Accelerating corrosion in a laboratory set-up for corrosion-fatigue of offshore steels

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Abstract: Corrosion-fatigue is a dangerous failure mechanism that is not yet fully understood. Structures subjected to corrosion-fatigue are over conservative in design, which is economically unfavourable. To counter this, representative laboratory experiments simulating the corrosion-fatigue conditions of an offshore structure should be performed. Lab testing is, for obvious reasons, performed at frequencies much higher than these of wave and wind actions. However, this means that corrosion needs to be accelerated in the same manner. In this work two different ways to accelerate corrosion were selected, namely temperature and oxygen content adaptation. S-N curves were determined in different test conditions in order to evaluate the damage evolution. It has been found that high temperatures and high levels of oxygen content will result in earlier failure. The fracture surfaces are somewhat different than fracture surfaces obtained due to fatigue in air. More crack initiation sites can be observed and the fracture surface is generally rougher due to corrosion.

Keywords: corrosion fatigue, acceleration, fatigue limit, S-N

1 INTRODUCTION

In many cases fatigue and corrosion damage mechanisms interact in harsh environments such as is the case for offshore structures. ASTM defines corrosion fatigue as the sequential stages of metal damage that evolve with accumulated loading cycles, in an aggressive environment compared to inert or benign surroundings, and resulting from the interaction of irreversible cyclic plastic deformation with localized chemical or electrochemical reactions [1].

Contemporary high strength steels are not yet included in design codes and therefore new offshore structures are often over conservative in design which is economically unfavourable. Figure 1 shows the difference between an S-N curve in air and in a corrosive environment. Typically, a fatigue limit is absent in corrosive environments [2]. An improved knowledge of the fatigue corrosion life of offshore structures by means of representative laboratory scale experiments can help in expanding the design codes.

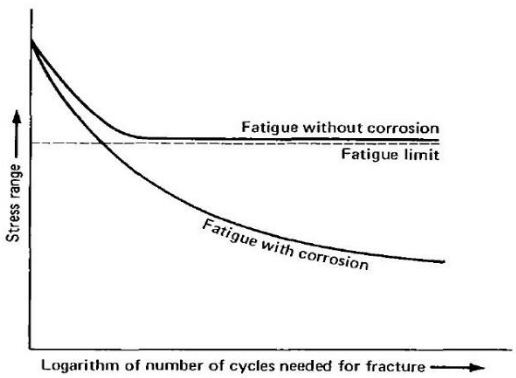

Figure 1: S-N curve in air and in corrosive environment[9]

Frequencies of waves, wind and currents generally lie around 0,1 – 0,5Hz in the North Sea [3]. Laboratory experiments at these frequencies would require very long test periods. To shorten testing time, it is normal practice to increase the testing frequency. However, the corrosion fatigue interaction changes with frequency [4]. In other words, when fatigue damage is accelerated, corrosion damage needs to be accelerated in the same manner. Literature shows that corrosion can be accelerated in different ways [5], [6]. Two different acceleration methods were selected, namely temperature and oxygen content adaptation. In the next paragraph both options will be further explained.

To evaluate the corrosion fatigue damage evolution in different test conditions, S-N curves can be used. These curves show how test conditions influence the amount of cycles a specimen is able to survive at a certain stress level. Experimental determination of the S-N curves under different conditions will be further explained in paragraph 4.

To achieve a better insight in this failure mechanism, offshore conditions are recreated in a laboratory setup. Effectiveness of acceleration and time to failure under different test conditions are investigated.

2 TEST SETUP

The test setup consists of a servo-hydraulic testing machine, a mobile conditioning unit (see Figure 2 and 3) and an acrylic test chamber (see Figure 4). The temperature of the seawater inside the tank is controlled by a PID controller. A thermocouple in the middle of the heating element is used as feedback. Additionally, temperature, dissolved oxygen level and pH level are measured inside the acrylic test chamber.

The oxygen content in the test chamber can be increased by turning on the air compressor. This compressor feeds the air diffusers in the test chamber. The oxygen content can be measured by a dissolved oxygen meter. The probe is connected to the measurement device which displays the dissolved oxygen in % saturation or mg/l up to 50ppm and 600%. The device has a built in temperature compensation up to 50 degrees. Next to the dissolved oxygen content, a pH probe is present. The pH probe is connected to the MCU on the mobile conditioning unit. Both probes also measure temperature.

