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**Case Report**

# Durability Design of a Sea-Crossing Bridge in Zhejiang, China

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**Abstract:** Durability design of a sea-crossing bridge in Zhejiang Province was carried out. Exposure condition of the marine environment was divided into four zones, i.e., atmospheric zone, splash zone, tidal zone and subsea zone. Environment condition surrounding the bridge was introduced, and then the factors affecting the deterioration of the concrete structure were analyzed. It was found that the main factor was chloride ions invasion. Then a chloride ion intrusion model was built based on Fick's second law. Design parameters corrected by Fully Probabilistic Method were used. Besides, the effect of stress on chloride diffusion coefficient was also considered. Using a variety of supplementary cementitious materials, the concrete mix was examined by Rapid Chloride Migration Tests to meet durability requirements. Finally, through capillary crystalline technology, the resistance to chloride ion penetration was further enhanced.

**Keywords:** Sea-Crossing Bridge, Durability Design, Chloride Diffusion Coefficient, Fick's Second Law, Rapid Chloride Migration Test

## 1. Introduction

Bridges play a vital role in the economic development of any country or state. Taking into account many advantages, reinforced concrete is widely used in bridge construction. It is generally believed that under normal circumstances, concrete structures have good durability and do not require special maintenance. However, in certain harsh environments, especially marine environment, performance degradations including corrosion of steel rebar are susceptible to occur, so durability issues deserve serious consideration [1-3]. The durability issues of bridges are attracting more and more attention from academic circles and engineering circles. Due to design flaws and some other reasons, more than 300 highway bridges collapse in China between 2000 and 2014 [4]. At the time of designing, durability improving measures should be considered. The durability design of the large-scale Hong Kong-Zhuhai-Macau Bridge with a service life of 120 years is one of the bridges emphasizing durability design [5]. In the durability design of a new type bridge in Denmark, strength and frost resistance are considered key factors [6].

The proposed bridge is located in East China Sea, Zhejiang province. The bridge comprises prestressed concrete box girders and hollow core concrete piers. Through the investigation of its hydrogeology, environmental conditions and local climatic circumstances, some basic data were obtained. The annual average temperature is 20.2 ~ 22.8 degrees Celsius, that is a relatively warm environment. The chloride ion concentration in seawater is 10000 mg ~ 18000 mg / L, and the content of sulfate is 1100 mg ~ 2400 mg / L. The pH value of the water is between 6.62 and 8.56. The high water level and low water levels are 3.62 m and -1.64 m for 100-year return period. The design wave height is 5.66m. According to current Chinese standard [7], the divisions of exposure condition consist of: atmospheric zone (above 6.60 m), splash zone (-0.40 m to 6.60 m), tidal zone (-2.10 m to -0.40 m) and subsea zone (below -2.10m).

Based on the environmental conditions, the environmental class of main structural components of the bridge can be obtained according to Chinese standard GB / T50476 [8], see table 1 for detail.

***Table 1.*** *Environmental class of main structural components.*

| Type | Harmful Substances | Class | Exposure Conditions | Structural Components |
|---|---|---|---|---|
| I | $CO_2$ | I-B | hidden | girder(inner) |
| | | III-C | seawater submerged | pile, cap (partial) |
| III | $Cl^-$ | III-D | salt spray | bridge deck (partial), abutment (partial), pier(partial) |
| | | III-F | tidal zone | cap (partial), pier(partial), girder(outer) |
| V | $SO_4^{2-}$, $Mg^{2+}$, $CO_2$ | V-D | seawater submerged | cap (partial) |

## 2. Analysis of the Degradation Process

In marine environment, corrosion of steel bars caused by chloride intrusion is a major factor in the durability of concrete structures. According to the basic data of the bridge, it can be seen that sea water contains large amounts of chloride ions, so this factor is particularly important for the study of performance degradation of the proposed bridge. Other factors affecting durability, such as alkali aggregate reaction, can be eliminated by quality control of the materials used. Considering the lack of research on sulfate attack, it's probably insufficient to be used for quantitative durability design.

