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Corrosion Fatigue in Concrete for Marine Applications

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Synopsis: Structural concrete is widely used in marine environments, but a relatively recent development has been its use in structures such as oil production platforms, ships, wave energy devices etc., where fatigue loading can be significant. It is well known that the effect of a corrosive environment on structural steelwork is to reduce its fatigue life, and this paper describes work in progress to determine whether or not the same is true for structural concrete, both reinforced and prestressed.

Reinforced and prestressed concrete beams are being tested in unidirectional bending, and in reverse bending, in jackets containing sea-water, at slow cycling rates (about 0.17 Hz)which approximate to sea-wave frequencies. The sea-water is pH and temperature controlled and is continuously circulated from a storage tank. Control specimens are tested at higher frequencies (3 to 5 Hz) and these show the expected reduction in fatigue endurance, compared with tests in air.

However, the wave-frequency test results show that deposits are formed in the flexure cracks after 3 to 4 days of cyclic loading, and this has the effect of increasing, rather than decreasing, the fatigue lives of the beams - certainly when the bending is unidirectional. Under reverse bending this effect is not yet confirmed, although the crack-blocking is observed to take place.

Electron-microscopy of the failure surface is being utilised to establish the mechanism by which corrosion fatigue failure occurs under these conditions.

Keywords: beams (supports); bending; concretes; corrosion; cracking (fracturing); fatigue (materials); fatigue tests; marine atmospheres; offshore structures; prestressed concrete; reinforced concrete; sea water.

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INTRODUCTION

Structural concrete has been widely used for many years in marine environments but a relatively recent development has been its application to structures such as oil production platforms, ships and boats, and the many projected wave energy and other ocean-based energy devices. In all of these cases fatigue loading may be significant and it is obvious that corrosion is also a possibility. It is well known that the effect of a corrosive environment on unprotected structural steelwork is to reduce its fatigue life, (1,2) and it would be expected that the same would be true for structural concrete, both reinforced and prestressed.

At the time when the work described in this paper was started there were, unfortunately, few data available on the fatigue behaviour of concrete members in seawater. Those which were available applied only to reinforced concrete (3-5) and had yielded rather conflicting results. (1,6,7). The work had been restricted to high frequency loading conditions (3 Hz. or more) and so was of limited applicability where the fatigue loading was likely to be applied at low frequencies, as is the case with wave-loaded structures. In addition, tests at 3 Hz. or above are usually of only short duration (one day or so at high stress ranges) and thus they do not reproduce the effects which any time-dependent environmental processes such as corrosion might have on the fatigue endurance of the material.

The work described in this paper is an initial step in helping to provide a clearer understanding of the inter-relation between corrosion and fatigue in reinforced concrete in a marine environment so that designers may be able to draw on the results to interpret, and extrapolate from, available data with increased confidence. It began with tests on reinforced concrete beams bent in one direction only, but reverse bending is now being studied. The paper presents some interesting results and suggests hypotheses to account for the effects observed.

SPECIMENS AND TEST PROCEDURES

The specimens were beams of identical overall dimensions, shear reinforcement, and cover. Beams intended for bending in one direction only were reinforced with two 10 mm dia Torbars on the tension side, with two 8 mm dia mild steel lacing bars to provide anchorage for the stirrups, while those intended for reverse bending tests had two 10 mm Torbars top and bottom. Full details are given in Figs. 1a and 1b. Details of the steel and concrete are given in Table 1, and full particulars of the method of production, curing, etc. are given in a previously published article. (8) For stress level calculations the concrete strength (cube tests) was taken as 60 N/mm^2, and the elastic modulus of the steel as 200 kN/mm^2. Stress levels were referred to the specified characteristic proof stress of 460 N/mm^2.

In the main series of tests carried out up to the present beams in seawater have been subjected to ten applications of load per minute (0.17 Hz.), which is the approximate frequency of very large waves in the North Sea. A few tests were done in seawater at 5 Hz. in order to study the effect of frequency on endurance. As control tests, and for comparison with other published results (5) tests were done in air over the same frequency range (0.17 to 5 Hz.).