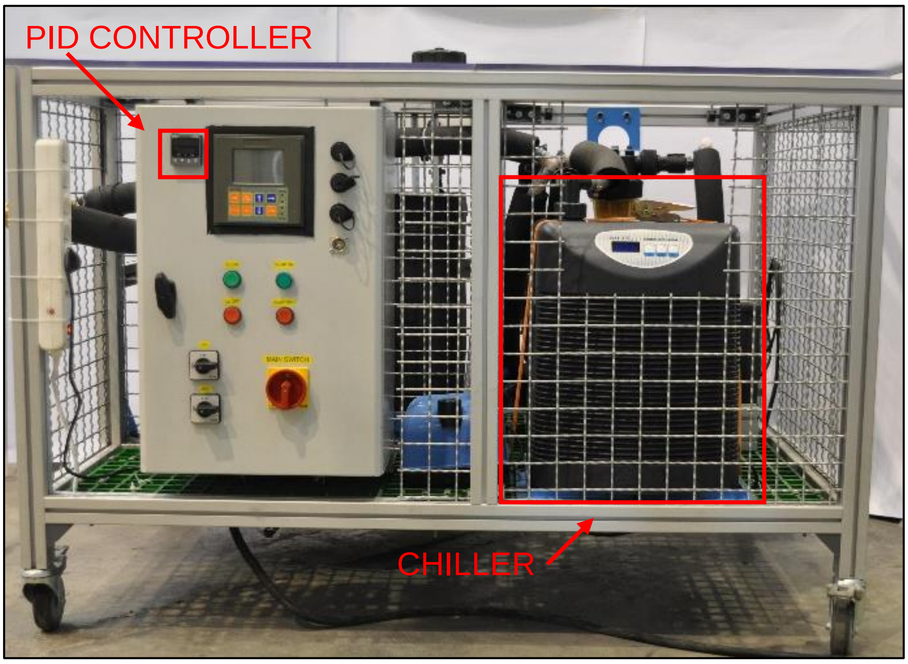

Figure 2: Mobile conditioning unit front side

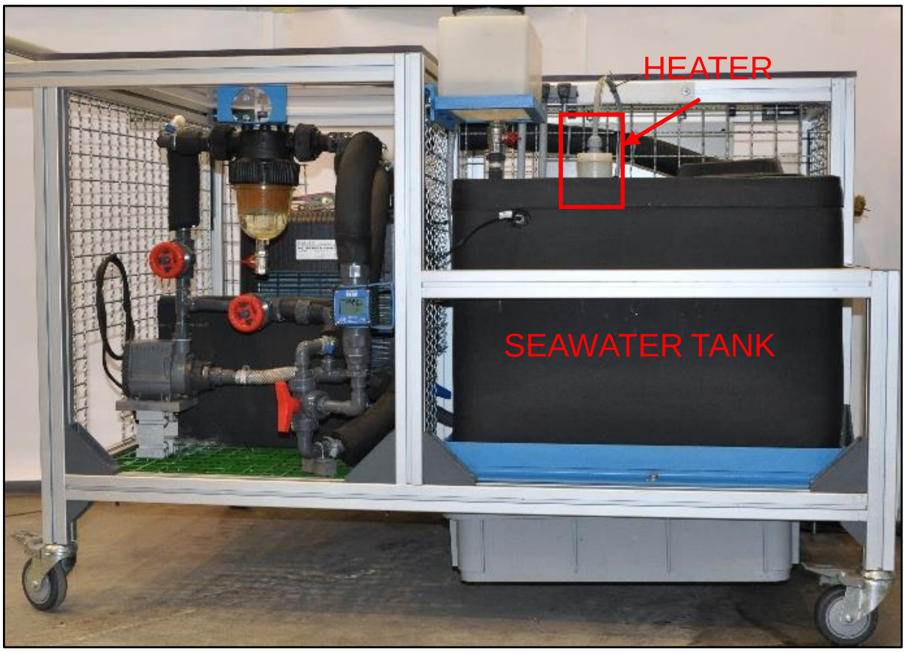

Figure 3: Mobile conditioning unit back side

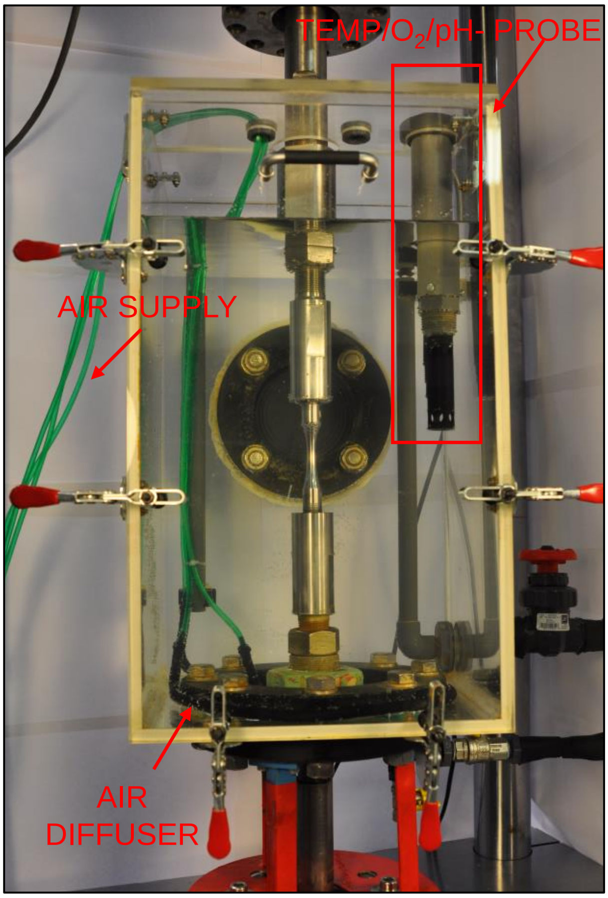

Figure 4: Acrylic test chamber

3 TEST SPECIMENS

The material used is a high strength steel equivalent to grade NV F460 which is often used in offshore structures. The chemical composition in weight percentage and the main strength properties are presented in Table 1 and Table 2 respectively.

Table 1: Chemical composition of offshore steel NV F460

	C	Mn	Si	P	S	Cu	Ni	Cr	Mo
[%]	0.08	1.24	0.24	0.01	0.001	0.05	0.21	0.05	0.005

Table 2: Main strength properties of offshore steel NF460

Yield stress σ_{y} [MPa]	Ultimate tensile strength σ_{UTS} [MPa]
520	603

The round bar fatigue specimen configuration was defined based on the ASTM E466 standard [3]. Figure 5 shows the dimensions of the round bar fatigue specimen.

