CHEMICAL ENGINEERING TRANSACTIONS
VOL. 55, 2016
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet
Guest Editors: Tichun Wang, Hongyang Zhang, Lei Tian

ISBN 978-88-95608-46-4; **ISSN** 2283-9216
DOI: 10.3303/CET1655063

Study on Fatigue Performance of Concrete Highway Bridge under Corrosive Environment

Canbin Yin, Fang Yu

Hunan City University, Hunan, China.

Under different environment, reinforced Concrete (RC) Highway Bridge will have different damages along with time and corrosive damage is one of the most frequent damages. In order to have further understand of the influence of corrosive damage to fatigue performance of RC Highway Bridge, experiment to study fatigue performance of RC Highway Bridge under corrosive environment is designed. In the experiment, RC Highway Bridges in coastal cities are selected as object of study and "electro-osmosis, continuous current and drying and wetting cycle" process was used to accelerate corrosion of RC Highway Bridge. Multifunctional load type lab for climate simulation is used to conduct experiment of fatigue performance of RC Highway Bridge. Experiment results are that if it is corrodes for a short period of time, fatigue life mid-span deflection and strain of concrete pressured region of RC Highway Bridgewill be influenced slightly. If RC Highway Bridge is in corrosive environment for a long time, fatigue life would be shortened, and beam deflection and strain of concrete pressured region would be accelerated. Under corrosive environment, fatigue crack source, crack expansion and crack can be seen at the reinforcement fracture of damaged bridge. According to this study results, lifespan of destroyed bridged under corrosive environment can be tested and bridge maintenance can be provided with reliable basis.

1. Introduction

Reinforced Concrete Bridges would be damaged differently by outside environment because it is in outdoors. Coastal bridge would be damaged by salt mist, wet-dry cycle of seawater and infiltration of chloride of deicing salt (Yuan and Jiang, 2012). So far, fatigue test is the most frequently used method to study fatigue performance of reinforced concrete structure. With fatigue test, different damage of concrete bridge can be compared and changing law of parameters of fatigue life, strain and deflection can be found to establish damage criterion model of fatigue accumulation (Cho et al, 2011).
"Electro-osmosis, continuous current and drying and wetting cycle" process was adopted to accelerate corrosion and conducts fatigue test of reinforced concrete beam under corrosive environment with multifunctional load type lab for climate simulation. Thus, damage form, fatigue life, mid-span deflection, and crack width and form of RC beam under corrosive environment are studied.

2. Experiment design

2.1 Specimens design

(1) Material parameters and proportion of concrete mix
C30 is strength grade of concrete design. P·O42. 5 ordinary Portland cement is used. Rubble is used as coarse aggregate and the maximum particle size is 20mm. River sand is used as fine aggregate. Proportion of concrete mix (kg /m^3) is water: cement: sand: rubble=220:449:1125:606. 28daxial compressive strength of concrete is measure as fc= 34.0N / mm^2. Mechanics performance test is conducted on steel and the result shows that its yield strength is 320MPa and ultimate strength is 452MPa.
(2) Specimen size and reinforcements
This experiment was to pour five reinforced concrete beams and the reinforcement ratio was 1.22%. One of the beams was used for static load test and the rest was divided into two groups to conduct fatigue test under atmospheric environment and corrosive environment respectively. Beam's shear capacity shouldn't lower its flexural capacity to ensure that beam's static load failure was the bending failure of mid-span bending. The

Please cite this article as: Yin C.B., Yu F., 2016, Study on fatigue performance of concrete highway bridge under corrosive environment, Chemical Engineering Transactions, 55, 373-378 DOI:10.3303/CET1655063

beam was rectangular section of which size was 1500mm×200mm×150mm and thickness of the protective layer was 20mm. Longitudinally beam's tensile reinforcement was 2Ø14. Both ends of the longitudinal bar were bending up 100mm to ensure anchoring. Wires were used to connect the end of RC longitudinal bar that was used in corrosive fatigue test. When pouring, a stainless steel sheet of size 30mm×1300mm×0.2mm was pre-embedded on the end of beam in the middle and wires were used to connect it. Concrete beams used in the experiment were poured in the same patch, which were watered for 28 days under normal temperature. Then, those were exposed to the air for 3 months. When pouring concrete beams, concrete cube of size 1500mm×150mm×150mm to conduct RCM experiment, in order to get tested concrete's coefficient of unsteady diffusion of chloride.

2.2 Control of corrosive environment

(1) Experimental system composition

Corrosion fatigue experiment of RC beam was conducted in multifunctional load type lab for climate simulation (Liu and Zhang, 2012), which could simulate various environments.