Chloride ions can ingress into concrete by the following processes: diffusion, convection, permeation, and capillary suction. Usually these transport processes occur simultaneously, but in marine environment of East China Sea, concrete is in a water-saturated state due to a high humidity, and the seawater pressure is not large, so the diffusion process plays a major role in chloride invasion.

## 3. Design Equation

Quantitative method and mathematical model were adopted in this study. The model parameters were calibrated through specific environmental conditions combined with test data. The reliability was based on fully probability theorem [9] and expressed in the form of partial coefficient, and the corresponding reliability index was set to 1.3.

Fick's diffusion model was introduced to describe the transport of chloride ion into concrete, and the state that chloride ions reach the surface of steel rebar was taken as the limit state conservatively.

Based on Fick's second law, the durability design equation can be written as equation 1.

$$G = C_{cr} - C_s \left[1 - erf\left(\frac{x_d}{2\sqrt{D_{cl} t_{SL}}}\right)\right] \quad (1)$$

where, $C_{cr}$ - critical chloride concentration; $C_s$ - the surface concentration of chlorides; $x_d$ - the thickness of the cover concrete; $D_{cl}$ – apparent chloride diffusion coefficient; $t_{SL}$ – design service life; and erf () - error function.

Through long-term observation, it is found that the apparent chloride diffusion coefficients of concrete exponentially decrease with exposing time, so the formula can be expressed as equation 2.

$$D_{Cl}(t) = D_{cl}^r \left(\frac{t_r}{t}\right)^n = D_{cl}^r \, \eta(t_r, t) \quad (2)$$

Where, n - decay index; $D_{cl}^r$ - reference value of apparent chloride diffusion coefficients at age $t_r$; η – decay coefficient; t - age.

With the hydration of cementitious materials, chloride diffusion coefficient of concrete will continue to decrease. The hydration period was set as 30 years, and the chloride diffusion coefficient of the concrete after 30 years would be considered constant. The concrete cover plays an important role in the anti-penetration of external harmful substances, so adequate thickness must be ensured. The values of concrete cover thickness were based on relevant Chinese specifications, and chloride ions diffusion coefficients were selected as design variables. Characteristic values and partial coefficients of design parameters corrected by Fully Probabilistic Method are shown in Table 2.

***Table 2.*** *Characteristic values and partial coefficients of design parameters.*

| Items | | Subsea Zone | Tidal Zone | Splash Zone | Atmospheric Zone |
|---|---|---|---|---|---|
| $C_{cr}$ (% binder) | Characteristic Value | 2.0 | 0.75 | 0.75 | 0.85 |
| | Partial Coefficient $\gamma_c$ | 2.0 | 1.7 | 1.7 | 1.1 |
| $C_s$ (% binder) | Characteristic Value | 4.50 | 3.82 | 5.44 | 1.98 |
| | Partial Coefficient $\gamma_s$ | 1.05 | 1.05 | 1.05 | 1.1 |
| $D_{Cl}$ ($10^{-12}$ $m^2/s$) | Characteristic Value | To Be Solved | To Be Solved | To Be Solved | To Be Solved |
| | Partial Coefficient $\gamma_D$ | 1.05 | 1.1 | 1.1 | 1.1 |
| $\eta$ | Characteristic Value | 0.074 | 0.067 | 0.061 | 0.047 |
| | Partial Coefficient $\gamma_\eta$ | 3.0 | 1.05 | 1.05 | 1.35 |
| $x_d$ (mm) | Nominal Thickness $x_d^{nom}$ | 70 | 90 | 90 | 60 |
| | Construction Tolerances $\triangle x_d$ | 10 | 10 | 10 | 10 |

Based on Fick's second law, the design equation expressed using partial coefficients can be written as equation 3.

$$G_1 = \frac{C_{cr}}{\gamma_c} - \gamma_s C_s \left[1 - erf\left(\frac{x_d^{nom} - \Delta x_d}{2\sqrt{(\gamma_D D_{cl}^0)(\gamma_\eta \eta) t_{SL}}}\right)\right] \geq 0 \quad (3)$$

The calculated chloride ion diffusion coefficients of four different zones are: $3.12\times 10^{-12}$ $m^2/s$ (subsea zone), $3.99\times 10^{-12}$ $m^2/s$ (tidal zone), $3.69\times 10^{-12}$ $m^2/s$ (splash zone), and $4.25\times 10^{-12}$ $m^2/s$ (atmospheric zone), respectively.

