached or exceeded their designed service life require durability and reliability assessment to determine their continued safety for use. There are still some durability problems of some structures under the coupling effect of environment and load, and durability reliability assessment needs to be conducted to guide subsequent maintenance and repair. Therefore, conducting a systematic analysis of the durability reliability of existing railway engineering and proposing the corresponding evaluation method is of great significance for ensuring the durability of the existing railway structures. However, the standard system for durability evaluating of existing structures in the field of railway engineering in China is still incomplete, and there is still a lack of durability reliability evaluation methods. Therefore, the research purpose of this article is to analyze the factors affecting the durability of existing railway engineering, sort out the existing methods for evaluating the durability of railway engineering and provide technical support for the durability evaluation of railway engineering in China.

1.1 Research status

The increasingly prominent issue of durability of concrete structures has attracted the attention of relevant institutions and researchers in civil engineering industry around the world. Various academic institutions have also established more and more academic exchanges and experimental research on the durability of concrete structures. The research on the durability of concrete structures can be traced back to the 1930s and 1940s, but has only received widespread attention in the past decade or so.

1.1.1 International research status. In 1991, American Concrete Institute (ACI) in the United States of America proposed the latest research report on "Resistance Evaluation of Existing Concrete Buildings", proposing detailed methods and steps for experimental inspection (ACI Committee, 1991). The Federal Highway Administration of the United States of America has developed a plan to study the durability testing of bridge decks and the protection against steel corrosion. The Ministry of Construction of Japan has organized the research of "Building Durability Improvement Technology" since 1980 and submitted a summary report of research results in 1985. Since 1986, it has successively published the "Building Durability Series Regulations". The Japanese Architectural Society released the "Guidelines for Investigation, Diagnosis, and Maintenance of Building Status" in 1992. In the same year, the European Concrete Commission issued the "Design Guidelines for Durable Concrete Structures", which reflects the current level of research on the durability of concrete in Europe (Lu, 1997). In 1993, International Association for Bridge and Structural Engineering (IABSE) held an international academic conference on structural residual capacity in Copenhagen, Denmark (Ren, Qian, & Nie, 2002). The International Conference on Durability of Building Materials and Components in Europe has been held every three years since 1976.

1.1.2 Research status in China. The durability of reinforced concrete structures is gradually receiving attention in China. In April 1990, the Ministry of Construction organized the establishment of the National Committee for Building Appraisal and Reinforcement. The Concrete Structure Durability Study Group of the National Reinforced Concrete Standard Technical Committee was established in 1991. The Concrete Durability Professional Committee of the Concrete and Prestressed Concrete Society of the Chinese Civil Engineering Society was also established in November 1992. The Science and Technology Forum on "Safety and Durability of Civil and Structural Engineering" was organized by the Key Laboratory of Structural Engineering and Vibration Education of Tsinghua University in 2001 (Chen, 2003). This forum analyzed the status of safety and durability in civil engineering structures in China, exchanged research results in this field in recent years, explored major issues and response approaches that urgently need to be addressed and actively proposed suggestions. The above suggestions will provide important references for relevant departments in China to formulate or revise relevant technical policies or standards.

Qu and Che *et al.* proposed criteria for the repair and scrapping of existing bridge beams and optimization methods for the economic service life of bridges as early as 1996 (Qu & Che, 1996). Jiang *et al.* conducted reliability analysis on existing railway concrete bridges and estimated the failure probability of components during their remaining service life based on the proportional relationship between the failure probability during the residual service life (Jiang & Che, 1998); Liu *et al.* studied the resistance probability model of existing railway bridge structural components and conducted a systematic study on time-varying reliability evaluation of existing bridges based on detection data from multiple existing bridges (Liu & Zhang, 2001). Guo *et al.* used Carlo numerical simulation method to calculate the structural reliability of Runyang Yangtze River Bridge under random variables such as temperature, wind, vehicle load and vehicle impact (Guo & Li, 2005). Lv *et al.* applied random reliability theory to study the load probability model, resistance probability model, reliability evaluation process and reliability calculation method of in-service concrete bridges and proposed a reliability analysis method for in-service concrete bridges based on the probability of load occurrence (Lv, Ren, & He, 2005).

1.2 Existing problems and deficiencies

Based on the above analysis, domestic and foreign scholars have conducted comprehensive and in-depth exploration on the factors affecting the durability of concrete structures, improvement technologies and guarantee measures after nearly 40 years of research and have established a relatively complete technical system for ensuring the durability of concrete structures. However, research on durability evaluation techniques for existing concrete structures is still in its early stages, and the systematic nature of related research results still needs to be strengthened. Based on these researches, this article will systematically analyze the main factors that affect the durability and reliability of existing railway structures, clarify the main evaluation methods of existing railway structures and provide technical support for improving the durability and reliability of existing railway engineering.