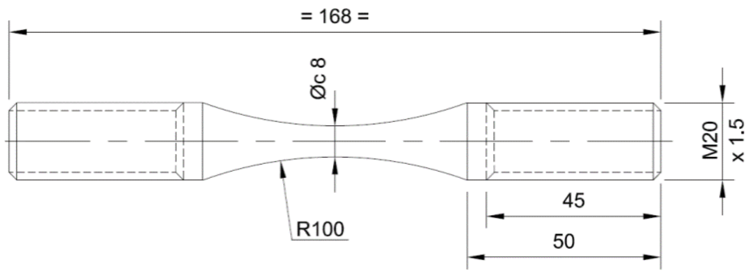

Figure 5: Round bar specimen

The tested specimens were extracted from seamless steel pipes with an outer diameter equal to 323.8mm, and 23.8mm wall thickness. All of them were mirror polished with sand paper in a sequence of 180, 220, 350, 800, 1200 and 2400 in order to reduce stress concentration effects from surface roughness and thus to delay the fatigue crack initiation. The specimen is mounted in the test rig by means of an M20 threaded connection at both sides.

4 S-N TESTS

As stated before, different test conditions were set in order to evaluate the effect of accelerated corrosion on fatigue corrosion damage. Tests at 15°C, 45°C and 45°C with added air were carried out. The amount of cycles the specimen survives at several stress ranges in these conditions is plotted in an S-N diagram.