The central section of the beam was enclosed in a transparent plastic water jacket containing seawater. The seawater used was a synthetic type which included all the inorganic constituents of natural seawater including trace elements. Its composition is given in Table 2. Initially the seawater was drip-fed from a header tank to waste, but in later tests it was rapidly circulated and dosed to maintain a constant pH level. Its temperature was controlled in the range 18 to 21°C by means of simple combined heaters and thermostats, and it was continuously aerated in the jackets to maintain full saturation with oxygen. The beams were generally immersed in seawater almost up to their top surfaces, but in one case involving uni-directional bending the water jacket was filled only to the level of the main tension steel to study the effect of "splash-zone" corrosion.

Symmetrical two-point loading was applied, as shown in Fig.2, on a span of 2.8 metres, the shear span being 1.0 metre. Two different types of water jacket have been used and their dimensions are also given in Fig. 2. In the unidirectional bending tests on "singly reinforced" beams a minimum stress level of 10% of the specified characteristic yield strength of the reinforcement was set, i.e. 46 N/mm^2, and the upper stress levels varied from 92% to 40% of the characteristic strength, giving stress ranges varying from 377 to 138 N/mm^2. The corresponding ranges of compressive stress in the extreme fibre of the concrete varied from 20 to 5 N/mm^2. For concrete with a cube strength of 60 N/mm^2 this meant that there was little chance of fatigue failure of the concrete before the steel failed.

The initial tests in reverse bending have all been carried out with the load controls set to give a range of stress of from 281 N/mm^2 to -9 N/mm^2 in the bars on the side more highly stressed in tension, i.e. the lower bars. The corresponding stress range on the less highly stressed side is from 207 N/mm^2 to -14 N/mm^2, so there is little chance of failure occurring on this side.

The simple fatigue machines used for the slow tests (Fig. 3b) employed a 0.75 kW hydraulic pump-set operating a single acting ram, in the case of the unidirectional bending tests, and a double-acting one for the reverse bending tests. The load was monitored by means of strain gauge load cells mounted in spherical seats attached to the ram body. Load variation was achieved by means of pressure control valves and cycle frequency controlled by a constant speed cam. The wave-form of load against time was arranged to be nearly sinusoidal by the adjustment of fine control valves operating on the ram inlet and outlet pipes, and, for the single-acting rams, the lower load was controlled by a further flow restriction in the oil return line. Seven unidirectional bending, and three reverse bending machines have been constructed. The higher frequency tests used Losenhausen servo-controlled equipment with a demountable packless ram mounted on a loading frame bolted to a hollow structural testing floor, (Fig. 3a).

During the tests measurements were made of beam deflection, variation in concrete crack width, strain in the concrete, and in some cases, strain in the main tension steel. The seawater pH and the reinforcement electrode potential were also monitored. Failure normally occurred by the fracture of one or other of the main tensile bars due to fatigue, usually followed immediately by yield of the remaining bar. In some cases it was possible to stop the test before the second bar yielded. Occasionally two bars failed simultaneously in fatigue. After the completion of a test the beam was broken up and the main bars removed for microscopic examination to study the nature of the failure surfaces and determine the frequency of other incipient fatigue cracks.

RESULTS

To date about 87 tests have been completed, 77 in unidirectional bending and 10 in reverse bending. The results are given in Tables 3a to 3e and 4a and b. They are shown graphically in Fig. 5 in which intended stress range is plotted against fatigue endurance.