(2) Method to accelerate corrosion

In order to make the environment closer to true chloride environment, corrosion accelerated method of "electro-osmosis, continuous current and drying and wetting cycle" was used to make non-uniform corrosion when conducting experiment in multifunctional load type lab for climate simulation. The first step, electro-osmosis (Tarifa et al, 2015) was used under constant voltage to make chloridion move to surface of longitudinal bar that needs corrosion. Then, constant current used in process of fatigue loading to conduct drying and wetting cycle (Verma et al, 2013).

Before conduct the electro-osmosis experiment, it was calculated with RCM method that under 30V constant current, 87.3 h were needed to have chloridion move to steel surface.

Usually, using continuous current to accelerate corrosion is the most frequently used method to study corrosion performance of RC structure. When using continuous current to corrosion, steel in concrete beam was connected to positive pole of the power while the stainless sheet was connected to negative pole, and the corrosion can be control by controlling current intensity and conduction time. Current density of natural corrosion of steel in concrete is generally 50~100mA/cm (Li et al, 2014). In order to make simulated environment was closer to current situation and to accelerate corrosion, current density used in this thesis is: iwet =0.20mA/cm2 when it is in wet cycle and idry =0.10mA/cm2when it is in dry cycle.

Fatigue loading is a process that relatively consumes a short time, thus dry-wet time need not to be too long. So dry time could be set at 8 hours, wet time could be set at 8 hours and dry-wet ratio of is 1:1. In multifunctional load type lab for climate simulation, when conducting wet cycle 5%NaCl solution was to be sprinkled; and when conduction dry cycle, solar light and natural wind simulation were opened, and temperature was set at T=35°C and humidity RH=80%.

(3) Loading program and measuring scheme

Clear span of test beam was 1200mm and bending of mid-span is 400mm. The only sensor of LVDT was put in the middle of beam span and supports at the both ends. Strain gage was put on the side and top of the beam span and this should be completed at the process of pouring beam.

Before conducting fatigue test, static load destructive test was conducted to one of the test beam to define the ultimate bearing capacity of beam and then the loading amplitude of fatigue test. Before conducting fatigue loading, graded static load is used to ensure the fatigue test reached the maximum load and then unload it. (Zhu et al, 2014)Above steps were repeated again. After above preparation, concrete beam crack would fully extend, thus fatigue test was to be conducted. Fatigue cycle was conducted according to predetermined times. When fatigue load stopped, sine wave of loading frequency 4.0Hz was used in fatigue load. Loading system of fatigue test is shown as Figure 1.

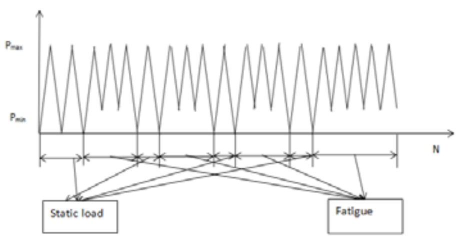
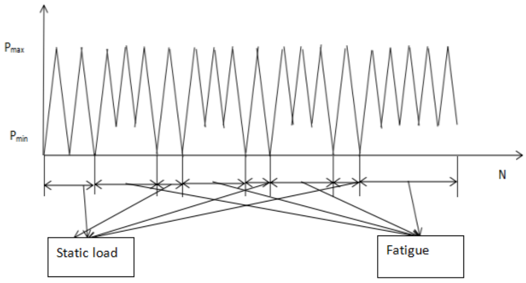
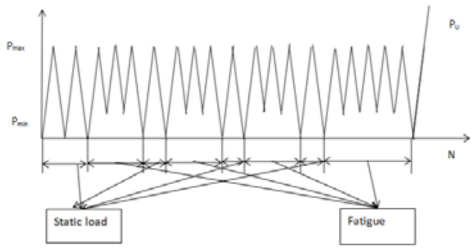


Figure 1: Loading system of constant amplitude fatigue test under atmospheric environment

Concrete beam to conduct corrosive fatigue test was tested by above method to accelerate corrosive. 8 hours wetting-drying cycle was conducted. One week was needed to completed one cycle and one completion is one period. After this period, next period, brine spray, was conducted. Frequency of constant amplitude fatigue test under corrosive environment is 2.0Hz. And loading waveform is sine wave. Fatigue loading system is shown as Figure 2.