# 4. Chloride Diffusion Coefficient Correction

Actual structures are often subjected to a certain load, which will affect the mesoscopic structure, and so the chloride ion transport property. Under a sustained compressive load, i.e., the case of piers, the following equation [10] was used as a correction of chloride ion diffusion coefficient.

$$D = D_0(1 - 0.873R_s) \quad (4)$$

Under bending load (mainly refers to the case of the box girder), the stress correction is expressed as equation 5 [11].

$$D = D_0(-0.36R_s^2 + 0.96R_s + 1) \quad (5)$$

Where, $D_0$ is the diffusion coefficient in stress-free state; $R_s$ is the stress level, i. e, the ratio of stress to concrete strength. Taking into account the actual condition, an approximated value 0.5 is taken for $R_s$.

The chloride ion diffusion coefficients after stress correction are 3.12 / (1-0.873×0.5) $\times 10^{-12} m^2/s$ = $5.53\times 10^{-12} m^2/s$ (for concrete piers) and 3.69 / (-0.36×0.5×0.5 + 0.96×0.5 +1) $\times 10^{-12} m^2/s$ = $2.65\times 10^{-12} m^2/s$, respectively.

# 5. Mix Design and Rapid Chloride Migration Tests

P.O. 42.5 cement, class 1 fly ash, F95 slag, quartz sand and crushed limestone, in compliance with Chinese standards, were selected as main materials. Superplasticizer was added to obtain good workability. Three selected mixes, as shown in Table 3, were designed. Mixing and molding are shown in Figure 1 and Figure 2.

***Table 3.*** *Mix design.*

| Mix No. | cement (kg) | slag (kg) | fly ash (kg) | Water (kg) | Sand (kg) | limestone (kg) | w/c | strength level |
|---|---|---|---|---|---|---|---|---|
| M1 | 308 | 132 | 0 | 140.8 | 727.7 | 1091.5 | 0.32 | C50 |
| M2 | 220 | 110 | 110 | 140.8 | 727.7 | 1091.5 | 0.32 | C50 |
| M3 | 352 | 0 | 88 | 140.8 | 727.7 | 1091.5 | 0.32 | C50 |

***Figure 1.*** *Mixing.*

***Figure 2.*** *Molding.*

After 28 days of curing in a standard moist curing room, the specimens were individually cut to 50 mm thick to facilitate RCM testing (NT Build 492) [12].

According to NT BUILD 492, the rapid chloride migration test was conducted (see Figure. 3). After the RCM test, the specimens were split into two parts using a hydraulic pressure testing machine (see Figure 4). A 0.1mol / L $AgNO_3$ solution was sprayed on the split cross section and the white precipitate of silver chloride appeared (as shown in Figure 5).

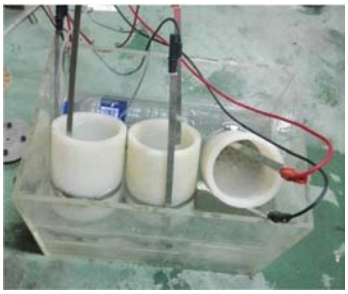

***Figure 3.*** *RCM test.*

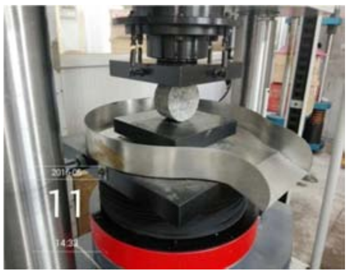

***Figure 4.*** *Specimen splitting.*

***Figure 5.*** *Chloride intrusion depth.*

The stress-corrected non-steady-state electro-migration coefficient is M1: $7.22\times10^{-12}m^2/s$, M2: $6.18\times10^{-12}m^2/s$, and M3: $5.23\times10^{-12}m^2/s$, respectively.