1. Unidirectional Bending

a. Tests in air-- The effect of frequency of load application on fatigue life in air is shown in Fig. 4 in which all the results of unidirectional bending tests in air at an upper stress level of $0.85f_y$ are plotted. This shows that the test cycle frequency in the range from 0.17 to 5 Hz. has no noticeable effect on the endurance of beams tested in air. This result was expected but its confirmation made it possible to do the majority of the air control tests at about 5 Hz. and so save time. These tests also agreed generally with the work of Bannister (5). In the air tests failure always occurred at main flexure cracks in the concrete, and there were usually about 8 to 10 of these in the maximum bending zone. In 9 cases the failure was between the load points, and in three it was at a load point. This could represent a statistical spread throughout the 8 to 10 concrete cracks.

b. Tests in seawater -- i. Tests at 5 Hz. As shown in Table 3c the endurances at a stress range of 345 N/mm^2 were all less than 200,000 cycles. Failure occurred in all cases but one, close to midspan and within the seawater environment.

ii. Tests at 0.17 Hz. In most of the initial tests the load range applied was that calculated to produce a stress range of 345 N/mm^2 in the tension steel, and Table 3d and Fig. 5 show that the scatter in the fatigue lives of the seawater tests in the short tanks is similar to that of the tests in air (Tables 3a, 3b). Failure occurred inside the tank in only two of the short tank tests. In all the other tests it took place at the first or second crack in the concrete outside the tank, and in some of these cases seawater could be observed seeping from such cracks during part of the test period. It is presumed that this seawater reached these external cracks by some internal path.

Because the early tests did not produce consistent failures within the corrosive environment the use of tanks double the original length was adopted. Using these tanks the fatigue lives in seawater at a load range calculated to produce a stress range of 345 N/mm^2 yielded the surprising result (See Table 3e and Fig.5) that the fatigue endurances were greater than those found using the short tanks. Of the four beams which have failed to date one has done so outside the extended tank, i.e. in the shear span, where the moment is less than is required to produce the intended stress range. Two beams which failed within the environment had fatigue endurances of 8.29×10^6 cycles or greater - more than ten times that to be expected in an air test at the same intended stress range. Three tests on beams in long tanks are still running, with endurances already greater than in any air or short tank tests at the same intended stress range.

It has been observed that, during the first ten or so days of a test, a deposit builds up at each immersed crack in the concrete. This deposit increasingly inhibits crack closure on reduction of load and deflection measurements, together with observations of crack width changes, have confirmed this effect which will be considered in more detail later in the paper. The deposit consists of calcium carbonate, ($Ca\ CO_3$), and/or magnesium hydroxide, ($Mg(OH)_2$) and experiments carried out elsewhere have confirmed this.

Another feature of the early slow seawater tests was that the pH of the seawater within the tanks was generally higher, at 8.5 to 9.5, than that of newly prepared synthetic seawater whose pH, at 7.8 to 8.2, was typical of natural seawater. Because of the obvious importance of the crack-blocking effects mentioned above, and with the knowledge that deposition of chemical species from seawater generally becomes more prevalent as the pH rises, it was decided that all subsequent tests should be undertaken with the pH controlled to between 7.8 and 8.2. This has been done by a system of rapid circulation of seawater through the jackets from a large tank which is dosed with hydrochloric acid as necessary. Beams tested under this regime continue to show the effects of crack-blocking and increased endurances.

2. Reverse Bending

a. Tests in air -- Up to the present time a total of six reverse bending tests in air have been completed (See Table 4a) all at the same stress range. Endurances have ranged from 161,000 to 573,000 cycles, and all failures have taken place either between the load points or at a load point. These results overlap with the scatter of the air tests and fast seawater tests at the same range of stress in unidirectional bending but are generally lower.

b. Tests in seawater -- Only four results are available to date from the programme of reverse bending tests in seawater and the results are listed in Table 4b. Endurances range from 161,000 to 208,000 cycles; short tanks were used initially and one failure has taken place within the tank, the other two occurring at load points. One long tank test has been completed and the failure was within the tank. The results fall within the scatter of the air test results in Table 4a but are all at the low end of the range. Although there is evidence from crack width measurements that crack blocking is occurring, as it did in the unidirectional bending tests, there is no indication of any increase in fatigue endurance.

DISCUSSION

As is indicated in Tables 3a to 3e and 4a and b and in Fig.5 most of the tests carried out so far have been at high stress amplitudes. The first phase of the work was planned in this way to enable as many tests as possible to be completed quickly in order to obtain early indications of the effects to be expected. In seeking useful conclusions, therefore, only these high-stress results may be drawn upon at present, and this discussion will be limited to that section of the research programme. The study of the detailed mechanism of corrosion fatigue deterioration in reinforced concrete will be left to another occasion.

