CHEMICAL ENGINEERING TRANSACTIONS
VOL. 62, 2017

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Fei Song, Haibo Wang, Fang He

ISBN 978-88-95608- 60-0; **ISSN** 2283-9216

DOI: 10.3303/CET1762167

Experimental Study on Deflection of Partially Prestressed Concrete Beams at Different Corrosion Rates under Fatigue Load

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This paper studies the deflection under fatigue load failure and the corrosion fatigue life of partially prestressed concrete beams through the static test and fatigue test of 6 different corrosion rates of partially prestressed concrete beams. The experimental results show that: 1) The corrosion inserts a great influence on the fatigue failure of concrete beams; the fatigue failure of reinforced concrete beams at a low corrosion rate is mainly caused by fatigue fracture of tensile rebars; and when the corrosion rate is high, the failure mode of concrete beams evolves into the cracking and final crushing of reinforced concrete in compressive zone. 2) As the corrosion rate increases, the fatigue life of concrete beams decreases significantly, which affects the fatigue performance of concrete beams. (3) With the increase of fatigue load, the development of mid-span deflection of the test beams shows an obvious rule of three stages: the deflection grows faster at the initial stage, and slower at the medium stage

1. Introduction

The reinforced concrete structure is one of the most widely used structures in the world because of its advantages, including rich materials, low cost, convenient construction, easy molding, etc. It is extensively used in high-rise buildings, highways, railways, bridges, airports and terminals with the economic development, social progress, rapid growth of population and development of modern transportation. In addition to bearing the weight, the reinforced concrete is also under the effect of vehicles, wind, wave, crane and cyclic loading accompanied by a variety of typical environmental factors, such as, embroidered candle, carbonation, freezing and thawing, rot clock and temperature (Xu J. and Xu Y.D., 2017). Under the influence of these environmental factors, the performance of concrete structure degrades, bearing force is reduced, durability is lowered, service life is shortened, and the safe use of the structure is affected as well. Therefore, the fatigue load and the environmental penetration of candle lies in the time and space. It is of great theoretical significance and engineering value to study the coupling effect of environmental factors on concrete damage and fatigue damage, as well as analyse the impact of environmental damage on fatigue life (Saiiidi et al., 1994).

1.1 Introduction to deflection calculation method of prestressed concrete beams

The main calculation methods of the flexural deflection of partially prestressed flexural members at home and abroad include linear bilinear method, effective moment of inertia method and curvature integral method. This paper adopts the linear bilinear method to calculate the deflection of reinforced concrete beams strengthened with prestressed CFRP sheets. The linear bilinear method should be used for flexural members, which are composed of two parts of straight prestressed concrete if the deflection curve is used. Correspondingly, the bending moment M can be divided into the cracking moment Mcr and the post-bending moment increment M', which is equal to M minus Mcr; and the part before the cracking moment can be calculated according to the inertia moment I_0 to get f1. The effect of pre-stress on the moment deflection curve of prestressed concrete flexural members is not considered after the crack occurs. The deflection of the partial M exceeding the cracking moment is calculated to get f2; and the deflection of the flexural member is f, which is equal to f1 plus f2. The deformation formula is as follows:

Please cite this article as: Qiyu Zhang, 2017, Experimental study on deflection of partially prestressed concrete beams at different corrosion rates under fatigue load, Chemical Engineering Transactions, 62, 997-1002 DOI:10.3303/CET1762167

$$f = al^2 \frac{M_{cr}}{E_c I_0} + \frac{M - M_{cr}}{0.75 E_c I_{cr}} \quad (1)$$

In the formula, a is the calculation factor of deformation related to bearing and loading conditions;
I is the calculation span of the flexural members
M is the actual bending moment of corresponding sections;
Mcr is the cracking moment of corresponding sections;
Ec is the elastic modulus of the concrete;
I_0 is the moment of inertia of the converted sections before the cracking of the strengthened beams;
Icr is the moment of inertia of the converted sections after the cracking of the strengthened beam (Liu et al., 2016).