It should be noted that, the chloride diffusion coefficient calculated with Fick's second law is actually the apparent non-steady-state diffusion coefficient, which is different from the non-steady-state electro-migration coefficient obtained from the NT BUILD 492 test. According to a large-scale statistics, a relationship between the two can be established, i.e., $D_{RCM} = 2 \times D_{NSD}$. Therefore, the required $D_{RCM}$ for piers and box girders are $11\times10^{-12}m^2/s$ and $5.3\times10^{-12}m^2/s$, respectively.

So it can be seen that all the three concretes meet the durability requirement of piers, but only M3 meet that of box girder.

## 6. Method to Enhance Durability

In general, measures to improve the durability of concrete can be divided into two categories, one is the basic measures, and another is supplementary measures. The basic measures aim at improving the durability of concrete structures essentially, i.e, reduce the environmental destruction through its own resistance, including: optimized water-cement ratio and reasonable structural design, high quality of materials and adequate thickness of the concrete cover, etc. Complementary measures refer to the fact that when the environment in which the concrete is placed is relatively harsh, or there are construction or design mistakes, the durability of concrete structure cannot be guaranteed by the basic measures. At this time, the use of concrete surface treatment, electrochemical protection or other protective measures should be necessary.

In this research, XYPEX was applied to improve the durability of concrete. Concrete is porous. Its tunnel-like capillaries are a natural part of its mass, and permit the passage of water and other liquids. Xypex can be used for a chemical treatment that would fill these capillaries to prevent the penetration of water and other liquids from any direction. By means of diffusion, the reactive chemicals in Xypex products use water as a migrating medium to enter and travel down the capillaries of the concrete. This process precipitates a chemical reaction between Xypex, moisture and the by-products of cement hydration, forming a new non-soluble crystalline structure. This integral structure fills the capillary tracts rendering the concrete waterproof.

The mass ratio of XYPEX powder to clean water was 6:8. In order to get high quality paste, the mixture was stirred carefully for three minutes. After water was wiped from the concrete surface, the concrete surface was painted three times using the XYPEX paste (see figure 6). Figure 7 shows a comparison of concrete specimens with and without painting. Then it was placed under moist conditions for 3 days before RCM testing. The chloride intrusion depth is shown in figure 8.

***Figure 6.*** *XYPEX treatment.*

***Figure 7.*** *Surface comparison.*

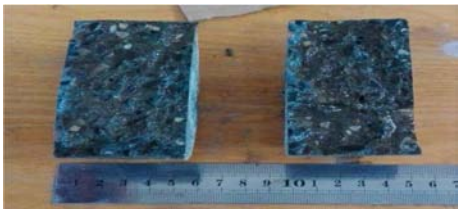

***Figure 8.*** *Chloride intrusion depth.*

The specimen was split into two parts using a hydraulic pressure testing machine, then AgCl solution was sprayed on its surface. White precipitate was observed, and the thickness of the white area was measured. The calculated chloride diffusion coefficient was as follows: M1: $1.49\times10^{-12}$ $m^2/s$, M2: $1.65\times10^{-12}m^2/s$, and M3: $3.26\times10^{-13}m^2/s$.

It can be seen that, after crystallization treatment, the resistance to chloride intrusion is greatly enhanced.

## 7. Conclusion

In this paper, the durability design process of a proposed sea-crossing concrete bridge was provided. The hydrogeological and climatic conditions were investigated, and then the classification of environmental action for different bridge parts was given. Chloride ingress was considered the major factor affecting the durability of this bridge.

For the chloride ions ingress in marine environment, the diffusion coefficient was investigated by using Fick's second law. The state that chloride ions reach the surface of steel rebar was taken as the durability limit state conservatively. The reliability analysis was based on fully probability theorem and expressed in the form of partial coefficient, and the corresponding reliability index was set to 1.3. Concrete mix was designed to meet durability requirements and strength requirements. The measure of improving durability was introduced. It was found that the chloride diffusion coefficient of XYPEX treated specimens was significantly reduced.

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