(a) Fatigue loading system of constant amplitude within 2 million times



(b) Fatigue load system of constant amplitude over 2 million times

Figure 2: Loading system of fatigue test under corrosive environment

DH5922 dynamic data collecting instrument was used to collect and record data of the experiment and the collecting frequency is 200Hz.

3. Experimental results and Analysis

3.1 Phenomenon of experiment and destroy

When conducting fatigue test, corresponding maximum fatigue load of the maximum strains 0.6 and 0.5were 69.6kN and 58.0kN respectively. Results of constant amplitude fatigue test of concrete beam were as Table 1.

Table 1: Test results of corrosive fatigue test

Beam number	B1	B2	C1	C2
Smax	0.6	0.5	0.6	0.5
Environments	Atmospheric environment	Atmospheric environment	Corrosive environment	Corrosive environment
Destruction for,	Fatigue crack of longitudinal bar	Static load destroy after 2 million times	Fatigue crack of longitudinal bar	Fatigue crack of longitudinal bar
Fatigue life	453121	2000000	438129	174301

Analysis of phenomenon of fatigue test and destroy.

(1) Constant amplitude fatigue test under atmospheric environment: steel of crack B1 of test beam destroyed. Because the maximum fatigue load is relatively small, at the beginning of the fatigue load, vertical crack of beam B2 appears only at pure bending region. And the diagonal crack extends to the up end of the beam along the experiment. After around 5000 times fatigue cycle, diagonal crack appears and extended to application point of concentrated force. Test beam still remained unbroken when times of fatigue cycle reached 2 million times. Thus, fatigue load was stopped and static force load was conducted until test beam was broken. The maximum bearing capacity of beam was 114.1kN.

(2) Constant amplitude fatigue test under corrosive environment: crack pattern and distribution law of corrosion fatigue loading of corrosion fatigue beam C1 and C2 were similar to those of beam B1 and B2. With the fatigue loading, concrete cracks were rhythmic opening and closing. When the crack opening, NaCl solution and air were entered the inner of concrete. When the crack closes, NaClsolution and its corrosion products would be squeezed out. When fatigue cycle reaches 100, 000 times, light yellow corrosion would appear around the concrete crack. With the conducting of the experiment, the color of the corrosion would be deepened into yellowish-brown. When 900, 000 times of complex cycle was conducted on beam B2, corrosive crack along bars were appeared at the bottom and side of the beam. Gradually, those cracks were connected to each other and the width is widening. No corrosion crack appeared on beam 1 because corrosion action was lasted for a short time. (François and Khan, 2012)

When under corrosion environment, broken pattern of reinforced concrete remained longitudinal bar fatigue failure in crack position. Bread position of beam B1 is at crack while the break position of beam B2 is around the mid-span. Usually, steel would have local stress concentration when crack appears at where the steel was. Besides, corrosion around the crack would be deepened because of the open and close period of crack. Corrosion with chlorine salt is uneven, so corrosion degree around crack is different. Break position of steel was defined by the stress and corrosion degree.

3.2 Changing law of deflection of concrete beam under corrosion environment

Table 2, 3, 4 and 5 shows the changing law of mid-span deflection of concrete beam that bearing the same fatigue load under different environment.

Table 2: Changing law of mid-span maximum deflection

Fatigue life/million times	1	5	10	15	20	25	30	35	40	45
B1mid-span deflection /mm	2.24	2.28	2.32	2.36	/	2.39	/	2.39	/	2.5
C1mid-span deflection /mm	2.2	2.24	2.25	/	2.28	/	2.32	/	2.36	/

Table 3: Changing law of residual deflection in mid-span

Fatigue life/10, 000 times	1	5	10	15	20	25	30	35	40	45
B1mid-span deflection /mm	0.4	0.42	0.45	0.45	/	0.46	/	0.47	/	0.5
C1 mid-san deflection/mm	0.49	0.49	0.5	/	0.55	/	0.54	/	0.56	/

It was known from table 2 and table 3 that under fatigue load of the maximum strain Smax=0.6, changing law of the maximum deflection and residual deflection of beam 1 and beam 2 is similar. In the initial loading stage (10, 000-50, 000 times) deflection increased quickly and after this stage, deflection increased in a lower speed. Also, when beam 1 and beam 2 were under the same fatigue times, their maximum deflection and residual deflection was almost the same. Thus, influence of short time deflection to deflection development of reinforced concrete beam was rather small.