2. Main influencing factors on the durability of railway engineering

2.1 The influence of concrete body

2.1.1 Raw materials. Cement, aggregates, water and admixtures are the main raw materials that make up concrete. The performance of these raw materials is a key factor affecting the performance of the concrete. Among them, cement is an important raw material for ensuring the strength and durability of concrete, and the national standard GB175-2007 "General Portland Cement" sets clear requirements for the performance of cement used in concrete (Standardization Administration of China, 2007). In addition to meeting the standard requirements for strength, the content of magnesium oxide and sulfur trioxide in cement is also an important factor affecting the volume stability of cement. Its content has a significant impact on the volume stability of concrete. The boiling method is usually used to test the stability of cement. Ensure that under high temperature boiling conditions, the volume change of the cement hardened body is uniform, and there are no problems with poor stability such as expansion, cracking and warping of the cement stone. The content of alkali metals such as potassium and sodium in cement is also a key factor affecting the performance of concrete. Due to the potential alkaline activity of aggregates in concrete, aggregates with alkaline activity will react with alkali metals and water in cement to generate expansive hydration products. The hydration product will directly cause volume expansion and even cracking of the cement paste. Therefore, controlling the alkali metal content in cement is of great significance in reducing the risk of alkali aggregate reaction in concrete.

The volume of aggregates in concrete exceeds 80% and is an important component of concrete. Therefore, the performance of coarse and fine aggregates is an important factor affecting the durability of concrete. For coarse aggregate, the alkali activity of the aggregate is the key factor affecting the durability of concrete. Similar to the alkali content in the cement mentioned earlier, the alkali metals contained in the aggregate will also cause alkali aggregate reaction problems during concrete service. Therefore, strict control of the alkali content in aggregates is of great significance in reducing the risk of alkali aggregate damage in concrete. The Cl^- content in coarse aggregate is an important cause of steel corrosion in concrete structures and controlling Cl^- in coarse aggregate plays an important role in reducing the risk of steel corrosion in reinforced concrete. For fine aggregates, their requirements for alkali activity and Cl^- content are consistent with those of coarse aggregates.

Admixtures are one of the most important components of modern concrete, and with the progress of material technology, the types and functions of admixtures are gradually increasing, including water reducing agents, air entraining agents, slump retention agents, etc. Overall, the use of new chemical admixtures is beneficial for ensuring the durability of concrete. However, the use of some chemical admixtures will introduce harmful ions into concrete, which will have a certain impact on the durability of the concrete. For example, some admixtures will significantly increase later shrinkage deformation after use, while some admixtures will introduce chloride ions or alkali metals into the concrete after use. The above effects will to some extent affect the long-term durability of concrete. Therefore, China's national and industry standards have put forward clear requirements for the content of harmful ions and shrinkage deformation in chemical admixtures to regulate the use of chemical admixtures in concrete.

2.1.2 Mix proportion. The mix proportion is an essential factor determining the workability, mechanical properties and durability of concrete. The scientific and reasonable design of the mix proportion will effectively ensure the safe and durable service of concrete structures. However, the durability issues of railway engineering structures due to unreasonable mix design are constantly emerging, which directly affects the service performance of railway engineering structures. Taking the concrete of railway bridge piers as an example, the concrete will release heat due to hydration after casting. Due to the large volume of bridge pier bodies and the high cumulative heat release of concrete, the core temperature can usually reach 60–70 ℃, while the ambient temperature is usually around 20 ℃. Under such a large temperature gradient, the concrete of the bridge pier body is prone to cracking. Therefore, reducing the hydration temperature rise from the perspective of concrete mix design is an important technical means to reduce the risk of cracking in large volume concrete of bridge pier bodies. The above technology is also applicable to the construction of large volume concrete structures such as tunnel lining.

2.1.3 Construction technology. The construction process of concrete is also an important factor affecting its long-term durability, including pouring, vibration, curing and other processes. For concrete components with larger volumes or complex shapes, pouring and vibration techniques are the key factors affecting the quality of concrete formation. The long-term durability of concrete is greatly affected by the quality of formation. Therefore, for typical concrete structures such as railway bridge piers and tunnel secondary lining, the pouring and vibration techniques have a significant impact on their durability. The use of scientific construction techniques such as layered pouring and multi zone vibration will significantly improve the compactness of concrete, which is beneficial for improving its long-term durability. Concrete surface maintenance is another key factor in ensuring its long-term durability. And with the continuous development of maintenance technology, there are more and more diverse methods of concrete surface maintenance. A series of new maintenance technologies have emerged, including permeable template cloth, moisturizing maintenance film and so on. However, the above maintenance techniques still need to be scientifically designed based on the characteristics of the concrete body being cured and the environmental characteristics (Wang, 2021; Wang, Xie, & Zhong 2022a, b).