1.2 Necessity of study on prestressed beam deflection

It is well known that the stress and strain of a structure are two mechanical indexes that should be covered in theoretical study. At present, the theoretical study on the external prestressed structures is mostly focused on the study of stress, with extensive studies being mainly concentrated on the bending capacity of normal sections, and the influence of two prestressed steel beam effects on the internal force of structures; while there is rarely any study on the mechanical index of "strain". The deflection is an important parameter in macroscopic response of structural strain (Yang et al., 2010). The study of deflection of the externally prestressed structures is an integral part of the theory of externally prestressed structures. With regard to the concrete structures, the deflection is an important parameter to control the structure design, and also a comprehensive index on the safety and comfort level of the structures (Xue et al., 2008). Meanwhile, the externally prestressed tendons and concrete are un-bonded, and the pre-stressing force acts only on the beam body through the steering blocks and anchorage points. Therefore, as for the calculation of deflection of externally prestressed beams, the relationship between the deformation coordination of hand tendons and concrete is not simple; and the strain of them is no longer equal on the section of the anchorage points between the reinforcement and concrete; thus, the method cannot be used to calculate the deflection of prestressed concrete. On the other hand, apart from cross sections outside of the anchor points, the vertical force of the reinforcement and the displacement of concrete are no longer equal either; therefore, the method cannot be copied simply for the calculation of the deflection of un-bonded prestressed concrete structures (Antonio et al., 2009).

Scholars both at home and abroad have studied the flexural performance of corroded reinforced concrete beams under the static load. Gao Ying proposed the static model through the analysis of stiffness degrading factors, which affect the flexural stiffness of corroded reinforced concrete beams by combining the degradation of bonding effect (Gao et al., 2001). Some scholars have carried out a series of studies on the fatigue performance of corroded reinforced concrete beams. For instance, Liang J Q and Xiao Y carried out the fatigue tests of reinforced concrete beams at different corrosion rates (Liang et al., 2013). However, few studies have been done on the corroded prestressed concrete beams, and the calculation method of deflection under fatigue load is still at its initial stage.

Among the factors that affect the durability of reinforced concrete structures, corrosion is the most common and influential one (Xu et al., 2016); whihc causes the reduction of surface area and degradation of mechanical properties; and uneven rust pits produced therefrom may also cause the local stress concentration of the rebars. Therefore, a large number of studies have been conducted on the fatigue properties of the rebars. The existing researches mainly focus on the influence of single factor on the structural durability; rather than the deflection of concrete prestressed concrete beams at different corrosion rates under fatigue load (Xiong et al., 2004). Hence, this paper studies the influence of corrosion caused by environment, conducts a series of fatigue load tests with PMS-500 hydraulic pulse fatigue test machine at different corrosion rates; analyses the fatigue life of reinforced concrete beams at different corrosion rates; and summarizes the deflection of concrete under fatigue load with the change of corrosion factors.

2. Experiment

2.1 Experimental parameters

The experiment adopts C30 concrete, test beam with a size of 160mm*300mm*2400mm, HRB335 longitudinal rebars with a diameter of 16 and HRB300 stirrup with a diameter of 8. The section size of stirrup spacing beam is shown in Figure 1. The measured value of the compressive strength of concrete cubes is determined according to the standard on test methods of the concrete structures (GB/T50152-2012) (Yi et al., 2006).

