Study on Life Prediction of Reinforced Concrete Members in Underwater Environment

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Abstract
The purpose of this paper is to design the durability of reinforced concrete structures in underwater environments and to determine their endurance life. The damage mechanism and influencing factors of reinforced concrete structures are discussed. The method of predicting the durability of reinforced concrete structures is summarized. The parameters of the underwater reinforced concrete structure are analyzed. The service life of concrete bridge is predicted. According to different criteria, a dynamic reliability calculation model is proposed, and the formulas of the random parameters are given. Combined with practical examples, specific steps and methods were introduced. The results show that the raw material has a significant effect on the service life of reinforced concrete. Therefore, the application of a protective layer on the surface of a reinforced concrete member can prevent the infiltration medium in the air from penetrating and diffusing into the concrete, thereby improving the durability of the concrete structure.

Key words: Reinforced concrete bridge, Durability assessment, Life prediction, Marine environment, Chloride ion

1. INTRODUCTION

Today, concrete is made from gelled materials, water, aggregates and admixtures. Due to excellent physical and mechanical properties, wide range of materials and low cost, concrete has become the most widely used building material in civil engineering. At present, China's large-scale infrastructure projects, such as bridges, ports and other infrastructure projects, are mostly concrete structures. Generally, the design life of concrete structures is 50~100 years. However, in fact, many concrete structures have different service life because of the influence of concrete structure or external deterioration factors. Some structures can be used for 10~20 years without maintenance, while some structures require maintenance only over a period of several years (Akiyama, 2017). The root causes are mainly three points, which are inadequate structural design resistance, adverse changes in load usage and durability of structures. Compared with the first two reasons, most of the concrete structures appear to be related to durability in the course of using. In order to ensure the normal use of concrete structure, the durability of the structure must be emphasized. Especially, the marine engineering concrete structures such as cross sea bridge, submarine tunnel, port pier and so on, should pay more attention to the durability of these structures because of the special environmental conditions.

Durability of structures refers to the ability of structures or structural members to maintain their original performance for a long time under various conditions that may lead to deterioration of material properties (Liberati, 2014). Among them, the possible role mainly refers to the role of external environment. The original performance mainly refers to the original shape, performance and safety performance of the structural or structural components (Nanukuttan, 2015). On this basis, the durability of marine concrete structure can be defined as the ability of the marine concrete structure and its components to maintain the original performance under the conditions of normal use and maintenance under the marine environment during the design life cycle. As one of the three characteristics of the concrete structure (safety, applicability, durability), the durability of concrete structures at service time does not depend on the strength of the concrete structure, but largely depends on the working environment of the structure. The durability damage or durability failure of concrete structures refers to the deterioration of material properties over time in the long-term use of concrete structures in the working environment (Attari, 2016). The further deterioration of concrete properties will lead to the attenuation of structural properties and the decrease of the bearing capacity of structural members, which will affect the structural safety. This is an irreversible process.

The main forms of concrete durability damage are concrete carbonization, steel corrosion, alkali aggregate reaction, sulfate corrosion and freeze-thaw damage. Among them, concrete carbonization, alkali aggregate reaction and other forms of destruction mostly occur in some specific environmental conditions or local areas, and the scope of influence is small. With the increase of service time and the change of environment, corrosion of steel bars will appear in any concrete structure. It can be said that the corrosion of rebar is the most common durability problem. Especially for the marine concrete structures such as bridge engineering and harbor engineering, the corrosion of reinforced concrete structure is more serious (Kim, 2016). At present, domestic and foreign statistics, due to durability problems caused by economic losses, or reinforcement, maintenance, investment, etc., are mainly concentrated in these areas of engineering (Tang, 2015). Compared to other working...
conditions, the marine environment is a more complex and worse natural corrosive environment. As for the infrastructure projects such as cross sea bridge engineering, the chloride ion in the environment will accumulate on the surface of the concrete structural elements, and then migrate to the interior, because of the marine environment of chloride corrosion (Aldred, 2017). Once the intrusion of chloride ions in the concrete reaches the critical value of steel corrosion, which will cause a huge maintenance investment. If the structural maintenance is not timely, the continuous development of rebar corrosion will lead to a series of structural problems, such as the falling off of the protective layer and the reduction of the bearing capacity of the structural members, which will bring great risks to the structural safety. Therefore, the durability of concrete structures in coastal or offshore infrastructure projects is particularly prominent.

