Experimental Study on the Durability of Monorail Track Beam After Acid Rain Corrosion

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Abstract An experimental study is proposed in this paper to investigate about the durability of monorail track beam after acid rain corrosion in a monorail transportation system. Firstly, a 20-m full-scale beam was built to analyze the causes of corrosion of a monorail track beam, and the corrosion pool was used to make a catalyzed corrosion test on the beam. Then the strand steels were contrasted after 3000-h of accelerated corrosion test. Next, experimental study was performed and the characteristics of strand corrosion in the monorail track beam with corrosion is discussed based on experimental observations. The results show that after the acid rain corrosion, the cross-sectional area of the prestressed steel strand was reduced, although the degree of corrosion was not serious compared with the plain bars, it was more dangerous because of high stress, so further research is necessary to clarify the effects of acid rain corrosion on the durability of the track beam.

Keywords Monorail track beam · Durability · Acid rain · Corrosion model

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1 Introduction

The straddle monorail transportation system mainly adopts the PC (prestressed concrete) track beam, and the existing weaknesses are mostly concentrated in the cracks of the component; the grouting deficiency and the corrosion are caused by environmental factors such as steel corrosion. Scholars have done a lot of research on the durability of concrete structures. The primary damage to concrete structure was the deterioration due to corrosion of steel bars, and the main factor affecting the corrosion of the steel bars was the penetration of chloride ions in the environment [1, 2]. Concrete carbonization and acid ions that lead to steel reinforcement was the main reason for corrosion [3]. Through the studies on the determination of the chloride concentration in concrete, it points out that different erosion environments would establish different erosion models [4]. The effects of chloride content on the chemical transmission properties of cement in concrete was studied, and the factors affecting the solidification of chloride ions and the factors causing chloride corrosion were analyzed [5]. Through the experiment, the penetration mechanism of chloride in concrete was analyzed, and the corresponding calculation model was established [6, 7]. Based on the time-dependent effect, the corrosion of reinforcement in concrete was discussed in the literature [8]. Combined with the experimental data at home and abroad, the mechanical properties of corroded reinforcement were studied, and the mathematical model of stress-strain relationship of corroded reinforced bar under different environmental conditions was established [9, 10]. The bond stress in anchorage zone of corroded specimen was obtained by accelerated corrosion test, and the bond slip constitutive relationship of corroded reinforced concrete was established [11]. Based on the theory of elasticity

and the theory of fracture mechanics, the calculation formula of corrosion expansion cracking, reinforcement corrosion rate and corrosion expansion cracking time of concrete protective layer were established [12].

It can be seen that the existing research mainly focuses on the durability of ordinary reinforced concrete structures, such as concrete cracking and durability vulnerabilities of reinforced concrete structures in the marine climate and corrosive environments. There were few researches on concealed weaknesses of prestressed structures, especially for the hidden vulnerabilities of PC track beam under special conditions. Due to the environmental conditions, duct deficiency of grout bleeding, and prestressed steel strand, the deficient mechanism of subway prestressed concrete structure differed from that of the ordinary concrete structure. Based on this observation, this paper researches on the hidden weakness of PC track beams after acid rain corrosion in a monorail transportation system and analyzes the durability of PC track beams after the vulnerability is induced, in order to lay the foundation for the life expectancy of PC track beams.

2 Corrosion Experiment

2.1 Experimental Program

A full-scale post-tensioned concrete beam was designed with a rectangular cross section of $b \times h = 625 \times 1500$ mm and a total length of 20,000 mm. One plain bar of HPB235 with 12 mm diameter at the bottom, two deformed bars of HRB335 with 16 mm diameter on the top, and stirrups with 90-mm spacing and 8 mm diameter were used in each beam. A duct with 50 mm diameter was reserved inside the beam during casting in the laboratory to ensure that a single 15.2-mm-diameter strand composed of seven wires can be arranged. The details of the beam are shown in Fig. 1.

The mechanical properties of the steel bars and strands are shown in Table 1. The initial strength of steel strand was 1228 MPa, i.e., 0.70 times of the ultimate strength. The concrete mix of concrete is given in Tables 2.

There were two grouting techniques used in the beam grouting test: ordinary grouting technique and vacuum grouting technique. The bellows used were divided into plastic bellows and metal bellows, with a diameter of

50 mm. The steel strand used was divided into ordinary steel strands and coated steel strands. The durability tests for the 12 groups were carried out on the test beam.