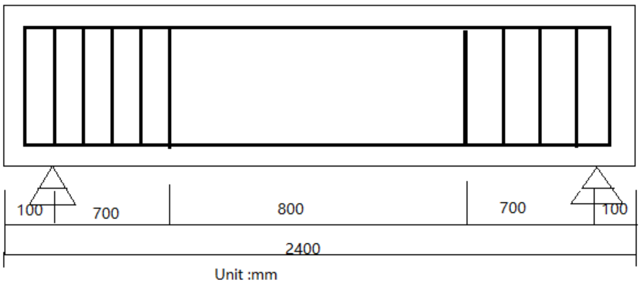

Figure 1: Component section and reinforcement map

Select the corrosion rates of five levels according to the test requirements: 0%, 4%, 8%, 12% and 16% respectively. Meanwhile, we employ a contrast beam in the static load test in order to determine the fatigue load. Taking into account all these factors, we determine that the number of experimental beams should be 6, and the experimental parameters are shown in Table 1.

Table 1: Design parameters of specimen

Beam number	Corrosion rate (%)	Type of test
JZ	/	Static load test
S0	/	Stress test
S1	4	Stress test
S2	8	Stress test
S3	12	Stress test
S4	16	Stress test

2.2 Experiment on corrosion of concrete reinforcement

In the experiment, we connect the rebars with a direct current at a stable voltage, which is intended to simulate the electrochemical reaction of rebars in order to make the rebars in reinforced concrete be corroded rapidly, so as to achieve the expected corrosion effect. Corresponding results show that the effect of accelerated corrosion is similar to that of natural corrosion in actual projects. During the experiment, the test of reinforced concrete beams is performed by means of electrifying corrosion; and it can be seen from the test that the electric solution cannot infiltrate into the entire concrete beams in a relatively short time with the protection of concrete. The theoretical effect of corrosion cannot be achieved if the resistance of concrete is too high, which make the induced current be too small. Therefore, the reinforced concrete beams should be soaked in the solution for a period of time to reduce the resistance of concrete prior to energization. In this test, we soak the reinforced concrete components in the sodium chloride solution with a concentration of 5% for 2 months to make sure that the solution can penetrate into the concrete, so as to increase the ion exchange capacity in components and accelerate corrosion. During the test, the corrosion current density of the rebars should be no higher than 3mA/cm^3; and the actual corrosion process of the reinforced concrete may be simulated. Calculate the energization time of each rebar with the following Formula (2).

$$it = 13441D(1-\sqrt{1-\rho}) \tag{2}$$

It refers to the current density passing through the rebars (unit A / cm^3).
Calculated the corrosion rate of rebars using the method as specified in the *Long-term Performance Test Method of Ordinary Concrete*; and calculate the final corrosion rate of rebars based on the following Formula (3):

$$M_W = \frac{m_0 - m}{m_0} \times 100\% \tag{2}$$

Mw - weight loss rate of rebars after corrosion (%);
m - weight of rebars after corrosion (g / mm);
m_o - weight of rebars before corrosion (g / mm).
After the treatment of rebars is completed, calculate the length and weight of each specimen (Wu et al., 2012); then calculate the actual corrosion rate with Formula (3). The measured results are shown in Table 2.

Table 2: Test beam measured corrosion rate

Beam number	S1	S2	S3	S4
Design corrosion rate	4%	8%	12%	16%
Measured corrosion rate				
1	3.78%	8.26%	11.98%	16.61%
2	4.19%	7.99%	12.41%	15.97%
3	4.22%	8.05%	12.14%	16.21%
4	3.91%	8.16%	12.28%	16.12%
5	4.28%	8.06%	11.28%	16.29%
6	3.88%	7.59%	11.31%	15.96%
Average value	4.04%	8.02%	11.90%	16.19%

2.3 Load test program

The test consists of two parts: static load test and constant amplitude fatigue test. The former test includes the comparison of the static loading with the fatigue test of the beams; and the static test of the beams is loaded with a jack, the pressure is measured with a pressure sensor, while the fatigue test is carried out using a PMS-500 hydraulic pulsation tester. The static load failure tests are conducted so as to determine their basic mechanical properties, including, cracking load, yield load, ultimate load and the corresponding burnout deformation; and fatigue test is conducted with the upper and lower fatigue load limits as well, so as to provide the basis for calculation (Tang et al., 2016).