At present, all countries in the world study the durability of concrete structures through scientific research, investigation of actual structures, promulgation of relevant standards, codes and guidelines on durability of concrete structures. The durability of concrete structures is systematically studied from the aspects of environmental action, material degradation and durability damage of structural members. A relatively systematic theoretical framework has been preliminarily formed. It plays an important role in guaranteeing and improving the durability of concrete structures and predicting the durability and service life of concrete structures. Therefore, it is an important subject in the field of civil engineering to study the durability of marine concrete structures, and to improve the durability design and life prediction of concrete structures. It also has important social and economic significance for the national sustainable development strategy.

2. THEORIES

2.1 Durability Design of Marine Concrete Structures

Durability design of concrete structures are generally divided into two categories: qualitative design and quantitative design. At present, China adopts two kinds of concrete structure durability design methods: traditional experience method and quantitative calculation method. The traditional empirical method is also called qualitative design method. Based on the different environmental conditions and design service life of concrete structure, the degree is qualitatively divided into several function grades. On the basis of engineering experience, specification directly specifies requirements for the construction quality of concrete materials under different environmental action grade (such as concrete strength, water cement ratio, cementitious material consumption and other indicators) and reinforced protective layer thickness of the structural requirements. The quantitative calculation method is mainly based on the theoretical or empirical calculation model. Through calculation and analysis, the concrete protective layer thickness and the durability quality control measures are determined to meet the design life (Ali, 2017). At present, China's design of the general concrete structure is still based on qualitative design, and for important engineering structures, such as marine concrete structure, it is generally through quantitative analysis and engineering experience to determine the design of the required life of the protective layer thickness and concrete materials construction quality control measures (Yu, 2017).

The basic principles of durability design of concrete structures are as follows. For the concrete structure in different environmental conditions, the design life of the concrete structure is ensured by selecting the appropriate thickness of the concrete structure protective layer and the concrete material properties (concrete strength grade, quality level, etc.). Therefore, for the marine concrete structure, its durability design mainly need to solve two problems. The first is to give a design life, determine the thickness of the protective layer used in the concrete structure, and select the material properties (such as concrete strength grade, water-cement ratio, the amount of cementing material, the type and number of admixtures), that is, select the appropriate chloride ion diffusion coefficient. The second is to give the design service life, determine the material quality requirements (concrete strength grade, water-cement ratio, the amount of cementing material, admixture type, etc.), especially the chloride ion diffusion coefficient, and select the thickness of the concrete protective layer (Torres-Luque, 2014).

2.2 Life Prediction Method of Marine Concrete Structures

The life expectancy of the marine concrete structure actually includes two aspects: one is to predict the service life of the new structure, and the other is to predict the remaining life of the existing structure. At present, the evaluation of marine concrete structure of the main methods is the following. The first is the empirical method. This is a semi-quantitative method for estimating the structure and predicting the service life of concrete structures by means of field structure detection and laboratory measurements, relying on experienced technicians (or experts) to estimate the structure. The method considers that when the concrete structure is strictly followed the standard method for design, preparation, pouring and construction, it will have the required life. However, the predictive results are man-made, and the reliability of the results is related to the level of knowledge of the experts and the richness of the accumulated experience. This method is applicable to the concrete structure in the general working environment, the design life of the structure is shorter and the structure meets the performance requirements in the design life period. When the concrete life to be predicted is greater...
than the experience of existing knowledge, concrete structure encountered new use of the environment or the use of environmental conditions, this method will be limited and prone to errors.