2.2 Corrosion Test Design

The corrosion pool at different ion concentrations was placed on both sides of the beam to simulate different corrosion environments. The corrosion pool shown in Fig. 2a and b with different pH values was, respectively, arranged at each side of the beam body. The plastic foam was placed in the test beam; after the completion of the casting, the plastic foam was removed, and the openings in the bellows allow the corrosion solution to enter the bellows. The acid rain corrosion test adopted periodic immersion method, and every 6 days was a test cycle. In order to keep the pH of the solution constant, the pH value was determined and adjusted to the original acidity everyday. The test temperature was 25 °C, and the humidity of the test environment was the same as that of the operation environment. 3000 h was used as the acid rain corrosion test time interval, so it can effectively reflect the situation of a structure under long-term corrosion. After the corrosion was finished, the steel strand in the center section was intercepted and tested (Figs. 3, 4).

3 Result Analysis

After the corrosion test, the bellows were cut and broken into 3 m. Then the strands that were not severely bent or damaged were taken out, and the dust on the surface was removed by purified water. The diameter of the strand was measured at this time, accurate to 0.01 mm; following this, the corroded strands were cleaned by hydrochloric acid solution and then neutralized by the acid with alkali. Then the measurement procedure was repeated, until the difference of the measured values was less than 0.1 mm.

The experiment results are shown as follows: (1) The steel strands and corrugated pipes of N9 and N12 did not undergo obvious corrosion. It proves that the epoxy-coated steel strand has better durability than ordinary steel strands in environments susceptible to acid rain corrosion; (2) for ordinary steel strands produced by different factories, the corrosion degree is the same; (3) comparing and analyzing the corrosion of strand under stress-free and high

Fig. 1 Details of the corroded beam (unit: mm)

Table 1 Mechanical properties of reinforcement and steel strand

Type	Diameter (mm)	Yield strength (MPa)	Elastic modulus (GPa)
Steel strand	15.2	1830	195
Deformed bars	16	335	210
Plain bars	12	235	210

Table 2 Concrete mixture proportion

Water-to-cement ratio (%)	Cement (kg/m ³)	Water (kg/m ³)	Fine aggregate (kg/m ³)	Coarse aggregate (kg/m ³)
0.4	415	189	685	1109

Fig. 2 **a** Location corrosion pool (pH = 1.5), **b** location corrosion pool (pH = 3.5) **Fig. 3** Corrosion of concrete **Fig. 4** Corrosion of steel strand

stress conditions, it is found that there is no obvious change in the corrosion depth of steel strand; (4) for the steel strand without stress, it is found that the lower the pH value of the simulated acid rain, the stronger the corrosion to the steel strand.

4 Damage Model of Steel Strand

4.1 Corrosion Depth of Prestressed Steel Strand

After the prestressed steel strand was corroded, its quality, thickness, mechanical properties, and organizational structure will be changed, and the rate of change in its physical and mechanical properties can be used to indicate the degree of metal corrosion. The corrosion of prestressed steel strand was evaluated by the current index and mechanical performance index of metal corrosion speed.

According to Faraday's law, the quality of the dissolved material on the corrosion electrode is related to the amount of electricity which has passed through the electrode and the number of electrons participating in the reaction. It can be expressed as:

$$\Delta W = \frac{m}{Fn} \times It \quad (1)$$

where ΔW is the quality of corrosion of dissolved substances, I is the intensity of electric current, t is the general time interval, F is Faraday's constant, m is relative atomic mass, n is the number of electrons in the reaction.

This can be introduced as the weight loss of the metal v in the unit surface area per unit time and can be expressed as:

$$v = \frac{\Delta W}{St} = \frac{Im}{FnS} = \frac{iN}{F} \quad (2)$$

where $i = I/S$ is the current density (unit: A/m²) and S was metal surface area (unit: m²).

The corrosion thickness of the metal was $d = v/\rho$. The time-varying characteristics of the corrosion current density of prestressed steel strand were considered while the unit conversion was unified, and the corrosion depth of the prestressed steel strand at a certain time D can be expressed as:

$$D = 3.268 \times 10^{-3} \frac{\int i(t) dt N}{\rho} \quad (3)$$

where $i(t)$ is the current density relative to the change in time.