2.2 The influence of environment

2.2.1 Carbonization environment. Carbonization is the process in which calcium compounds (such as ettringite) in concrete react with carbon dioxide in the environment to generate calcium carbonate and water. This process will cause the alkaline substances in the concrete to be neutralized, resulting in a decrease in the pH value of the concrete. The impact of carbonization on the durability of concrete can be divided into two aspects. On the one hand, carbonization will cause a decrease in the pH value of the environment in which the steel bars are located in the concrete, resulting in their surface becoming dull and making the steel bars more prone to corrosion. This is the disadvantage of carbonization on the durability of concrete; On the other hand, carbonization will densify the surface area of concrete, thereby reducing the migration rate of harmful ions from the outside to the inside of the concrete to a certain extent and improving the frost resistance of the concrete to a certain extent. This is the advantage of carbonization on the durability of concrete. However, carbonation has a limited effect on improving the compactness of concrete, while its impact on steel corrosion is more severe (Peng, Jiang, & Ban, 2023). Therefore, the carbonization resistance of concrete should be improved from the perspective of strengthening the compactness of the concrete body, thereby improving the carbonization resistance of railway structural concrete.

2.2.2 Chloride environment. Chloride ions are one of the important factors affecting the durability of concrete. For marine environment concrete structures, the impact of chloride ions on the durability of reinforced concrete structures should be particularly considered. The impact of chloride ions on the durability of concrete structures mainly includes the impact of chloride ions on concrete strength and the impact of chloride ions on accelerating steel corrosion. Specifically, when chloride ion intrudes into the concrete, it will form a chloride ion penetration layer in the concrete and react with the aluminate in the concrete to generate gel type hydration products, thus destroying the microstructure of the concrete and reducing its mechanical properties and durability. At the same time, chloride ions will damage the protective film on the surface of steel bars in concrete, completely exposing the steel bar surface to oxygen and moisture environments, thereby causing corrosion and volume expansion of the steel bars. The above effects will directly lead to insufficient bearing capacity or even structural failure of reinforced concrete structures.

2.2.3 Chemical erosion environment. Chemical erosion mainly refers to sulfate erosion of the environment and also includes salt crystallization erosion, acid erosion, carbon dioxide erosion and magnesium salt erosion. When salts such as sulfates invade the interior of concrete, the salts gradually aggregate in the pores of the concrete and react with hydration products, resulting in an increase in the volume of crystals in the pores. The expansion effect in the pores will lead to the overall expansion of the concrete. The ultimate problem is a decrease in concrete strength and even structural failure. When constructing concrete in soil or water rich in sulfate, it is necessary to focus on the impact of sulfate erosion on the durability of concrete structures.

2.2.4 Salt crystallization environment. Unlike chemical erosion, salt crystallization environment refers to the environment where harmful ions invade the interior of concrete but do not react with cement hydration products. It only causes concrete to expand through the crystallization process. Salt crystals in the pores of concrete will directly lead to the coarsening of the pores and damage the structure of the pores, ultimately leading to structural failure. Therefore, when the salt content in the environment is high, the durability design of reinforced concrete structures should focus on considering the impact of salt crystallization damage.

2.2.5 Freezing and thawing damage environment. When the ambient temperature changes below freezing point, water in the pores of concrete will solidify into ice, and the volume of ice will expand, resulting in a certain amount of internal stress on the concrete. When the temperature rises, the ice in the pores melts, and the internal stress in the concrete decreases accordingly. The repeated action of the above process will lead to the failure of the microstructure of the concrete pore wall and ultimately affect the macroscopic mechanical properties of the concrete. Under repeated freeze-thaw cycles, the surface of concrete will experience cracking, peeling and other problems, directly affecting the service performance of the structure. Moreover, when the water in the pores of concrete solidified into ice, the concentration of solution in the pores of concrete will increase. The water in adjacent capillary pores will migrate towards high concentration areas under the action of concentration gradient. This is another important reason for the damage of concrete microstructure caused by freeze-thaw cycles.