All tests were carried out using an MTS810 servo-hydraulic system equipped with a load cell of 100kN capacity. The tests were performed in load-controlled mode at a stress ratio R = 0.1 and a frequency of f=10Hz. The specimens were subjected to constant amplitude fatigue loads with stress ranges from 430MPa to 500MPa until the event of failure.

In Figure 6, the different curves are displayed. In full black line, a reference S-N curve is shown describing the fatigue behaviour of the material in air conditions. As with many metals, a fatigue limit can be observed. For the material under investigation, NV F460, the fatigue limit is about 440 MPa.

Additionally, tests were conducted in a seawater environment. Different test conditions were set forward in order to accelerate the corrosion damage. Three conditions were tested, a seawater environment at 15°C, one at 45°C and one at 45°C with added air in the test chamber. For all tests in seawater, a fatigue limit was not yet observed down to a stress range of 430MPa. It is expected, for NV F460, that a fatigue limit will not be achieved in a corrosive environment. This would mean that at any fatigue stress level, failure will always happen [2].

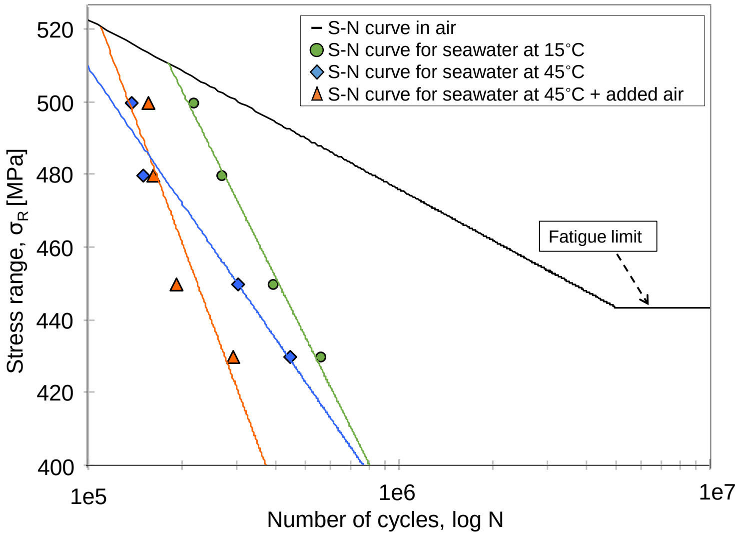

Figure 6: Comparison of S-N curves obtained for different environmental conditions

In general, at the highest stress levels where fatigue life is shorter, the corrosive environment has less time to play a significant role in the damage of the specimen. Therefore, this region is mainly stress dependent and the difference between the S-N-curve in air and these in seawater is negligible. As the stress range drops, the deviation becomes more significant. The deviation clearly depends on the environmental condition, e.g. comparing the S-N curve for seawater at 15°C with the one at 45°C with added air. The most significant corrosion acceleration is achieved with seawater at 45°C with added air.

Around stress levels of 480MPa the trend lines for seawater at 45°C and for seawater at 45°C with added air intersect. Above this stress level, the influence of additional oxygen is minor. Probably because at these high stress ranges the test duration is short and thus corrosion damage is limitedly present. As said earlier the damage is mostly stress and thus fatigue dependent. For a stress range below the intersection, the added air gets the upper hand in corrosion acceleration at 45°C as the total lifetime is lower compared to the 45°C condition. The general trend of all seawater conditions suggests that a fatigue limit will be absent. Further, the trend of both S-N curves for seawater at 15°C and the one at 45°C intersect at a stress range of approximately 400MPa. This could indicate that at high cycle corrosion fatigue all conditions ultimately tend to one point.

The difference in fatigue life between the air and seawater environment was already introduced in Figure 1. In general, the mechanism behind corrosion fatigue can be explained as follows. Specimens with smooth surfaces will mostly accelerate initiation due to the creation of surface defects leading to stress concentrations and possible pitting zones. Once initiation is present, it will also accelerate crack growth due to mechanisms as hydrogen embrittlement and anodic dissolution [7].