In the case of acid rain simulation with pH = 3.2 solution, the corrosion current density can be approximated to 90 $\mu\text{A}/\text{cm}^2$ if the current density is not considered according to the test results.

The calculation of the corrosion of steel strand is as follows: $t = 3000$ h, $i(t) = 100 \mu\text{A}/\text{cm}^2$, which put into formula (3), and it can be expressed as:

$$D = 3.268 \times 10^{-3} \frac{\int i(t) dt N}{\rho} = 3.268 \times 10^{-3} \frac{i(t) \times t \times N}{\rho} = 0.3503 \text{ mm}$$

Compared with the test data obtained in Table 3, the corrosion depth and theoretical value of other common steel strand were close to the theoretical value except for the epoxy-coated steel strand, which shows that the prediction of corrosion depth of steel strand can be carried out by the above formula.

Table 3 The diameter of strand with high stress after 3000-h accelerate corrosion test (cm)

Duct	Corrosion	Steel strand diameter				
		A	B	C	D	Average
N1	Hard	1.540	1.550	1.540	1.550	1.545
N2	Hard	1.540	1.550	1.550	1.550	1.548
N3	Hard	1.550	1.540	1.550	1.530	1.543
N4	Hard	1.570	1.570	1.570	1.530	1.560
N5	Local	1.580	1.580	1.570	1.570	1.575
N6	Local	1.580	1.570	1.580	1.570	1.575
N7	Local	1.590	1.590	1.590	1.590	1.590
N8	Local	1.580	1.580	1.580	1.580	1.580
N9	Obsolete	1.670	1.660	1.680	1.680	1.673
N10	Hard	1.530	1.530	1.540	1.530	1.533
N11	Hard	1.550	1.550	1.560	1.540	1.550
N12	Obsolete	1.670	1.660	1.690	1.660	1.670

4.2 Strength of Prestressed Steel Strand After Corrosion

At present, the study on the mechanical properties of prestressed steel strand was mainly based on the experimental research, and the tensile test was carried out by steel strand of different corrosion degree, which can be used to count the change in mechanical properties. The relation between the loss rate of the tensile strength and the corrosion degree of the steel strand can be expressed as:

$$\gamma(t) = 1 - \frac{0.986 - 1.103\eta(t)}{1 - \eta(t)} \quad (4)$$

where $\gamma(t)$ is the tensile strength loss rate of the steel strand in the year, $\eta(t)$ is the loss rate of steel strand section in the year. The comparison between the final test value and the theoretical value is listed in Table 4.

All tensile strength of the steel strand decreased obviously after corrosion, except for steel strand A. The decline of the majority (B, C, D) was around 20 ~ 40 MPa, that is to say, the original tensile strength decreased by about 1.5 ~ 2.0%. It shows that if the corrosion rate of the prestressed steel strand is small (usually within 5% of the cross-sectional loss), the mechanical properties of

Table 4 Loss rate of tensile strength after corrosion

Steel strand	A	B	C	D
Predicted	1.34	1.63	1.78	1.92
Experimental	0.19	1.38	1.56	2.01

the prestressed steel strand will be affected by corrosion, but not very seriously. Corrosion of steel strands leads to the reduction of mechanical properties. On the micro-level, the electrochemical reaction occurred between the steel strand and the corrosion ion, and the microstructure of materials has been changed. On the macrolevel, the main factors may be the cross-sectional loss and the stress concentration. By comparing the theoretical values with test values, it can be seen that the theoretical rate of loss of tensile strength in ordinary steel is basically consistent with the test results, in addition to the epoxy-coated steel strand A. Therefore, formula (4) can be used as a model to evaluate the tensile strength degradation after normal prestressed steel strand corrosion.

5 Conclusions

1. The corrosive environment and poor construction quality may cause the hidden vulnerabilities such as concrete cracking and prestressed steel strand corrosion during service time, and it will affect the quality and safety of the monorail track beam.
2. The corrosion products produced by the corrosion of the tendons in the beam will produce swelling force and cause the cracking of concrete; the cohesive force between the tendons and concrete will be greatly reduced.
3. On the premise of understanding the mechanism of steel strand corrosion, it is necessary to study the mechanism of the deterioration of mechanical properties of corroded tendons and establish a reasonable prediction model of prestressed structures' durability.

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