1. Unidirectional Bending

The evidence from these preliminary results is that at high stress-cycle frequencies, and high stress ranges, which are conditions in which failure normally occurred in the tests after about one day, the effect of submersion in seawater was to reduce significantly the fatigue life of reinforced concrete compared with that in air. This result confirms the conclusions of Bannister (5) but conflicts with those of others (3,4). In these high frequency tests no signs of crack-blocking or reduced deflection range were observed. The reduced fatigue lives observed in this type of test are in agreement with results for unclad metals.

However, at 0.17 Hz. under conditions of high stress range (345 N/mm^2, 49,300 psi) the seawater did not appear to gave a deleterious effect on the fatigue lives of the beams. On the contrary, as the tests with the long tanks indicated, fatigue lives in the fully submerged condition may be longer in seawater than in air. This is the opposite effect to that observed in unclad metals where reduction of loading frequency progressively accentuates the deleterious effect of seawater, at least until extremely low frequencies of around 0.01 Hz. are reached.

Measurements of beam deflection range during a test yield the typical results shown in Fig. 6, and crack opening ranges show similar trends. It can be seen that from the first day these ranges start to decrease significantly and after only a few days the changes are quite marked. The fall-off continues until a state of stability is reached, after which the crack opening and deflection ranges remain virtually constant. In all tests, and particularly in the lower stress tests, a large proportion of the specimen lifetime is spent cycling under these substantially less severe conditions.

In the tests at the lower stress ranges the final crack opening displacement is much less than in the higher stress tests, but the time taken to reach the stable condition of reduced crack opening is approximately the same. This indicates that, while the effect of crack blocking on the stress range in a cycle is marked there is a limit to it, and the stress range never falls to zero, but only to a more or less constant fraction of the initial range. After about 10^6 cycles of load this fraction is approximately 0.5. This reduced stress range in the bars is the reason for the greatly extended endurances observed in the slow tests compared with those found in high-speed, and therefore short-duration, tests. In the slow tests it is clear that the deleterious effects of the corrosive environment are greatly outweighed by the beneficial effects of the stress range reduction due to crack blocking. The results shown graphically in Fig. 7 are untypical of the majority of the tests, but they are included for interest as they demonstrate clearly the correlation between the measured parameters that indicate blocking of the cracks, crack opening, concrete strain and beam deflection. It can be seen from all three parameters that at around 700,000 cycles partial unblocking of the cracks occurred, and it is interesting to note that blocking was re-established at about 1,400,000 cycles, precisely double the time required to block the cracks initially in the period before the unblocking event. There is no evidence to suggest a reason for the unblocking taking place - the pH, for example, was controlled well within limits and no sudden dissolution could be possible. It would seem that the event was mechanical, perhaps the effect of a branching crack reaching a free surface or some other similar happening. This argument is not wholly convincing as several blocked cracks suffered unblocking, and it might be the case that all of the submerged cracks were involved. This is apparent because the concrete strain was measured at different locations from either of the crack-opening gauges and yet the measured effects show the same indications. In addition, the change in deflection was consistent with the effect being widespread and was too great to be due to the changes in only one or two cracks.

This beam failed within the corrosive environment at 2.3×10^6 cycles of a load range intended to produce a stress range of 345 N/mm^2 (49,300 psi) in the tension steel. This fatigue life implies that the stress range was very much lower than intended for the larger fraction of its life, but not so low as would apply at the first crack outside the tank. The stress history of the beam would be of this nature:

No. of cycles		0	12,000	100,000	1,000,000	2,300,000
Inside tank	f_{min}/f_y	0.1	0.19	0.4	0.46	0.61
	f_{max}/f_y	0.85	0.85	0.85	0.85	0.85
	Stress range/f_y	0.75	0.66	0.45	0.39	0.24
At first crack outside tank	f_{min}/f_y	---------		0.08	------------------	
	f_{max}/f_y	---------		0.67	------------------	
	Stress range/f_y	---------		0.59	------------------	

From the above figures it is clear that it is not possible to quantify the effect on fatigue life by these methods, but it is also clear that the reduction in the severity of the stress conditions, which is of the nature shown in Fig. 8, is significant and begins early in the life of the beam. The beam (Test No. 98) failed within the tank whereas most of the others in that test series failed outside the tank. It may be that this was due to the unblocking which occurred during the test and which did not necessarily occur in the other specimens.