The fatigue load test is performed using a PMS-500 hydraulic pulsation tester, which is the same as the static load test. The static load test is conducted before the fatigue test prior to the loading of pre-stress, which is about 3kN in order to avoid the loosening of the bearing. We carry out static load tests on the beams when the fatigue load cycle reaches 10,000 times, 20,000 times, 50,000 times, 100,000 times, 200,000 times and 500,000 times respectively (Cao et al., 2016). The upper limit of the fatigue load of the beams is taken as the maximum load in the static load test, and the loading is carried out step by step in order to avoid the effect of static load test on the fatigue performance of the beam, and the mid-span deflection of the beams is measured. We continue increase the load until they are crushed if the beams do not fail after the load is increased to 100 million times.

3. Test results and analysis

3.1 Fatigue failure mode of reinforced concrete beams under different corrosion rates

The beam S0 with no damage acts as contrast concrete beam. When the initial static load is about 20kN, vertical and horizontal cracks appear in the middle of the pure bending section; when load is increased to 30kN, oblique cracks appear on the abdomen of the test beams, and gradually extend to the loading point; when the fatigue load is increased to about 4,000 times, micro-cracks appear at the bottom of the beams. S1, S2, and S3 are the reinforced concrete beams corroded, the measured corrosion rates are 4.04%, 8.02%, 11.90% and 16.19% respectively; and the test phenomena and damage patterns of S1, S2 and S3 are basically similar. Take the test beam S2 as an example, there are cracks in the longitudinal direction of the beam before the fatigue test, and with the increase of the candle rate, the cracks get wider gradually. When the fatigue load is increased to about 2,000 times, the pure horizontal cracks occur, followed by oblique cracks in the three-point loading position. During the loading process, the width and length of the cracks are developing gradually, with the oblique cracks developing more rapidly and wider than those transverse ones; two main cracks are formed; and the pure cracks are no longer new cracks. When the fatigue load is increased to about 10,000 times, the protective layer at the location of cross sections and the longitudinal reinforcement are exposed; and the reinforced concrete and the concrete are completely separated. When the fatigue load is increased to about 40,000 times, the concrete is crushed, resulting in the connection among cracks. The concrete layer at the top of the beam completely strips from the whole structure, and the cross sections are gradually reduced. Under the effect of cyclic loading, the concrete aggregates on both sides of the main cracks in the middle parts rub with each other at the contact surfaces gradually, the width of the cracks increases, and the cross sections are weakened and form plastic hinges. The test beam should be declared failed at the time when it loses its resistance against bending with the increase of load.

3.2 Impact of corrosion rates on fatigue failure of beams

According to the above corrosion situations, the fatigue failure of concrete beams has undergone great changes with the increase of the induced candles. When the corrosion rate is about 8% to 16%, cracking happens on the surface of the beams; the width of cracks increases with the increase in the number of fatigue cycles; and the rust and cracks are combined with the transverse cracks. The concrete protective layer falls off after repeated loading and unloading, and bonded fatigue damage appears. When the cycle reaches a certain number, the main longitudinal cracks will develop rapidly, leading to the fatigue damage. Whereas, when the corrosion rate is high (over 16%), the concrete damage will be more serious and the cracks will be wider. Under the fatigue load, the concrete in the pure compressive section is crushed, and the main cracks penetrate through the whole beams, which seriously weaken the cross sections and reduce the stiffness rapidly; and the test beams should be considered failed. Therefore, the longitudinal reinforcement corrosion has a great influence over the fatigue failure mode of the test beams. When the corrosion rate is low, the fatigue failure of the concrete is mainly caused by longitudinal cracks, such as, two broken rebars at the same time. When the corrosion rate is high, the fatigue failure evolves into a compressive zone, and the concrete is crushed finally.