At present, some methods and standards are used to estimate the service life of concrete structures. For example, China and Eurocode concrete structure design specifications generally classify environmental impacts and classify environmental levels (Duan, 2014). The durability design of concrete structures is carried out by different requirements for different years of use for each type of environment. The method of model analysis is to establish a method to predict the service life of the structure by analyzing the degradation law of the material durability, the mechanism of structural and structural member degradation and its influencing factors, the physical and chemical processes of concrete reinforcement corrosion. Based on Fick's diffusion law, Browne established a mathematical model for the relationship between chlorine concentration and diffusion time and diffusion depth in concrete. Tuutti has established a model for predicting the service life of reinforced concrete.

Model analysis is one of the most widely used methods. The accuracy of the predicted life of the structure is related to the rationality of the model and the accuracy of the material and environmental parameters. Because the factors that affect the durability of the concrete structure are mostly random variables, or with the time of the random process, and thus the corresponding concrete structure of the durability of life is also a failure probability of the use of time (Farahani, 2015). Therefore, the model analysis method needs to combine the probability reliability analysis to predict the durability of concrete structure. At present, the fractional coefficient method adopted in our country is a kind of model analysis method considering reliability.

3. METHODOLOGY

3.1 Concrete Carbonation

Concrete carbonation refers to the physical and chemical reactions of carbon dioxide and concrete (Moodi, 2014). With the increase of the degree of carbonation of concrete, the formation of calcium carbonate and other solid materials will block the concrete pores, so that the porosity of concrete is reduced, thereby inhibiting the continued diffusion of carbon dioxide and improve the density of concrete. Second, the carbonation of concrete will directly lead to lower pH value within the concrete. The concrete will gradually change from alkaline environment to neutral environment. When the pH value down to a certain extent, the surface of the passivation film will be damaged, resulting in steel corrosion reaction occurred. Therefore, the analysis of carbonation process and carbonation mechanism of concrete is of great significance to the study of the durability of concrete structure. The carbonization of concrete reduces its porosity and increases the density. The mechanical properties of the concrete and the mechanical properties of the components have also changed significantly (Troconis de Rincón, 2016). The carbonation of concrete makes its compressive strength and splitting tensile strength greatly improved, and the elastic modulus has also improved. The brittleness of concrete increases greatly, and the rising and falling sections of strain curves are steeper. The peak stress increases, and the peak strain does not change obviously. The bond strength between steel and concrete has a certain degree of improvement. The comparison of load deflection curves between carbonized and uncarbonized concrete beams is as shown in Figure 1.

![Figure 1. Comparison of load deflection curves between carbonized and uncarbonized concrete beams](image-url)
As can be seen from Figure 1, it can be seen that the bearing capacity of the concrete is improved after the concrete is carbonized, but the ultimate deflection is reduced and the ductility of the member is reduced. Under normal circumstances, the depth of carbonation of concrete shallow, and it is equivalent to the thickness of steel protective layer. Therefore, the concrete strength and brittleness caused by carbonization have no obvious effect on the mechanical properties and mechanical properties of concrete. The most unfavorable consequences of concrete carbonation on concrete structures are mainly steel corrosion problems.

3.2 Effect of pH on Corrosion of Reinforcement in Concrete

The pH of the solution is different and the corrosion rate of the steel is different. In the solution at 22 °C, when the pH is 4 ~ 10, the corrosion rate of the steel is basically the same. When the pH value is less than 4, the corrosion rate increases faster. When the pH value is greater than 10, the corrosion rate gradually slows down. Therefore, when the pH value is greater than 11.5, the reinforcement in the concrete is in a passivation state, and it will not react with corrosion. When the pH value is 9 ~ 10, it is in the state of being blunt, and the corrosion velocity of steel bar is less affected by the pH value. When the pH value is less than 9, the corrosion of steel begins to occur with the gradual destruction of the passive film on the surface of the reinforcement. The effect of pH on the corrosion rate of steel bars is shown in Figure 2.

