Corrosion-fatigue behaviour of a HSLA steel subjected to periodic overloads

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Abstract

The fatigue behaviour of a high strength low alloy steel used for reinforcing bars in concrete structures was examined. Axial fatigue specimens were subjected to a loading spectrum consisting of a periodic overload of yield magnitude followed by 50 smaller cycles. The specimens were fatigue tested while they were fully immersed in an aerated and recirculated 3.5-wt% NaCl simulated seawater solution. The results were compared to data obtained for the same overload spectrum applied in laboratory air. A damage analysis showed that the presence of the corrosive environment accelerated the damage accumulation rate in cycles following overloads to a much greater extent than that observed in air. There was a drastic reduction in the fatigue strength of the material when it was simultaneously subjected to overloads and a corrosive environment. For practical purposes, the endurance limit of the material virtually disappears under these conditions.

1 Introduction

Fatigue failure of reinforced concrete structures is generally a result of the failure of the tension reinforcement which is often made of high strength low alloy (HSLA) steel. The failure location coincides with tension cracks in the concrete which localize the strain intensity on the steel reinforcement. When the structure is exposed to a corrosive environment, the concrete cracks also provide the corrosive media relatively easy access to the highly strained area in the steel resulting in a corrosion-fatigue (CF) process [1]. Offshore structures, structures near marine coastlines, and highway structures in northern climates where de-icing salts are used in winter are all subjected to corrosive chloride solutions and CF mechanisms are potentially detrimental to their longevity.
The occurrence of CF in steels has been described as a three-stage process [2-4] corrosion pit formation, pit-to-crack transition (also considered to be short fatigue crack growth) and finally long (Mode I) crack propagation. It has been estimated that 60%-70% of the total fatigue life may be spent in the first two stages where corrosion pits are forming [2,3]. There is considerable evidence that the magnitude of the applied strain has a strong influence on pit formation, short crack growth, and the subsequent stages in the process [2-4] and that strain intensification is likely the dominant mechanism for accelerated corrosion rates and accelerated fatigue damage evolution during CF. Others [5,6] have found evidence that hydrogen embrittlement caused by diffusion of H⁺ species to the regions ahead of an advancing crack during CF is another active mechanism for accelerating crack growth rates. In general, CF has been found to decrease fatigue strength by factors of about 3 at lives of about $10^7$ cycles, and that an endurance limit does not exist during CF of steels in simulated seawater (3.5-wt% aqueous NaCl) [3,7,8]. However, most experimental studies have been conducted using either simple constant amplitude loading or block loading but relatively few [e.g., 9] have considered the effects of overloads and variable amplitude loading as experienced by real structures.

The investigation reports the results of CF experiments conducted on a CSA G40.16 Gr400 HSLA reinforcing steel subjected to periodic overloads in a simulated seawater environment. Fatigue results for this steel subjected to the same periodic overload spectra, but tested in air, were reported previously [10]. The periodic overload spectrum has been shown to give fatigue data that are reliable and can be used to obtain accurate to slightly conservative fatigue life predictions for metal structures subjected to variable amplitude loading in service [11].

2 Experimental details

The material used in this study was a high-strength low-alloy (HSLA) steel provided in the form of cold-drawn and deformed reinforcing bars conforming to CSA G40.16M Grade 400. The chemical composition (wt%) of this steel was: 0.25 C; 1.6 Mn; 0.009 P, 0.020 S, 0.186 Si, 0.18 Cu; 0.087 Cr, 0.01 Mo, 0.045 V, remainder Fe. The material had ferrite-pearlite microstructure with an ASTM grain size number of 7, as shown in Figure 1. The steel has a monotonic yield strength (0.2% offset) of 450 MPa, ultimate tensile strength of 650 MPa, area reduction of 60% and Brinell hardness of 188. Axial fatigue specimens with cylindrical gauge sections 4.5 mm in diameter as shown in Figure 2 were machined from 25M bars (nominal diameter 25mm). The machined specimens were mechanically polished in the longitudinal direction using progressively finer grades of emery cloth prior to corrosion-fatigue (CF) testing.
Figure 1: Microstructure of Gr400 reinforcing steel in the longitudinal direction.

Figure 2: Corrosion fatigue specimen details.

The specimens were contained within a plastic corrosion cell and the fatigue tests were performed in a closed loop, servo-controlled electrohydraulic testing system, as depicted in Figure 3. The corrosion cell contained a 35 cm³ solution which was maintained at a steady-state temperature of 31°C. A fresh reservoir containing one litre of simulated seawater was made from laboratory grade sodium chloride (3.5-wt% NaCl) and de-ionized water for each test. The corrosion solution had an initially neutral pH and it was continuously aerated with lab air and recirculated at a rate of 5 cm³/s. The corrosion was allowed to occur freely on the specimen without impressed currents. The CF tests were performed in load control at cyclic frequencies generally at 5 Hz, although some tests were performed at a frequency of 0.1 Hz to determine the effect of exposure time on the CF behaviour of the steel.
Figure 3: Experimental arrangement showing the corrosion cell and recirculation apparatus.

Figure 4: Periodic overload spectrum.

