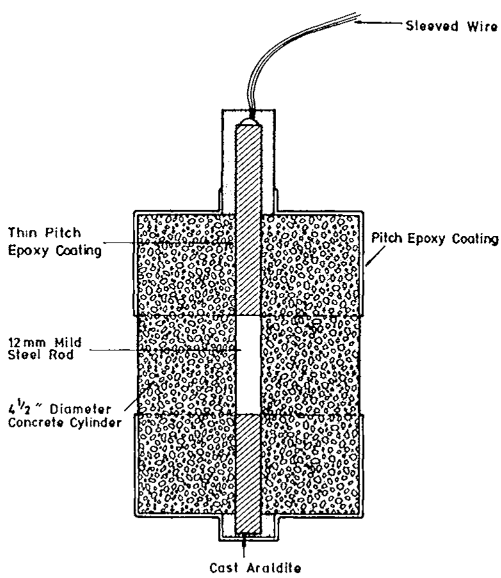

FIGURE 6 Specimen used in laboratory investigation

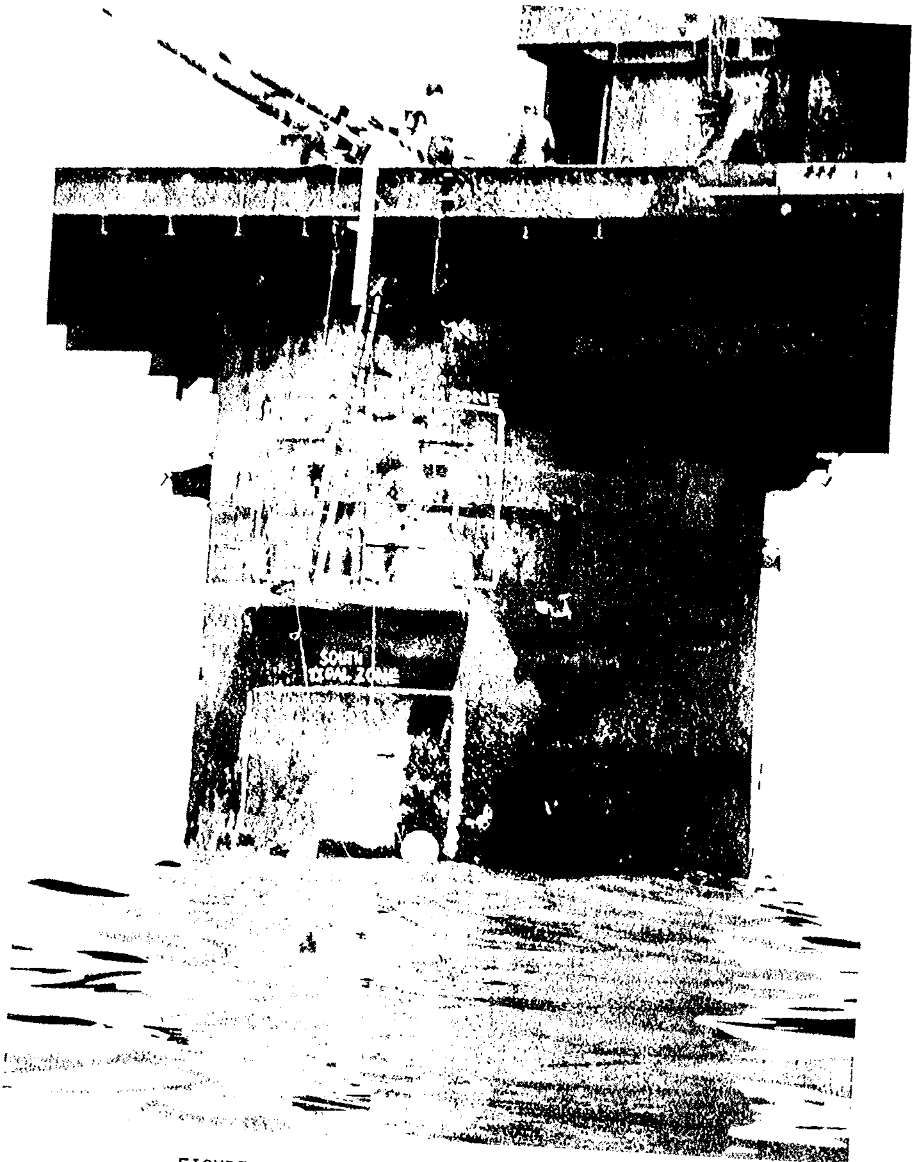

FIGURE 7 One leg of the Tongue Sands Fort

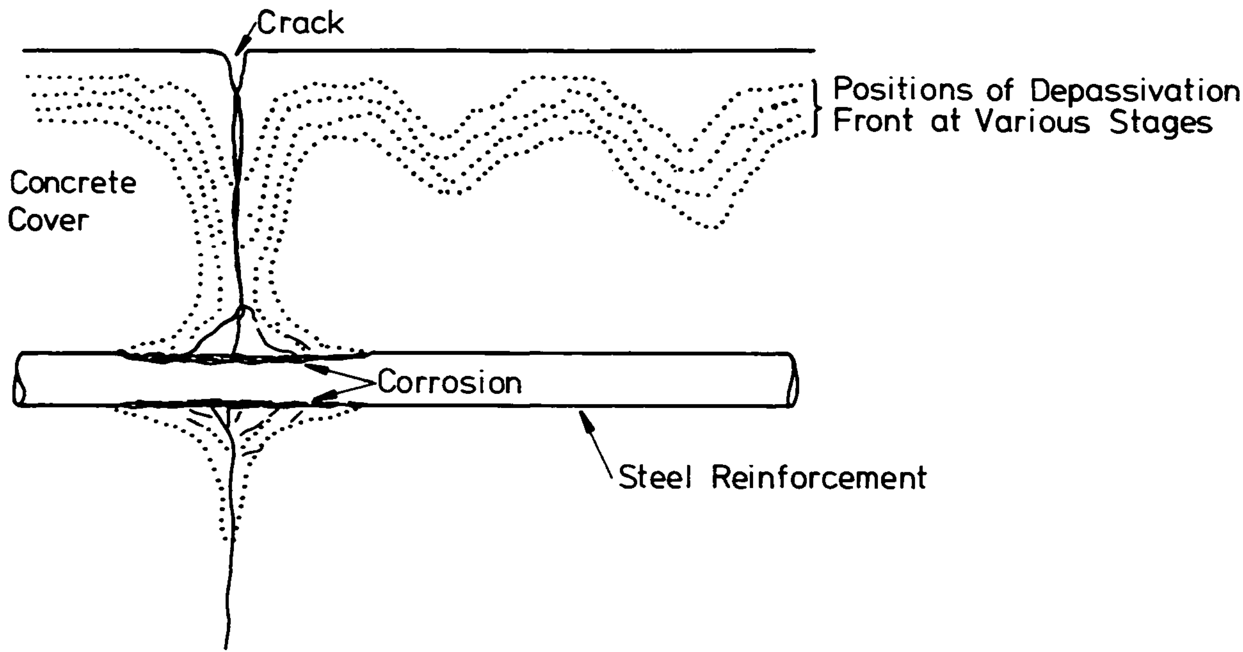

FIGURE 8 Penetration of depassivation fronts at cracks in concrete

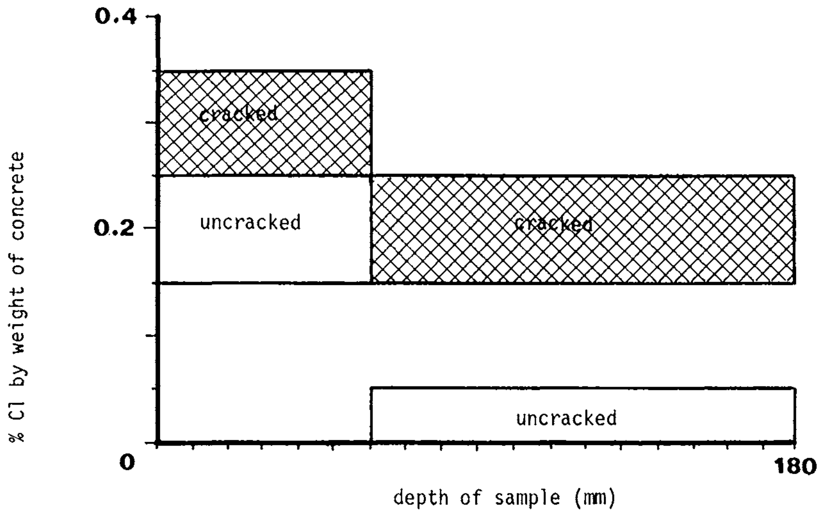

FIGURE 9(a) Chloride penetration into concrete fully submerged in sea water

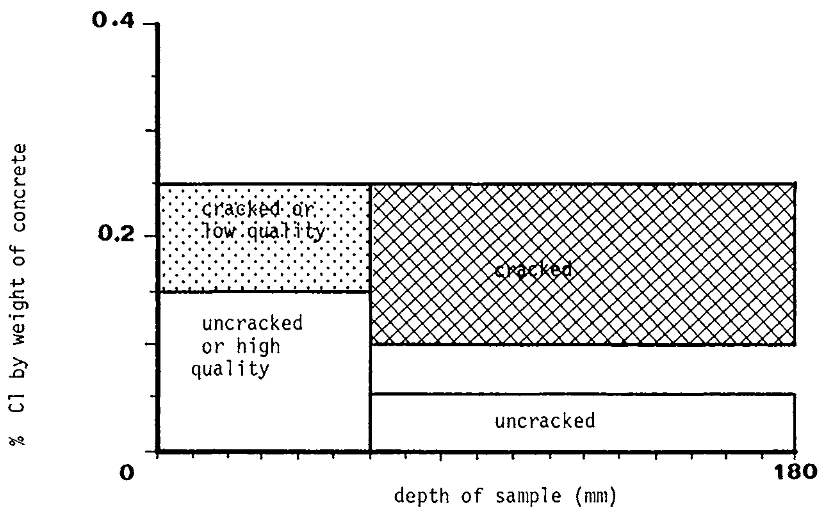

FIGURE 9(b) Chloride penetration into concrete in saline atmosphere, splash or tidal zones

SP 65-23

Fatigue of Reinforced Concrete in Sea Water

By W. S. Paterson

Synopsis: Tests have been carried out to determine the fatigue life of Torbar cold worked reinforcement in concrete beams in a seawater environment at a loading frequency of 0·1 Hz (near wave frequency) and also at 3·0 Hz so that long endurance tests at low stress ranges could be accomplished within a reasonable time scale.