The interpretation of the concrete strain readings requires consideration of the changes in shrinkage strain which take place during the duration of a test. The ages of the beams at the start of test varied from about 40 days to, in some cases, as much as 200 days, so considerable shrinkage strain could have taken place before loading was applied. The effect of submersion would be to permit the recovery of some of that shrinkage strain and allowance was made for this.

The following hypothesis is suggested to explain the phenomenon of crack-blocking and its effect on fatigue lives of reinforced concrete beams cycled slowly in unidirectional bending in a corrosive environment. As the cracks are geometrically similar blocking should take place at approximately similar rates irrespective of initial crack width. The product near the crack tip will be compacted as the beam recovers its deflection on each cycle, thus increasingly inhibiting the beam in its attempt to return to its original minimum deflection on reduction of load. The salts away from the crack tip experience no such compaction and may remain less dense. However, they are still able to prevent mass transfer into and out of the crack, causing the deposition process to slow down at the crack tip. New salts are thus no longer available for further compaction and blocking ceases to affect the stress range when this condition of equilibrium is reached.

2. Reverse Bending

The results of the reverse bending tests are too limited in number, and in the range of parameters covered, to justify doing more than suggest a few tentative indications. Although crack blocking does occur with reverse bending at slow cycling rates there are no indications of increased fatigue endurances as a result. Our seawater test results are within the scatter of air test results, but they are concentrated at the low end of the range. This suggests the likelihood that, as more test results become available some reduction in fatigue life in seawater will be shown. Tentative support for this conclusion is given by suggestions that the effect of crack-blocking under reverse bending is to prestress the beam, locally, at each crack site, in tension. This would increase the mean stress level in both top and bottom main steel, while leaving the stress range virtually unchanged, and so it would be expected that there would be some reduction in endurance, irrespective of any corrosive effects which might also take place.

3. Mechanism of Corrosion Fatigue Failure

Observations, both visual and microscopic, confirm that corrosion of the reinforcing steel does take place in seawater tests. Rust stains are seen in the region of cracks at an early age in the duration of a test, and it is clear that the hypothesis that the alkaline environment of the concrete would prevent corrosion does not hold when cyclic loading is applied. Visual examination of the failed bars taken from the beam after a test confirms this, and electron microscopy applied to the failed parts of the bars is beginning to yield interesting results which may help to elucidate the mechanism of failure in this type of situation.

FUTURE WORK

In addition to completion of a full programme of reverse bending tests covering a more complete range of the relevant parameters future work will be directed towards gaining a better understanding of the major mechanisms operating in the corrosion fatigue failure of reinforced concrete. To this end it is likely that more small scale tests, and model testing and analysis, will be carried out.

Plans are also in hand, and equipment is being manufactured, to allow some beam tests to be carried out under hydrostatic pressure equivalent to that experienced at sea-bed depths of up to 200 m (650 ft).

A programme of tests on post-tensioned prestressed concrete, which is also widely used in marine environments, has recently been started.

CONCLUSIONS

The results of the programme of testing carried out up to the present time enable the following conclusions to be drawn, for the range of variables studied:-

1. Reinforced concrete beams immersed in seawater and loaded cyclically in unidirectional bending applied at low, ocean wave, frequencies experience progressive blocking of the cracks on the tension side. The effect of this is to reduce the range of bar stress, with an increase in the mean stress, and to increase the fatigue lives of the beams, compared with their expected fatigue lives in air.

2. Otherwise identical beams, when tested at higher, 3 to 5 Hz., frequencies, do not experience crack blocking, and have slightly reduced fatigue lives, compared with their expected fatigue lives in air.