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DURABILITY TESTING OF MARINE REINFORCED CONCRETE UNDER FATIGUE LOADING, PART I AND II

by

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ABSTRACT

This study addresses the evaluation of the durability of reinforced concrete marine structures subjected to fatigue loading. The laboratory investigation was carried out on full and half size reinforced concrete specimens with three different water cement ratios (0.3, 0.4, and 0.56), static and fatigue loading conditions, and epoxy-coated and regular black steel reinforcements.
The marine tidal zone was simulated by alternate filling and draining of the tank (wet and dry cycles), and a galvanostatic corrosion technique to accelerate corrosion of reinforcement was used. Half-cell potentials and changes of crack width were measured periodically during the exposure and followed by ultimate strength testing. The significant findings include adverse effect of fatigue loading, existence of an explicit size effect, poor performance of epoxy coated steel, and negative effect of increasing water/cement ratio.

Keywords: anodic direct current, corrosion, durability, epoxy-coated reinforcement, fatigue loading, galvanostatic corrosion technique, half-cell potentials, accelerated simulated marine environment, size effect, ultimate strength, water cement ratio.

INTRODUCTION

Concrete is widely used in nearshore and offshore marine structures, bridge substructures, and superstructures. Experience has shown that the durability of marine concrete structures, is generally good. This is not to say that the experience has been undividedly satisfactory, as long as numerous structures with poor performance can be found in the coastal areas [3]. There are still many unexplained factors in the deterioration process and the relation between the deterioration and the durability of marine concrete structures. This is because of the uncertainties in the construction process and environmental conditions affecting deterioration of reinforced concrete.

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Once concrete is placed in the sea, maintenance becomes very difficult due to its surrounding environment and very expensive. Therefore, the magnitude of the durability problem is considerable enough to merit national action. Concrete in an advanced state of deterioration is generally found to be suffering from more than one cause, and it usually becomes very difficult to identify the first cause which might have broken down the ability of concrete to resist attack from a host of other causes. The damage to concrete structures resulting from the corrosion of reinforcing steel is exhibited in the form of expansion, cracking, and spalling of concrete cover. In addition to the cover loss, a reinforced concrete member may suffer structural failure due to loss of bond between concrete and steel. This is why the corrosion of reinforcing steel is considered to be the most serious problem responsible for lack of durability [4]. Many marine concrete structures, such as floating structures, mobile drilling structures, offshore structures, and bridges, are subjected to a number of fatigue cycles. Fatigue loading is a significant factor in determining the life of the structure, besides corrosion as it considerably enhances the deterioration process in a corrosive marine environment.

OBJECTIVES

A) To evaluate whether specimens subjected to fatigue loading behave differently from those subjected to static loading in a simulated and accelerated marine tidal conditions. B) To evaluate the effect of W/C and the type reinforcement (regular black, epoxy coated) on corrosion damage. C) To evaluate the size effect between deteriorated full and half size specimens.

EXPERIMENTAL INVESTIGATION

Fatigue and Static Loading Test in the Accelerated Simulated Marine Environment

The test was carried out on 8 full (0.3x0.3x2.36m) and 8 half size (0.15x0.15x1.18m) concrete beam specimens with three different W/C (0.3, 0.4, and 0.56), two different reinforcements (epoxy-coated and uncoated regular rebar) at Ocean Front Laboratory. One set of 4 full size and another set of 4 half size concrete beams were subjected to third-point fatigue loading with 0.01Hz frequency (Figs. 1 and 2). Two companion sets of 4 full and 4 half size concrete beams were subjected to third-point static loading in yoked setups (Fig. 3). The load levels were selected to cause initial cracks, with smaller crack widths than the maximum permissible crack width, 0.15 mm for marine concrete (ACI 224R-80). The 200 kN maximum fatigue load (minimum load=22.2 kN) from the actuator was distributed as 80 kN (40x2) for each full size specimen and 20 kN (10x2) for each half size specimen by the load distribution setup. Spring forces were applied to the control beams as a static loading, 80 kN and 20 kN for each full and half size specimens, respectively, by tightening the bolts and nuts on the sandwich yoked setup. All beam specimens were exposed to simulated tidal conditions by alternate filling and draining of seawater in the tank every 12 hours (one tidal cycle a day).