Table 4: Changing law of the maximum deflection of mid-span

Fatigue life/10, 000 times	5	10	20	30	35	48	50	65	80	100	125	150	200
B2mid-span deflection/mm	1.95	1.96	/	1.96	/	1.98	/	1.98	/	1.99	/	2.02	2.0
C2mid-span deflection/mm	1.96	2.0	2.01	/	2.02	/	2.04	/	2.07	2.1	2.12	2.15	/

Table 5: Changing law of the residual deflection of mid-span

Fatigue/10, 000 times	5	10	20	30	35	48	50	65	80	100	125	150	200
B2mid-span deflection/mm	0.3	0.31	/	0.32	/	0.33	/	0.36	/	0.37	/	0.39	0.4
C2mid-span deflection /mm	0.34	0.35	0.36	/	0.37	/	0.38	/	0.4	0.41	0.45	0.48	/

It was known from table 4 and table 5 that under the fatigue load of the maximum strain Smax=0.5, deflections of beam B2 and beam C2 both had the rapid development stage and the steady increase stage. If liner fitting the residual deflection, the growth rates of residual deflection of beam B1 and beam C2 were 4.773×10-4 and 9.327×10-4, respectively. Growth rate of residual deflection under corrosion environment was higher than that of under atmospheric environment. Thus, deflection development of reinforced concrete beam could be accelerated if it was under corrosion environment for a long time.

3.3 Changing law of crack on concrete beam under corrosion environment

Under the same fatigue load but different environment, changing law of the maximum crack on concrete beam is shown in below table 6, 7, 8 and 9.

Table 6: Changing law of the maximum vertical crack

Fatigue life /10, 000	1	5	10	15	20	25	30	35	40	45
B1 Crack width /mm	0.20	0.20	0.21	0.23	/	0.23	/	0.23	/	0.25
C1 Crack width /mm	0.19	0.20	0.21	/	0.21	/	0.2	/	0.2	/

Table 7: Changing law of the maximum diagonal crack

Fatigue life/10, 000 times	1	5	10	15	20	25	30	35	40	45
B1 Crack width/mm	0.12	0.21	0.21	0.23	/	0.24	/	0.25	/	0.25
C1 Crack width/mm	0.11	0.19	0.20	/	0.20	/	0.20	/	0.21	/

Table 8: Changing law of the maximum vertical crack

Fatigue life /10, 000 times	10	15	20	30	35	45	50	65	80	100	125	150	200
B2 Crack width /mm	0.18	0.18	/	0.18	/	0.18	/	0.19	/	0.19	/	0.19	0.20
C2 Crack width /mm	0.17	0.17	0.16	/	0.18	/	0.18	/	0.19	/	0.20	0.20	/

Table 9: Changing law of the maximum diagonal crack

Fatigue life/10, 000 times	10	15	20	30	35	45	50	65	80	100	125	150	200
B2 Crack width /mm	0.10	0.12	/	0.14	/	0.15	/	0.15	/	0.16	/	0.16	0.17
C2 Crack width /mm	0.09	0.10	0.12	/	0.12	/	0.14	/	0.16	0.17	0.18	0.19	/

It was known table 6 and table 7 that under fatigue load of the maximum strain Smax=0.6, the change law of the maximum crack width of beam B1 and beam B2 is the same that width change of the maximum vertical crack within 0.05mm can be ignored. At the first stage, the expand speed of the maximum diagonal crack is very fast, which expand speed slowed down with the increase of the fatigue times. When the fatigue cycle times is less than 100, 000 times, the width of the maximum vertical crack and diagonal crack of beam B1 and beam C1is almost the same. When the fatigue is over 100, 000 times, width of the maximum vertical crack and diagonal crack of beam B1 is wider than that of beam C1. Air and NaClsolution would enter the concrete while the corrosion on the reinforcing steel bar would be squeezed out of concrete. The measured width of crack would be smaller because a small part of the corrosion would remain around the crack.

It was known from table 8 and table 9 that under the fatigue load of the maximum strain Smax=0.5, the changing law of the maximum crack of beam B1 and beam C2 was similar to that of beam B1 and beam C2 when Smax=0.6 that width change of the maximum vertical crack within 0.05mm can be ignored. There were no bending shear appeared on beam B1 and beam C2 in the two times' static force loading because the load is relatively small. Beam B1 and beam C2 appeared diagonal cracks when the fatigue load reached 5, 000 times, after which one beam entered rapid growth stage while the other beam entered slow growth stage. When fatigue times is less than 100, 000 times, width of the maximum vertical crack and diagonal crack of beam B2 and C2 were close. When the fatigue loading was between 100, 000 to 1, 000, 000 times, crack width of the maximum vertical crack and diagonal crack of beam C2 was narrow than that of beam B2 because of corrosion blocking. When it reached 1 million times, the maximum vertical crack and diagonal crack of beam C2 was wider than that of B2 because fatigue life of beam C2 was shorter. Thus, if the fatigue load times were the same, growth rate of crack width would be quick and which would be larger than that of the influence of the corrosion block.