3.3 Alkali - Aggregate Reaction

The alkali-aggregate reaction is an expansion reaction. It is caused by the chemical reaction of the alkali in the concrete with the alkali activated aggregate. The expansion reaction results in the expansion of concrete volume, the cracking of concrete, and the change of microstructure inside. The mechanical properties of concrete such as flexural strength, strength and modulus of elasticity decrease rapidly, which seriously affect the safety of structures (Samarakoon, 2015). Alkali-aggregate reaction is difficult to stop and difficult to repair. It is called "concrete cancer".

According to the different reaction mechanism of alkali and different active ingredients, alkali-aggregate reaction is divided into three kinds: alkali - silicate reaction; alkali - carbonate reaction; alkali - silicic acid reaction (Pang, 2016). Alkali silicate reaction refers to the reaction of some layered silicate aggregate with alkali, which makes the distance between silicate layers larger, and the expansion reaction of aggregate results in expansion and cracking of concrete. The alkali-carbonate reaction refers to the reaction of alkali in the cement with leached earthy dolomite limestone. Alkali-silicic acid reaction means that the alkali reacts with the activated silica in the aggregate. It can be divided into four stages, that is, the active silica on the surface of the aggregate is dissolved in the alkaline solution, the chemical reaction produces silicate gel, the volume of the reaction product is expanded, and the liquid sol is further reacted.

The alkali-aggregate reaction must have the following three conditions: When preparing concrete, aggregates, cement, admixtures and mixed water into a certain amount of alkali in the concrete, or the environment in which the concrete is conducive to alkali infiltration. There is enough alkali active aggregate. Moisture in humid environments can meet the needs of reactants for water swelling. The factors
influencing the alkali-aggregate reaction are: the content of alkali in the concrete, the content of active SiO$_2$ in the aggregate, the size of the aggregate particles, the temperature, the humidity and the force.

The relative ratio of the active SiO$_2$ content to the total alkali content of the aggregate determines the nature of the chemical reaction product, which determines the degree of expansion and destruction of the concrete. When the molar ratio of SiO$_2$ / Na$_2$O is 4.75, the molar ratio of SiO$_2$ / Na$_2$O in the sol reaches a maximum of 4.5. At this point, the SiO$_2$ content in the sol is the highest. The size of the colloid is very small, the sol has the strongest solidification ability, and the expansion failure ability is the strongest. The relationship between the original SiO$_2$ / Na$_2$O and the SiO$_2$ / Na$_2$O in the sol is shown in Figure 3.

![Figure 3](image-url)

**Figure 3.** The relationship between the original SiO$_2$ / Na$_2$O and the SiO$_2$ / Na$_2$O in the sol

### 3.4 Relationship between Stress State and Wear of Hydraulic Concrete Surface

There are three main types of concrete surface wear: Mechanical wear, such as concrete components subjected to frequent external friction and impact; A pile of gravel particles, sediment, scouring, and frictions that are trapped in the water stream; Cavitation, such as pier long-term by the direction of flow and velocity changes caused by the formation of the hole impact. The test shows that the higher the compressive strength of concrete, the better its abrasion resistance. Therefore, the abrasion resistance of concrete can be improved by reducing the water cement ratio and adding high efficiency water reducing agent to improve the strength of concrete. Because of the large volume of coarse aggregate in concrete, the variety and performance of coarse aggregate have an important influence on the abrasion resistance of concrete. The higher the hardness of the coarse aggregate is, the better the toughness is, and the better the abrasion resistance of the concrete. Referring to China's JJJ054-94 "highway engineering stone regulations", according to the resistance to pressure and wear rate, the coarse aggregate is divided into four grades, as shown in Table 1.