Galvanostatic Corrosion Test Setup

The galvanostatic technique was used to accelerate reinforcement corrosion by impressing anodic direct current. Each set of beams was connected in series with the constant current flowing through all the beams. Stainless steel 303 bars were used for the counter electrodes; the two bars were mounted in parallel near the concrete tension surfaces in the maximum bending moment region. Current levels applied during the exposure were changed to observe the change of behavior of the beams at different current levels. These current levels were as follows: 1) For the first 30 days: No current, and 2) from 30 to 60 days: 190 mA and 24 mA on each of the full and half size specimens. 3) From the 60th day to the end of the exposure, 48 mA and 380 mA for each of the half and full size specimens.

TEST RESULTS

Half-Cell Potential Readings during the Exposure

Half-cell potentials were measured periodically on all the beam specimens with a saturated calomel electrode (SCE) during the last one hour of the dry cycle. Measurements were carried out according to ASTM C876-87. Table 1 shows the half-cell potential readings during the exposure. It was difficult to determine the corrosion tendency of the reinforcement in the seawater environment, employing the standard test method for half-cell potential measurement described in ASTM C876. According to the ASTM standard, there is a greater than 90% probability that the reinforcing steel is corroding at the measured potential values (versus SCE) less than -273 mV. However, the measured half-cell potentials could be used for comparison of the active corrosion tendency of the various kinds of specimens under different loading conditions. The periodic half-cell potential differences between the specimens subjected to fatigue loading and those under static loading. Some specimens under fatigue loading had more positive half-cell potentials than those under static loading for the first month of the exposure. With further exposure, the values for those under fatigue loading became more negative until the end of the exposure period (90th day of exposure). Therefore, an adverse effect of fatigue loading on half-cell potential could be noticed. Full size specimens with W/C=0.3 showed more positive values than those with W/C=0.4 ; and half size specimens with W/C=0.4 had more positive values than those with W/C=0.56. It could be inferred that the reinforcement in concretes with higher w/c ratios had the more active corrosion tendency compared to those with lower w/c ratios.

Final Half-Cell Potential Measurement

After 78,000 fatigue cycles with simulated tidal exposure, the beams were dried in air for at least ten days and the half-cell potentials at different locations along the rebar were measured. All of them showed more negative potentials in the maximum bending moment region than near the ends. Also, the negative potentials were larger in the reinforcement on the tension side than that those on the compression side reinforcement. The measured potentials on the tension side in the maximum bending moment region from all the beams were considerably more negative than the value, -273 mV, SCE, that has been proposed by the ASTM standard C876 for 95 percent likelihood of corrosion. Therefore, reinforcement located on the tension side in the maximum bending moment region had more active corrosion tendency compared to that in other regions. Furthermore, more negative potentials were noticed near the cracks with rust staining in many cases. Even though the readings did not give any information on the extent of corrosion on reinforcement, they indicated that the reinforcement located near cracks have a larger probability for active corrosion than those further away from the cracks. Beams subjected to fatigue loading showed more negative potentials than those with static loading in the maximum bending moment region. It was also found that the potentials increased negatively as the W/C increased. Therefore, half-cell potential readings enabled the comparison of the corrosion tendency of beams subjected to different loading conditions with varying water/cement ratios. Fig. 4 shows cracks, rust staining, and half cell potentials on the beams, FD4.

Crack Investigation

Crack shapes of all the beams were observed after the exposure testing. Most of the beams showed more rust staining in the middle maximum moment region, indicating more corrosion damage than in the other regions (Fig. 4). The longitudinal cracks observed propagated from transverse cracks and sometimes bridged two or more transverse cracks. Based on the larger negative half-cell potentials measured, the corrosion damage on the main reinforcement, close to transverse cracks, was more severe than that further away from the cracks. On the other hand, transverse cracking resulted not only from loading, but also from corrosion-induced damage of stirrups. The similarity of the cracks formed by galvanostatic corrosion to those formed during the long term exposure test by Kobayashi and Hoshino (introduced by Uomoto and Misra [5]), indicates the adequacy of the galvanostatic method to accelerate the corrosion process in the laboratory tests. Therefore, an interaction between the effects of corrosion and loading is identified for the deterioration process of marine concrete through the simulated laboratory investigation. The choice of the galvanostatic method to accelerate the corrosion process in the laboratory tests was reasonable.