The adoption of a mechanical loading system offered a considerable saving in construction and running costs of the rigs compared with conventional servo-hydraulic systems. It also simplified the arrangements for tests at a simulated water depth of 30m which were performed in a purpose made pressure chamber.

The results have indicated that the fatigue life of Torbar in seawater is lower than in air when the test duration is greater than 1 to 2 months when the conditions exist for a fatigue crack to initiate at a corrosion site. A significant feature of the research was that the beams exhibited the phenomenon of 'cyclic stiffening' resulting from a build up of deposits in the cracks in the concrete. This caused a progressive reduction in the deflection range, the applied load range remaining unchanged. While the stress range in the Torbar was correspondingly reduced, corrosion was not inhibited.

Keywords: beams (supports); crack width and spacing; cyclic loads; fatigue (materials); fatigue tests; loads (forces); reinforced concrete; sea water.

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INTRODUCTION

There is considerable amount of test data available on the fatigue strength of plain and reinforced concrete under idealised loading conditions. These data have been used successfully for the design of concrete structures on land and it has been shown that there are no problems due to fatigue for the vast majority of structures when using current design methods. However, very little data exists on fatigue of reinforced concrete in seawater; such as there is has been obtained using mainly small diameter reinforcement ($<$ 12mm). The data suggested that the inclusion of a corrosion promoting medium can significantly lower the fatigue strength of reinforcement in concrete. It is also known that there is a size effect on the fatigue properties of steel reinforcement.