2.2.6 Abrasive environment. For hydraulic structural concrete, high-speed water flow containing sand has the effects of erosion, wear and cavitation damage on the surface of hydraulic structural concrete. Especially when suspended solids are mixed in high-speed water flow, their erosion effect on the surface of concrete structures is more intense. According to a survey, nearly 70% of large concrete dams experience such damage during operation, with some of the damage even endangering structural safety (Yan, Yang, & Zhang, 2011). Therefore, it is necessary to fully consider the influence of surface abrasion in the durability design process of hydraulic structure concrete.

2.3 The influence of load

2.3.1 The static load. For the railway structural concrete, each load-bearing structural component will bear external loads. In the process of structural design, designers fully consider the load situation of the structure to scientifically design the size of components, arrangement of steel bars and concrete strength level to meet the requirements of structural bearing capacity. In theory, railway concrete structures designed scientifically can fully withstand structural loads and ensure that there is no problem of insufficient bearing capacity. Therefore, the constant load on the structure usually has a small impact on the safety and durability of concrete structures.

2.3.2 The dynamic load. For railway structures, dynamic loads mainly include the dynamic loads generated by trains and the impact loads generated by wheel track contact. For the dynamic load of trains, the structural design process will fully consider the impact of train load on the overall bearing capacity of the structure and consider it through scientific design of cross-sectional dimensions and arrangement of steel bar angles. The impact load between train wheels and rails has a certain impact on the durability of concrete near the rail surface. Due to the influence of factors such as track irregularity on the amplitude of wheel rail impact load, its amplitude may exceed the bearing capacity limit of the track structure. At the same time, impact loads occur repeatedly during train operation, which directly leads to fatigue damage to the concrete. Due to the fact that concrete is a quasi-brittle material, its internal microstructure will undergo damage under repeated impact loads, and as the number of impacts increases, this damage will accumulate until the concrete structure is completely destroyed.

3. The durability evaluation technologies

Based on the investigation and analysis of a large number of deterioration phenomena in railway engineering, it was found that the deterioration characteristics of existing railway engineering mainly include the following five types. The following will summarize the corresponding durability evaluation methods for the main deterioration forms of existing railway structures.

3.1 Concrete carbonization

The rapid measurement methods for the carbonation depth of concrete can be divided into two categories: destructive and non-destructive, with the destructive detection method mainly being the phenolphthalein indicator method; The non-destructive testing methods mainly include ultrasonic testing, resistivity testing and electrochemical testing. The phenolphthalein indicator method is the most commonly used method for testing concrete carbonation. This method involves chiseling the surface of the concrete and applying phenolphthalein indicator. Observe the color change of the indicator to determine the degree and depth of carbonation of concrete. Phenolphthalein indicator appears red in alkaline environments and colorless in acidic environments. Therefore, when the surface of the concrete appears red, it indicates that the concrete in that area has carbonized. In non-destructive testing methods, ultrasonic testing is used to determine the degree of carbonation of concrete by measuring the propagation speed and attenuation of ultrasonic waves in concrete; Resistivity testing is used to determine the degree of carbonation of concrete by measuring its electrical resistivity; Electrochemical testing is used to determine the degree of carbonation of concrete by measuring the potential of steel bars in the concrete. The above nondestructive testing methods have the characteristics of nondestructive, fast and accurate, but these methods can only qualitatively determine the carbonization situation of the concrete surface.

3.2 Chloride penetration

The testing of chloride ion erosion depth in concrete can be divided into two categories: direct method and indirect method. Among them, the direct method is to cut open the concrete specimen to be tested and spray silver nitrate solution on the surface of the concrete splitting. At this point, some areas on the concrete splitting section will generate white precipitates. Through cross-sectional image analysis, the area where white precipitates are generated is the chloride ion erosion area, while the area where no white precipitates are generated is the unaffected area. The above method can directly obtain the range of areas affected by chloride ions on the concrete surface, but the given method is a destructive detection method, which needs to damage the integrity of the concrete components during the testing process. To achieve non-destructive testing of the depth of chloride ion erosion in concrete, research has proposed a method for determining the depth of chloride ion erosion in concrete based on electrochemical parameter measurement. Specifically, the changes in electrochemical parameters of concrete specimens with different erosion depths were measured through experiments, and a quantitative relationship between chloride ion erosion depth and electrochemical parameters was established. On this basis, the depth of chloride ion erosion in concrete can be determined by measuring the electrochemical parameters of actual structural components. The above test process is more convenient and has no damage to the concrete.