<table>
<thead>
<tr>
<th>Rock</th>
<th>Main rock name</th>
<th>Technical indicators</th>
<th>Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magmatic rock</td>
<td>Granite Basalt Andesite Diabase</td>
<td>Compressive strength (MPa)</td>
<td>&gt;120 100<del>120 80</del>100</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wear rate (%)</td>
<td>&lt;25 25<del>30 30</del>45 45~60</td>
</tr>
<tr>
<td>Limestone</td>
<td>Limestone Dolomite</td>
<td>Compressive strength (MPa)</td>
<td>&gt;100 80<del>100 60</del>80</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wear rate (%)</td>
<td>&lt;30 30<del>35 35</del>50 50~60</td>
</tr>
<tr>
<td>Conglomerate and gneiss</td>
<td>Quartzite Gneiss</td>
<td>Compressive strength</td>
<td>&gt;100 80<del>100 50</del>80 30~50</td>
</tr>
</tbody>
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<td></td>
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<td>Quartzite Gneiss</td>
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<td>&gt;100 80<del>100 50</del>80 30~50</td>
</tr>
</tbody>
</table>
The experimental results show that the higher the wear resistance of the fine aggregate in the concrete, the clay content is less. The concrete has good anti-abrasion resistance, and the anti-abrasion performance of the concrete with good gradation is better. The cement admixture of concrete wear resistance also affects the incorporation of silica powder and other active fine material can improve the wear resistance of concrete. Maintenance methods and quality can also affect the wear resistance of concrete. In construction, attention should be paid to the workability of concrete. It is very important to prevent the concrete surface from water splitting and to ensure the full hydration of concrete to improve the abrasion resistance of concrete.

4. EXPERIMENTS

4.1 Durability Prediction of Reinforced Concrete Structures

The concrete structure, like other products, has a service life. The service life can be defined and sorted from different perspectives. From the end of the life point of view, it is divided into the following three categories: Functional life: it is related to the use of function, and the structure is used to no longer meet the requirements of the time limit. Technical service life: refers to the structure to a certain extent into the non-compliance period. Economical service life: it is the time when structure is used to continue maintenance, but it is better to replace. At present, the service life basically refers to the technical life of the structure. There are many methods to forecast the life of the life. This paper mainly studies the life expectancy from the aspects of normal structure and carrying capacity.

At present, the durability evaluation of concrete mainly has the following life expectancy criteria: Carbonation life criterion is based on the protective layer of concrete carbonation, which lost the protection of steel, so that the time of steel corrosion as a concrete structure life. In general, it is basically the time of carbonization to reach the surface of the steel bar as the life of the concrete structure. The life of corrosion expansion cracking is the time required for the expansion of cracks along the concrete surface as the service life of the structure. According to this criterion, the corrosion of reinforcement in concrete causes the corrosion rate of steel to be obviously accelerated after the longitudinal cracking of concrete. This boundary is regarded as a precursor of crisis structure and needs to be repaired and strengthened.

The concrete structure rust expansion cracking life expectancy can be expressed as:

$$\Omega_{cr} = \left\{ \delta_{cr} - \delta_{cr}(t) \geq 0 \right\}$$

(1)

In the formula, $\Omega_{cr}$ refers to the concrete structure of the rust expansion cracking life standard, and it is a random process; $\delta_{cr}$ refers to the rust at the time of rust cracking (mm), and it is a random variable; $\delta_{cr}(t)$ refers to the amount of rust before the rust is cracked, and it is a random process.

The rust life of concrete can be expressed as:

$$T_{cr} = T_c + t_2$$

(2)

In the formula, $T_{cr}$ refers to the concrete structure rust expansion cracking life; $T_c$ refers to the concrete structure carbonization life; $t_2$ refers to the beginning of corrosion of steel to the protective layer of cracking time.

Based on the probability curve of structural cracking failure, according to Table 2, the reliable index value is selected, and the corresponding $t_2$ can be obtained. The probability of corrosion of steel bars is shown in Table 2.