In [8], results similar to the above findings are described for S-N tests conducted on low carbon steels in aerated and deaerated seawater. For completely deaerated seawater almost no difference between S-N curves for air and deaerated seawater tests was evidenced. The tests performed here were not with deaerated seawater but with naturally aerated seawater and aerated seawater, which could explain why there are still differences in S-N curves for air tests and all seawater tests. Still, as well as from literature, we can see that aerated seawater tests have a much more severe impact on the fatigue life behaviour compared to deaerated or low aerated seawater tests.

Finally, Figure 7 shows the fracture surface of a specimen tested in air conditions at 460MPa on the left and the fracture surface of a specimen tested in seawater at 15°C and 430MPa on the right. Comparing both fatigue fracture surfaces indicates some differences. For example, as can be seen from the right picture, there are several deep crevices on the fatigue fracture surface which can't be detected with the naked eye in the left picture. These crevices could have grown from initial corrosion pits, evolving into initiation points on the surface. It is to be evaluated if either more initiation points are being created in a seawater environment, or either the specimens in air have really small initiation points whereas the points are much more visible in the corrosive seawater environment. Also, the ductile end fracture surface seems rougher for the specimen tested in seawater environment compared to the one from the air specimen.

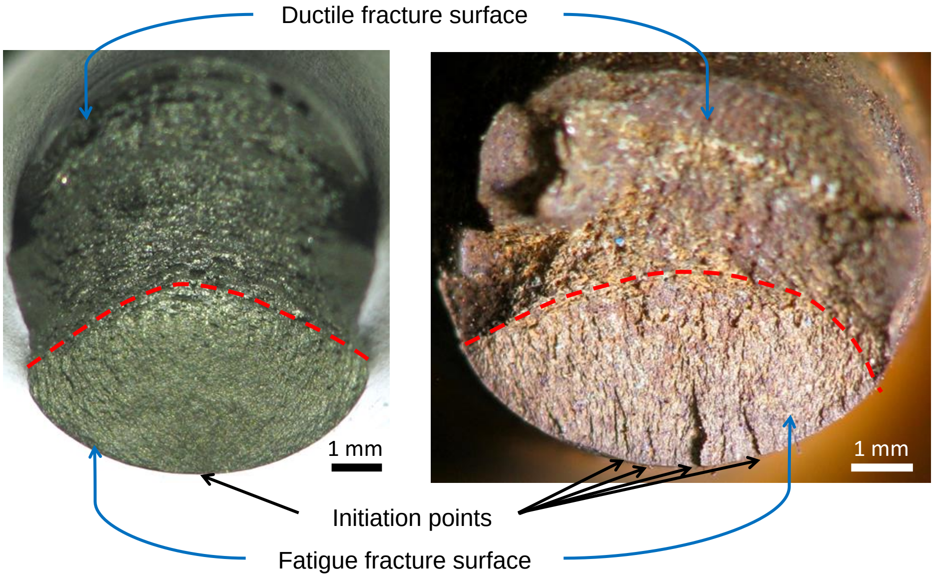

Figure 7: Fatigue fracture in air (left) and fatigue fracture in seawater (right)

5 CONCLUSION

Corrosion fatigue is a dangerous failure mechanism that is not yet fully understood. To remediate this, laboratory experiments simulating offshore environmental conditions are to be performed. A test setup has been built to recreate these offshore conditions, to condition seawater and to measure pH, oxygen level, temperature and salinity. By doing fatigue tests in a controlled seawater environment, S-N curves are determined for an offshore steel NV F460. These curves have been created at different conditions (15°C, 45°C and 45°C with added air) to evaluate the influence of temperature and oxygen level on fatigue lifetime. It has been found that high temperatures and high levels of oxygen result in earlier failure. The general trend of all seawater conditions suggests that a fatigue limit will be absent. Further, the S-N curves for 15°C and for 45°C intersect at a stress range of approximately 400MPa. This could indicate that for high cycle corrosion fatigue all conditions ultimately tend to one point. The fracture surfaces of specimens tested in seawater environment show more visible initiation sites and the fracture generally is rougher.

Future work includes extending the S-N curves of NV F460 to lower stress levels for the different test conditions at the frequency of 10Hz. In the end, accelerated corrosion and accelerated fatigue in a test setup should be related to the damage rate in a real life offshore condition.

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