The typical loading spectrum consisted of a periodic fully reversed overload of yield magnitude (±450 MPa) followed by 50 smaller cycles at a high stress ratio, as shown in Figure 4. The stress range of the smaller cycles was varied between tests by changing the minimum stress, $S_{\text{min}}$, of the small cycles, while the magnitude of maximum stress, $S_{\text{max}}$, was kept constant at 450 MPa. This loading spectrum has been shown to produce a practical upper bound on fatigue damage for tests performed in lab-air, because the small cycles are free of plasticity and roughness induced crack closure [11].
3 Results and discussion

The corrosion-fatigue stress-life data are given in Figure 5 in terms of the small cycle stress range, $\Delta S$, versus the total number of cycles to failure, $N_f$. The data generated previously for constant amplitude fully reversed ($R=1$) loading and for the same periodic overload spectra, both in lab air, are also shown in the figure. The figure shows that there is a distinct reduction in fatigue strength and fatigue life as a result of CF, and that the combined effect of periodic overloads and CF drastically reduces the fatigue performance compared to that in air. At a stress range of 900 MPa where all the cycles are overloads and the loading is constant amplitude $R=1$, there is a relatively slight reduction in the CF fatigue life (about a factor of 2) compared to that in air.

![Figure 5: Fatigue life data for Gr400 steel in air and 3.5-wt% NaCl.](image)

These observations are typical and are supported by those of Bernstein and Loebly [8] who reported CF life reduction factors of about 2 for a similar steel (SAE1045) CF tested in 3.5-wt% salt water using constant amplitude fully reversed stresses of yield magnitude. It is also clearly shown in the figure that the life reduction increases drastically at lower stress levels. However, it is not clear from this figure which mechanisms are responsible for the life reduction as there are several mechanism operating simultaneously: the periodic overloads are known to increase the damage done by the subsequent small cycles [11], compressive overloads increase the corrosion rate and increase the CF damage rate [9], and both corrosion rate and CF damage rates are known to increase with increasing stress ratio [5,6,9]. It is therefore beneficial to separate the overload
damage from the small cycle damage in the CF data to examine the synergistic behaviour of corrosion-fatigue and periodic overload effects.

### 3.1 Damage analysis

The damage done by the small cycles is characterised by the equivalent number of small cycles to failure $N_{eq}$, calculated by removing the damage done by the overload cycles according to Miner’s Rule:

$$N_{eq} = \frac{N_s}{1 - \frac{N_o}{N_{fo}}}$$  \hspace{1cm} (1)

where $N_o$ is the number of overloads and $N_s$ is the number of small cycles applied to failure ($N_F = N_s + N_o$ where $N_F$ is the total number of cycles to failure), and $N_{fo}$ is the number of overload cycles alone required to cause failure. In this investigation, the value of $N_{fo}$ was taken from the average life of six overload tests (three at 0.1 Hz and three at 5 Hz) for the CF experiments, and the average of 3 overload tests done in air, respectively. The magnitudes were $N_{fo}=6000$ cycles in 3.5-wt% NaCl, and $N_{fo}=12000$ cycles in lab air.

The equivalent lives of the small cycles were calculated using Eq (1) for all the overload tests done in lab air and in 3.5-wt% NaCl and the results are plotted in Figure 6. The figure shows that the fatigue life at all stress levels is reduced by the presence of the overloads by an order of magnitude or greater in the presence of salt water compared to that in air. It is also clear that although there is a fatigue limit in the constant amplitude and periodic overload data in lab air, there is no fatigue limit for the periodic overload data in 3.5-wt% NaCl. This means that for reinforced concrete structures exposed to salt water, all cycles in a service load spectrum will likely do fatigue damage. It is suggested that the corrosion-fatigue data of Figure 6 can be used to perform cumulative damage summation under these conditions using the modified Miner’s damage summation techniques developed previously [11].

Figure 6 shows that the test results for small cycles below 100 MPa subjected to corrosion-fatigue have equivalent lives of about a million cycles. These tests were performed at a frequency of 5 Hz and lasted a maximum of about 12 hours; this is a very rapid test in comparison with what a real structure would experience. Further experimentation using lower frequencies is required to determine if the observed detrimental effects of simultaneous exposure of the steel to periodic overloads and salt water are even worse for long exposure times.
Figure 6: Effective stress-life data for Gr400 steel in air and 3.5-wt% NaCl.

Figure 7: Fracture surface of CF specimens showing a crack initiating pit.

An examination of the surfaces of the failed specimens showed generalized corrosion and distinct pitting present throughout the test section. Angelova and Akid [2] observed that multiple cracks formed in a similar HSLA steel subjected to corrosion-fatigue in aqueous NaCl with constant amplitude stresses of yield magnitude, and that all cracks initiated in corrosion pits. This is in agreement with what was observed in this study. Figure 7 shows a typical fracture surface of a periodically overloaded specimen with a small cycle stress range of 450 MPa. Crack initiation and growth from a corrosion pit is evident. It was generally observed that multiple crack initiation sites occurred in corrosion pits on the surfaces of the corroded specimens.
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4 Conclusions

The fatigue life of CSA G40.16 Gr 400 reinforcing steel is drastically reduced by the application of periodic overloads in 3.5-wt% NaCl compared with equivalent tests performed in lab air.

The fatigue limit was, for practical purposes, eliminated for the periodic overloading spectrum and 3.5-wt% aqueous NaCl environment examined.

Multiple corrosion-fatigue cracks were typically found to initiate and then grow from corrosion pits on the surface of the specimens.

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