Accordingly, in order to broaden the range of data, one of the projects of the UK Concrete in the Oceans programme was designed to obtain data for a reinforcement size typically utilised in offshore structures. This followed a review of previous research in which a number of aspects of fatigue were identified as worthy of further study. Details of the project parameters are listed in Table 1.

DESCRIPTION OF THE BEAMS

Dimensional and reinforcement details of the beams are shown in Figure 1. Torbar is a cold worked high yield steel reinforcement; chemical and mechanical tests on samples indicated compliance with BS4461:

0.2% proof stress	446 N/mm^2
Ultimate stress	531 N/mm^2
Elongation	19%
Carbon	0.23%
Sulphur	0.009%
Phosphorous	0.077%

The 28 day compressive strength of the concrete measured on 100mm cubes was 62 N/mm^2. Other concrete properties were:

Drying shrinkage	0.05%
Modulus of rupture	6.0 N/mm^2
Modulus of elasticity	40 kN/mm^2

After removal from the moulds the beams were covered with damp hessian for one month followed by drying out in ambient conditions for two months.

Approximately 3 months after casting each beam was subjected to loading applied at the positions decided on for the fatigue testing to induce flexural cracks in the concrete. The beams to be tested in seawater were then placed in a tank containing seawater to saturate the concrete until required for test and to ensure that the Torbar was in a corrosive environment.

CHOICE OF TESTING METHOD

Cyclic fatigue can be applied to beams by means of either hydraulic or mechanical based loading systems. From discussions with various research establishments having servo-hydraulic equipment and the Transport and Road Research Laboratory (TRRL) where a fatigue programme based on mechanical rigs was currently under way, it was decided that the tests would be carried out using mechanical rigs. The reasons supporting this decision were:

(1) the very considerably lower running costs.

(2) a much simpler control arrangement given the duration of the tests (up to about 400 days).

(3) the relatively low cycle rate.

(4) the ease of incorporating the water circulation system in the test rig.

(5) simplification of the rig for the tests at a simulated water depth of 30m.

A disadvantage of mechanical loading was that manual adjustments to the load needed to be made to compensate for any load change resulting from reduced stiffness of the beam. This was because the load was applied through a mechanism producing a constant deflection to the beam. However, TRRL experience indicated that the extent of adjustment was likely to be small and of relatively short duration ($< 10^5$ cycles), after which conditions would stabilise.

Two methods for simulating the 30m water depth tests were considered. Firstly, the beam would be encased in a pressure jacket, the combined assembly being positioned in the test rig. This method presented difficult design problems of load transfer through the jacket, the circulation of the water and the measurement of crack widths. Secondly, the location of the complete test rig with beam inside a large pressure chamber; with the beam immersed in water the chamber would be pressurised pneumatically. The second method was adopted.

DESCRIPTION OF THE TESTING METHOD

Figure 2 shows the details of a rig, six of which were constructed. This was based on and was similar in many respects to the TRRL design although the component parts were more substantial to accommodate the higher loads applied. Cyclic loading was applied to the beam by a toggle action. The toggle was reciprocated by an eccentric and connecting rod mechanism. Coarse adjustment of the load was effected by varying the stroke of the machine by adjusting the throw of the eccentric. Fine adjustments were made by varying the length of the connecting rod. The static load could be varied without changing the cyclic load range by raising or lowering the pivot of the toggle tension links. Electric motors provided the drive via gear boxes which regulated the frequency of loading to 0·1 or 3·0 Hz. Control switches were incorporated which would shut off the power supply to the drive motor if either overheating in the motor or beam deflection exceeded pre-determined limits.

The toggle action produces a loading waveform which was substantially sinusoidal but with a small difference between maximum and minimum load.

The seawater circulation from a central reservoir was regulated at each rig tank with a valve. The water was pumped in at the bottom of the tank and flowed out through an overflow pipe positioned to keep it at the level of the reinforcement in the beam. Before being pumped to the tanks the water passed through a chiller unit to maintain the outflow at the required temperature. The seawater was replaced whenever the pH reached 8·4.

A general view of the test facility is shown in Figure 3.