Ultimate Strength

After 78,000 fatigue cycles, ultimate strength testing was carried out by applying four point flexural loading. The failure mode observed from all the beams at ultimate strength was a flexural failure, enhanced by longitudinal cracking due to corrosion on reinforcement on tension side. The ultimate strength values and strength reduction factor of the beams are compared in Table 2. The findings are as follows : 1) Ultimate strengths of all the half size beams were higher than those for the full size ones. 2) Beams subjected to fatigue loading during the exposure period showed lower ultimate strengths than those subjected to static loading, both full and half size. 3) The ultimate strengths decreased with increasing W/C. 4) Beams with epoxy-coated reinforcement showed less strength than those with regular steel reinforcement for both full and half sizes. The degree of deterioration can be expressed by the strength reduction factor, R which can be calculated as follows.

$$R = f_u / f_n$$

where f_n is the nominal strength of non deteriorated beams calculated from the formula (ACI 318-89 Building Code 10.3.1) and f_u is the ultimate strength from the test results. A bigger R means less deterioration. Therefore, it is indicated that 1) Beams subjected to fatigue loading deteriorated more than those under static loading, 2) The deterioration rates increased with increasing W/C, 4) Beams with epoxy-coated reinforcement deteriorated more than those with regular black reinforcement.

Damage Inspection of Beam Containing Epoxy Coated Reinforcement

The corrosion damage on reinforcement was investigated for beams HS6E, HS6, and HD6 by chiseling around the beam surface to see the damage. Unlike regular black reinforcement, epoxy coated reinforcement showed quite deep local pitting corrosion damage which caused stress concentration in the reinforcement.

DISCUSSION

All the full and half size beams were ranked in Table 3. The ranking was based on strength reduction factor of each specimen. Table 3 shows that, as expected before the testing, the beam with the lower w/c ratio, under static loading during the exposure, showed the better performance, and the one with the higher W/C, in fatigue loading under exposure, showed poor performance. Test results indicated that 1) beams subjected to fatigue loading deteriorated more rapidly, showing more negative half-cell potential values than those subjected static loading and 2) beams made with higher W/C mixtures had more negative half-cell potential values, less cracking resistance, and less ultimate strength bearing capacity than those made with lower water/cement ratio mixtures, for both fatigue and static loading conditions. The ultimate strength test results showed explicit evidence of the size effect for two deteriorated beams geometrically similar to each other.

CONCLUSIONS

1. Beams deteriorated more rapidly under fatigue loading than static loading. They showed more and longer longitudinal cracks induced by corrosion at the end of the simulated marine exposure, and less ultimate

strength bearing capacity, than those under static loading. **2.** Beams with epoxy-coated reinforcement performed more poorly than regular beams in the accelerated corrosive environment. Unlike regular black reinforcement, epoxy coated reinforcement showed quite deep local pitting corrosion damage, which caused stress concentration in the reinforcement. **3.** The durability of reinforced concrete decreased with increasing water/cement ratios in a marine environment. Beams made with higher W/C mixtures had more negative half-cell potentials, less cracking resistance, and less ultimate strength bearing capacity. The utilization of dense and less permeable high strength concrete with low water/cement ratios can contribute to the enhancement of the durability of marine concrete structures. **4.** The Size effect (a function of the ratio of the beam depth to maximum size of coarse aggregate) needs to be definitely considered in extrapolating the laboratory test results of concrete specimens to prototypes. This will avoid overestimation of prototype-strength based on laboratory testing. **5.** The cracking patterns from accelerated testing (by galvanostatic method) were representative of those observed under long term exposure of marine concrete structures, showing both transverse and longitudinal cracks along the beams.

REFERENCES

1. ACI Committee 224, " Control of Cracking in Concrete Structures "; Journal of American Concrete Institute, Proceedings Vol.77, American Concrete Institute, Detroit, October 1980, pp.3-20.

2. Bazant, Z. P. and Xu, K., " Size Effect in Fatigue of Concrete "; ACI Material Journal, Vol. 88, No. 4, American Concrete Institute, Detroit, July-August 1991, pp. 390-399.

3. Espelid, B. and Nilsen, N., " A Field Study of the Corrosion Behavior on Dynamically Loaded Marine Concrete Structures "; Concrete in Marine Environment Proceedings, Second International Conference, St. Andrews by the Sea Canada, ACI-SP109, American Concrete Institute, 1988, pp. 85-104.

4. Mehta, P. K. " Durability of Concrete-Fifty Years of Progress " Durability of Concrete, Proceedings of Second International Conference, Montreal Canada, ACI SP-126, Vol. 1, American Concrete Institute, 1991, pp. 1-31.