<table>
<thead>
<tr>
<th>The importance of the building</th>
<th>The possibility of injury</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extremely important</td>
<td>7%</td>
</tr>
<tr>
<td>Important</td>
<td>15%</td>
</tr>
<tr>
<td>General</td>
<td>30%</td>
</tr>
</tbody>
</table>

**Table 2.** The probability of corrosion of steel bars
4.2 Example Analysis

A reinforced concrete bridge was built in 1967. Its horizontal is 4 T-beam simply supported beam, and the span is 20m. There are seven crossings. The main beam flange plate is rigidly connected. The wing width is 1.48m, the seam width is 2cm, the web width is 0.16m, and the horizontal bridge width is 6m. The concrete adopts C25, and the average value of compressive strength is 25MPa. The thickness of the protective layer is an important parameter for the evaluation of the carbonization period of concrete. Therefore, the thickness of the protective layer should be accurately detected. The test method is to measure the 10 measuring areas at the main side of the main beam. The specific measurement results are shown in Table 3.

<table>
<thead>
<tr>
<th>Measuring area</th>
<th>Protective layer thickness</th>
<th>Measuring area</th>
<th>Protective layer thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>57</td>
<td>6</td>
<td>52</td>
</tr>
<tr>
<td>2</td>
<td>41</td>
<td>7</td>
<td>46</td>
</tr>
<tr>
<td>3</td>
<td>51</td>
<td>8</td>
<td>47</td>
</tr>
<tr>
<td>4</td>
<td>48</td>
<td>9</td>
<td>42</td>
</tr>
<tr>
<td>5</td>
<td>38</td>
<td>10</td>
<td>35</td>
</tr>
</tbody>
</table>

Finally, the thickness of the protective layer is 47mm. According to the formula (2), the time-varying failure probability and reliable index can be obtained. The results are shown in Table 4.

<table>
<thead>
<tr>
<th>Service time</th>
<th>10 years</th>
<th>20 years</th>
<th>30 years</th>
<th>40 years</th>
<th>50 years</th>
<th>60 years</th>
<th>70 years</th>
<th>80 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reliable indicators</td>
<td>2.1363</td>
<td>1.5670</td>
<td>1.2278</td>
<td>0.9961</td>
<td>0.8251</td>
<td>0.6921</td>
<td>0.5850</td>
<td>0.4963</td>
</tr>
<tr>
<td>Failure probability</td>
<td>0.0163</td>
<td>0.0352</td>
<td>0.1098</td>
<td>0.1596</td>
<td>0.2047</td>
<td>0.2444</td>
<td>0.2793</td>
<td>0.3098</td>
</tr>
</tbody>
</table>

Based on Table 4, the time-varying failure probability and the reliability curve of the structure can be plotted, as shown in Figure 4 and Figure 5.

![Figure 4. Failure probability change curve](image-url)
According to the general component in Table 2, the failure probability is 30%. The carbonation life of the structure is 76 years after being intercepted in Figure 4. As a result, the remaining carbonized life of reinforced concrete components is 76 - 45 = 31 years.

5. CONCLUSIONS

This paper discusses various factors that affect the durability of marine concrete structures. By using the reliability theory model, the reliability design and service life of underwater concrete structures were studied. The effects of external exposure environment and internal composition materials on the durability of marine concrete structures are taken into account. In addition, the durability life is analyzed and the remaining life is predicted by setting a reliable index limit. The main conclusions are drawn as follows: The types of diseases of different structures were summarized, and the causes of the damage of concrete structure were analyzed. The influencing factors of the durability of reinforced concrete structures were summarized. The mechanical properties of concrete members after corrosion are analyzed. It is concluded that the corrosion of steel bars has a great influence on the stiffness and bearing capacity of the members. Based on the study of the durability of reinforced concrete structures, the durability prediction method of concrete bridges is introduced. The dynamic reliability theory is analyzed for the carbonization life criterion, the frost burning cracking criterion and the bearing capacity life criterion respectively. The different reliability models are put forward and the calculation of some random parameters is introduced. Combined with engineering examples, the steps and methods of structural durability life prediction are further elaborated. However, the research of this paper needs to be further improved. Based on the existing research theory, it is necessary to establish a long-term performance monitoring and tracking system for reinforced concrete engineering structures in underwater environment. On the basis of collecting a large number of field data, the engineering environment numerical simulation is carried out to establish the theoretical model of life prediction.

Acknowledgements

The authors thank Shandong province Programs for Science and Technology Development, China (2014GGX101044).

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