3.4 Changing law of compressive concrete under corrosion environment

In the same fatigue load, changing law of the maximum strain and residual strain of compressive concrete in different environment were shown in table 11 and table 12. There would always be rapid growth stage and stable growth stage of the maximum strain and residual strain of the concrete whether in different strains of different environment. Besides, long time corrosion would accelerate the strain development of concrete.

Table 10: Changing law of the maximum strain of concrete

Fatigue life/10, 000 times	1	5	10	15	20	25	30	35	40	45
B1 Concrete deflection /*10-6	-710	-730	-740	-755	/	-760	/	-790	/	-840
C1 Concrete deflection /*10-6	-710	-710	-725	/	-730	/	-755	/	-760	/

Table 11: Changing law of residual strain of concrete

Fatigue life/ 10, 000 times	1	5	10	15	20	25	30	35	40	45
B1 Concrete strain /*10-6	-120	-140	-145	-155	/	-156	/	-170	/	-200
C1 Concrete strain/*10-6	-120	-130	-145	/	-145	/	-156	/	-170	/

Table 12: Changing law of the maximum strain of concrete

Fatigue life/10, 000 times	10	15	20	30	35	45	50	65	80	100	125	150	200
B2 Concretestrain/*10-6	-630	-630	/	-630	/	-640	/	-640	/	-645	/	-660	-660
C2 Concrete strain/*10-6	-610	-630	-640	/	-645	/	-650	/	-660	-670	-670	-685	/

Table 13: Changing law of residual strain of concrete

Fatigue life/10, 000 times	10	15	20	30	35	45	50	65	80	100	125	150	200
B2 Concretestrain/*10-6	-90	-95	/	-110	/	-120	/	-135	/	-135	/	-137	-150
C2 Conrete strain/*10-6	-100	-120	-130	/	-135	/	-140	/	-155	-160	-160	-165	/

4. Conclusions

Corrosion fatigue test of reinforced concrete beam with the “electro-osmosis, continuous current and wet and dry cycle” method to accelerate corrosionwas conducted. Following results were concluded. When the fatigue strain is between 0.5 and 0.6 and fatigue load times is less than 10, 000, reinforced concrete beams under corrosion or atmospheric environment were destroyed. This is the sign of steel fatigue break. Besides, the break place of steel in reinforced concrete beam under corrosion environment sometimes maybe changed. When it is under the same fatigue load, effect of a short time corrosion to fatigue life is less thanthat of the atmospheric environment, and the reason is that the periodicity opening and closing of the fatigue crack results in corrosion residual remaining around the crack. Finally, in the beginning of the fatigue load when other conditions are the same, crack of test beam under corrosion environment is relatively smaller than that under the atmospheric environment.

Reference

Cho K., Park S.Y., Kim S.T., 2011, Fatigue Performance of Precast FRP-Concrete Composite Deck with Long Span, Engineering, 03, 1115-1123.

François R., Khan I., Dang V.H., 2012, Impact of corrosion on mechanical properties of steel embedded in 27-year-old corroded reinforced concrete beams, Materials & Structures, 46, 899-910.

Li S., Tang H., Zhang X., 2014, Fatigue behavior of corroded reinforced concrete beams, Sichuan Daxue Xuebao, 46, 154-160.

Liu L.X., Zhang H.P., 2012, Experimental Study on Bending Behavior of Concrete Slabs Reinforced by Cold-Rolled Ribbed Steel Wires with Improved Elongation, Key Engineering Materials, 517, 583-588.

Tarifa M., Zhang X.X., Ruiz G., 2015, Full-scale fatigue tests of precast reinforced concrete slabs for railway tracks, Engineering Structures, 100, 610-621.

Verma S.K., Bhadauria S.S., Akhtar S., 2014, Monitoring corrosion of steel bars in reinforced concrete structures, Scientific World Journal, 957904-957904.

Yuan Y., Jiang J., 2012, Climate load model – Climate action spectrum for predicting durability of concrete structure, Construction & Building Materials, 29, 291-298.

Zhu H.B., Xu Y.Q., Xiu L., 2014, Fatigue Behavior of Reinforced Concrete T-Beam, Journal of Highway & Transportation Research & Development, 8, 46-51.