5. Uomoto, T. and Misra, S., " Behavior of Concrete Beams and Columns in Marine Environment When Corrosion of Reinforcing Bars Take Place "; Concrete in Marine Environment Proceedings of Second International Conference, St. Andrews by the Sea Canada, ACI SP-109, American Concrete Institute, 1988, pp. 127-146.

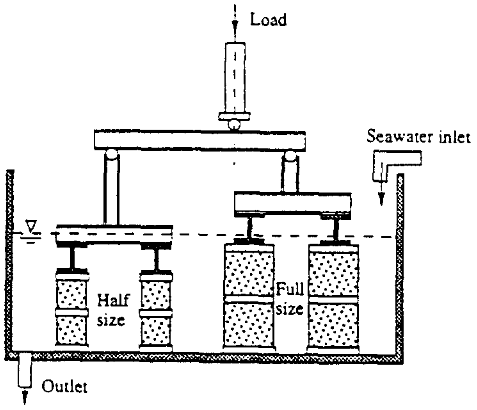

Fig.1 Transverse section at fatigue test setup

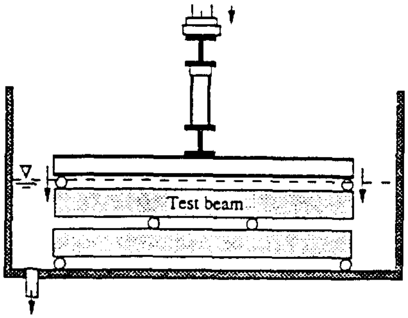

Fig.2 Longitudinal elevation of fatigue test setup

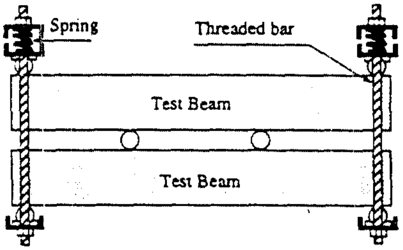

Fig.3 Control beams under static loading

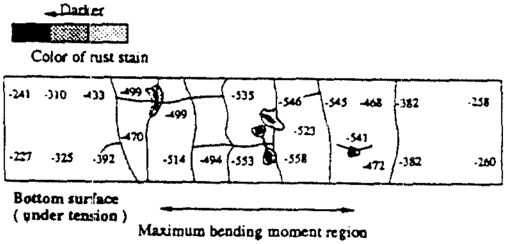

Fig.4 Final half-cell potentials (mV,SCE) and cracks on FD4

Table 1 - Periodic Half-Cell Potential Readings (mV, SCE)

Day	FD3	FS3	FD4	FS4	FS3E
1	-64	-183	-108	-157	-123
10	-349	-426	-305	-352	-464
30	-360	-433	-440	-392	-484
46	-458	-434	-486	-472	-526
65	-480	-424	-492	-452	-455
78	-492	-428	-519	-467	-512
90	-510	-439	-528	-480	-416

Day	HD4	HS4	HD6	HS6	HS6E
1	-31	-56	-12	-64	-90
10	-333	-370	-505	-558	-604
30	-347	-352	-587	-548	-630
46	-505	-467	-628	-582	-518
65	-527	-457	-618	-544	-548
78	-532	-463	-603	-566	-568
90	-549	-478	-638	-578	-529

Table 2 - Nominal strength, ultimate strength, and strength reduction factor

Beams	FS3	FD3	FS3E	FS4	FD4
Nominal Strength, fn (kPa)	29, 131	29,131	29,131	28,965	28,965
Ultimate Strength, fu (kPa)	24,953	24,422	24,450	23,588	23,040
Strength Reduction Factor, R	0.86	0.84	0.84	0.81	0.80

Beams	HS4	HD4	HS6	HD6	HS6E
Nominal Strength, fn (kPa)	28,965	28,965	27,746	27,746	27,746
Ultimate Strength, fu (kPa)	31,400	29,855	28,828	28,311	28,283
Strength Reduction Factor, R	1.08	1.03	1.04	1.02	1.02

Table 3 - Evaluation chart

Full size beams			Half size beams		
Rank.	R	Beam	Rank.	R	Beam
1	0.86	FS3	1	1.08	HS4
2	0.84	FS3E	2	1.04	HS6
3	0.84	FD3	3	1.03	HD4
4	0.81	FS4	4	1.02	HD6
5	0.80	FD4	5	1.02	HS6E