MONITORING METHODS AND INSTRUMENTATION

Load Measurement

The loading beams in the rigs were used for monitoring the load applied during the tests. Electrical resistance strain gauges were bonded to the top and bottom surfaces of these beams, the gauges being wired to produce a single fully active Wheatstone Bridge which was self compensating for any differential loading between the two beams.

Deflection Measurement

Beam deflection was monitored by an inductive linear displacement transducer mounted 200mm from the centre line of the beam under test, the loading arrangement preventing easy access for the mid-span deflection to be monitored.

Concrete Crack Width Measurement

Concrete crack width was monitored by inductive linear displacement transducers located at the level of the centre line of the Torbar at two of the previously induced cracks. The main body of the gauge was mounted in brackets bonded to the concrete on one side of the crack and the independent core was mounted from similar brackets on the other side of the crack. Both the main body of the transducer and the core were sealed against contact by the seawater and the core was free to move inside the main body.

Method of Monitoring the Gauges and Transducers

All the above gauges and transducers are monitored through an AC bridge. The output from the Bridge was recorded on a max/min/auto reading voltmeter and on an ultra/violet continuous chart recorder. Each of the gauges could be routed to the AC Bridge by a rotary switch controlling a 100 channel scanner box.

Cycle Counter

The number of cycles elapsed in each test were recorded by a simple mechanical digital counter with a 10 to 1 reduction on the input.

Seawater Composition

Chemical analyses for the main dissolved constituents of the seawater were made on receipt of the water and at approximately weekly intervals during its period of circulation through the test tanks.

More frequent measurements of temperature and pH value were made on the water in each tank.

Dissolved oxygen was measured by means of an E.I.L. dissolved oxygen meter in conjunction with a Mackereth type oxygen electrode.

Electrochemical Potential

Electrochemical potentials of the reinforcing steel in the beams being tested in seawater were measured using a silver/silver chloride reference electrode in conjunction with a high impedance voltmeter. The reference electrode was immersed in the seawater adjacent to the beam, account being taken of small variation in potential due to the position of the electrode along the beam and the part of the loading cycle at which the measurement was taken.

Deposits

Deposits occurring on the concrete surface at crack sites were analysed for chemical composition.

TEST RESULTS

A general summary of the results is given in the form of S-N curves in Figure 4.

Beam Deflection

The deflection range for the beams tested at 3 Hz in air were close to the calculated values.

The tests in seawater however were markedly different. The results both at 0·1 Hz and 3 Hz, the cycle rate having no significant effect, indicated an unexpected variation in the deflection range. This was due to pumping of water in the cracks, most noticeably in the beams in the long term tests. The cracks gradually blocked up (see below) while at the same time the deflection range reduced, even though the deflection at maximum applied load each cycle increased as a test proceeded. An example of this is shown in Figure 5. The load/deflection relationship thus approached an uncracked condition (the load range remaining unchanged), but with the stress range in the Torbar reducing in line with the reduced deflection range.

The deflection range during the short term tests at the highest stress range and frequency was monitored continuously on an ultra-violet chart recorder. During the last few hundred cycles the minimum deflection level increased rapidly until failure occurred. This was the only indicator noted which showed that failure was imminent. However, this was of such a short duration, less than 5 minutes, that unless the operator was actually watching the chart recording it was very easily missed.

Cracks in the Concrete

The crack opening related to load generally followed the predicted curve for maximum crack width as given by Beeby(1), Figure 6. Differences between individual cracks showed large variations but the results for the two highest load ranges indicated that the opening increased with both the higher cycling frequency and the change in condition from air to water.

The cracks were also changed by the presence of seawater. Local spalling at the concrete surface occurred due to the pumping of water out of the crack. This, together with salt deposits on the surface of the concrete gave a visual appearance of damage taking place at a faster rate than in the air tests, see Figure 7. However, the results in terms of fatigue life for the short duration tests showed that the visual appearance of the concrete had little to do with the fatigue life of the reinforcing bar being tested. The salt deposits on the surface of the concrete were slightly discoloured with rust only in the tests lasting 10 days or more and at the cracks in the shear span, i.e. in close proximity to the shear reinforcement.