3.3 Deflection of different test beams

According to the test loading mechanism, record the mid-span deflection and corresponding load values in the static load test when the fatigue loads reach 0 times, 10,000 times, 20,000 times, 50,000 times, 100,000 times, 200,000 times, 500,000 times and 1 million times respectively. Draw a curve of the number of cycles under different loads based on the experimental data.

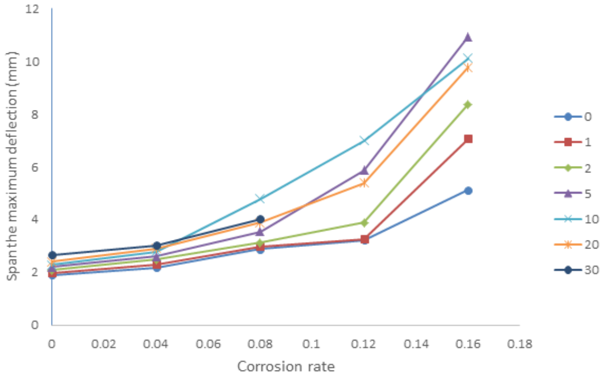

Figure 2: The relationship between the maximum deflection and the corrosion rate in the span

As can be seen from Figure 2 that the load and deflection are basically in a straight line, when loading is imposed gradually, indicating that the beams are basically at the elastic phase. Under the same load, the corrosion rate increases with the increase of the corrosion rate, which is mainly caused by the cohesive degradation between the rebars and concrete. Meanwhile, as the number of load cycles increases, the slope of the curve decreases gradually. That is because the cohesive performance between concrete and rebars is gradually degraded under the action of fatigue load, and its synergistic working coefficient is reduced either, which leads to the decrease in stiffness of cross sections, especially when the corrosion resistance of the beams is high.

3.4 Effect of different corrosion rates on deflection of concrete beams

Table 3: The maximum deflection of the beam in different corrosion rates

Cycles(Million)	Corrosion rate				
	0	4.04%	8.02%	11.90%	16.19%
0	1.99	2.79	3.02	3.87	4.35
1	2.38	2.99	3.21	4.09	9.11
2	2.89	3.11	3.86	4.18	/
5	2.97	3.37	3.91	4.33	/
10	3.01	3.59	4.12	4.78	/
20	3.09	3.87	4.38	5.23	/
30	3.21	4.01	4.58	5.96	/

Note: "/" in the table indicates no measured data

Table 3 lists the maximum deflection values of beams at different corrosion rates; among them the mid-span deflection under a static load of 60 kN is the largest. It can be seen from the experimental data that the mid-span deflection of concrete beams with the same number of cycles is greatly affected by the longitudinal reinforcement corrosion. Different beams have different fatigue lives, and the relationship between the maximum burn rate and corrosion rate cannot be obtained when the number of cycles is large; therefore, this paper selects 0 million times, 10,000 times, 50,000 times, 100,000 times, 200,000 times, 300,000 times to draw the tendency chart of the maximum deflection of the beams with the change of corrosion rates.

4. Discussion and conclusions

For the purpose of this paper, the static test and fatigue test of partially prestressed concrete beams are carried out; and impact of corrosion to the fatigue properties of reinforced concrete is studied by analysing the failure mode, fatigue life and mid-span deflection of beams at different corrosion rates. The conclusions of the experimental study are as follows: 1) The corrosion has a great influence over the fatigue failure of the concrete beams. The fatigue failure of reinforced concrete beams at a low corrosion rate is mainly caused by fatigue fracture of rebars under stress. When the corrosion rate is high, the failure form of the concrete beams evolves into the cracking and eventual crushing of concrete in compressive zone. 2) With the increase of the corrosion rate, the fatigue life of the concrete beams is significantly reduced, which affects the fatigue performance of the beams too. 3) As the fatigue load increases, the development of mid-span deflection of test beams shows an obvious rule of three stages: the deflection grows faster at the later stage, and slower in the medium term.

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