3.3 Freeze-thaw cycle

There are corresponding rapid testing methods for the frost resistance of concrete specimens and solid structures regarding the issue of freeze-thaw cycle failure of concrete. For concrete specimens, rapid freeze-thaw cycle testing can relatively accurately determine the freeze-thaw cycle resistance of concrete. By testing the dynamic elastic modulus or mass loss rate of concrete after different freeze-thaw cycles, the number of freeze-thaw cycles of concrete can be obtained. The core samples of engineering entities can also be subjected to freeze-thaw cycle testing using the above method. For concrete solid structures that have undergone freeze-thaw cycles, using appropriate methods to quickly determine the impact of freeze-thaw cycles on them is crucial to ensuring the safe service of concrete structures in this environment. Due to the impact of freeze-thaw cycles on the surface of concrete in railway ballastless track structures, this mainly manifests as surface peeling. Measuring the water absorption rate of the concrete surface can indirectly reflect the impact of freeze-thaw cycles on the concrete. Specifically, through freeze-thaw cycle tests, the surface water absorption characteristics of specimens with different strength levels of concrete undergoing different freeze-thaw cycles are measured. And the correlation between the freeze-thaw cycle times and surface water absorption characteristics of concrete with different strength levels is established. Based on this, water absorption tests are conducted on the surface of solid concrete that has undergone freeze-thaw cycles. And the equivalent number of freeze-thaw cycles of the concrete at this time is indirectly determined.

3.4 Concrete cracking

The cracking problem of concrete under load and non-load is the key factor affecting the durability of concrete structures. Quantitative testing of the cracking situation of existing railway engineering structures can comprehensively and accurately grasp the current service status of the structure and provide important reference for the development of future maintenance and repair strategies. For the rapid testing of concrete cracks in existing railway structures, there are mainly the following methods: acoustic wave detection, thermal image detection, electromagnetic wave detection and direct measurement. Among them, the acoustic wave detection method is a non-contact detection method that indirectly determines the crack situation in concrete by emitting ultrasonic waves and utilizing the propagation rate and attenuation of ultrasonic waves in the concrete. This method is suitable for large volume concrete structures, but its effectiveness in detecting surface cracks is poor; The thermal imaging detection method is a method that indirectly determines whether there are cracks on the concrete surface by detecting the temperature distribution on the concrete surface using an infrared thermal imaging instrument. This method has a good detection effect on surface cracks in concrete, but a poor detection effect on internal cracks in concrete; Electromagnetic wave detection method is a method that uses the propagation speed and attenuation of electromagnetic waves in concrete to determine concrete cracks. This method is suitable for structures with deep cracks, but its detection effect on concrete surface cracks is poor; The direct measurement method is to directly measure the width and depth of concrete cracks through certain tools, which can directly and accurately measure the surface and internal cracks of concrete.

3.5 Corrosion of reinforcement

The detection methods for corrosion of steel bars in existing railway engineering structures include direct method, resistance bar method, eddy current detection method, acoustic emission detection method and ray method. Among them, the direct method is to directly drill core samples and observe the corrosion on the surface of steel bars, which is a direct method to determine the corrosion of steel bars in concrete. But this method will damage the integrity of the concrete structure and the continuity of the steel bars and is a destructive detection method. The resistance bar method is a method developed to detect the remaining area of steel bars, which affects their electrical resistivity due to changes in the cross-sectional structure of the steel bars. Therefore, the corrosion of steel bars in concrete can be indirectly determined by measuring their electrical conductivity; Eddy current detection method is to place electromagnetic equipment on concrete components, and the excitation current generated by the electromagnetic device resonates with the infrasound waves inside the steel bars. By observing the abnormalities in the electromagnetic field image, the cross-sectional modification rate of the steel bars in the concrete can be obtained; The principle of acoustic emission method is that the expansion effect of corroded steel bars will lead to cracks in the surrounding concrete, and the speed of sound waves emitted by the acoustic emission device in the concrete will change due to the presence of cracks. Therefore, the acoustic emission method can indirectly determine the corrosion of steel bars in concrete; The X-ray method is to take X-ray photos of steel bars in concrete and analyze the corrosion of steel bars through imaging analysis.

4. Conclusion

The stock of railway engineering in China is enormous, and its safety and durability are important factors affecting the development of the national economy. Therefore, conducting a systematic evaluation of the durability of existing railway engineering projects and proposing targeted durability improvement methods is of great significance for ensuring the safe operation of railway projects. This article systematically analyzes the main factors affecting the durability of existing railway engineering from three aspects: the concrete material, environment and load. And analyzed the mechanism and rapid evaluation method of common diseases in existing railway concrete structures, including carbonization damage, chloride salt damage, freeze-thaw cycle damage, concrete cracking and steel corrosion. The above research systematically summarizes the durability problems faced by railway engineering structural concrete in China and their corresponding evaluation strategies, providing important technical support for the durability evaluation of railway engineering in China.

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