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#### INTRODUCTION

The discovery of large oil and gas reserves in the North Sea inspired a novel use of reinforced concrete: the construction of production platforms.

It was known from long experience in various fields of marine engineering that concrete is a most durable material when exposed to a marine environment. Constructions very similar to fixed offshore facilities has been in operation a long time, e.g. as lighthouses, with excellent experience. None the less, as the consequences of failure during oil production are potentially very great, one sought to obtain a level of safety for these structures which have rarely been applied before, except when building for nuclear engineering purposes.

As concrete was a novel material in this particular field of application, it was met with a good deal of sceptisism from oil companies and authorities, and its ability to perform satisfactory was questioned on several points; among these the corrosion resistance of the structures.

Det norske Veritas (DnV), as a modern classification society, seek to keep its Rules for Classification in harmony with the current State of Art. To this purpose the research program which is presented here was initiated. Its primary purpose was to study the question of crack-width, i.e. "How narrow must a crack be in order to avoid corrosion of exposed reinforcement in the bottom of the crack?". An important secondary aim was to study possible methods and instruments for the inspection the condition of the reinforcement.

Fig. 1 is a schematic representation of the galvanic corrosion cell which has been postulated as a hazard on offshore structures. It is traditionally assumed that the exposed steel is the anode while the reinforcement is the cathode in the galvanic coupling.

Corrosion takes place at the anode according to reaction 1, while the cathode reaction will be reduction of oxygen (reaction 2). The total reaction will normally be under cathodic control, and the rate of corrosion for a given corrosion cell depends on the oxygen flux to the cathode surface. (1)....Fe  $\rightarrow$  Fe<sup>2+</sup> + 2 e (2)....O<sub>2</sub> + 2H<sub>2</sub>O + e  $\rightarrow$  4 OH

The above polarity of the coupling was based on experiences from laboratory tests where steel in high alcaline environments, (such as saturated Ca(OH) -solutions), passivated readily and stabilized at a high potential (typically -200 mV vs AG/AgCl). Since steel exposed to seawater has a free potential of approximately -670 mV vs. Ag/AgCl, this would make it anodic with respect to embedded steel.

If the above reasoning is applicable to steel exposed in cracks in concrete, the idealized pictures of cracked concrete in fig. 2 show the reasoning behind speculations about crack-width criteria. If steel exposed in the bottom of a crack becomes the anode in a galvanic cell; then the cathodic area (reinforcement in uncracked concrete) could be very large compared to the area of steel in the crack. Thus the cathodic capacity would be large, giving a very high current density on the anode, i.e. extremely rapid corrosion!

When this research program was started, the main objective

was to determine the lower bound of crack width at which this process could take place. Additionally, we wanted to try out electrochemical measurements as tools for monitoring the state of reinforcement corrosion in concrete exposed to seawater.

# TEST PROGRAM

# Specimens

In order to restrain the volume of the experiment, a number of variables were fixed, so that the main variables introduced were:

- Cover to the reinforcement (Cl, C2): 50 and 20 mm
- Crack width (S1, S2, S3) 0.0; 0.1 - 0.2; 0.2-0.5 mm
- Depth of exposure (N1, N2), 1 and 10 m below LLW.
- Area of steel; i.e. varying bar diameter (25 and 32 mm, the normal was 16 mm).
- Longitudinal cracking; i.e. cracks along 8 mm stirrups.
- Hot-dip galvanized reinforcement.

The program which is now running encompasses 70 specimens.

The specimens were cast as beams shown in fig. 3. They were reinforced with two reinforcing rods. The reinforcement had been wire-brushed and treated with de-greasing agent and was equipped with leads for measuring purposes. These leads were soldered to the ends of the reinforcing rods, and the connection point was isolated with pitch epoxy.

The specimens were equipped with holes which were used to crack the beams. This is also shown in fig. 3.

 $3~{\rm m}^3$  of C-45 was used for concreting the 70 specimens, and ordinary hotrolled, deformed reinforcement was used. C-45 denotes a concrete with a characteristic cube strength of  $45 N/{\rm mm}^2$ . This is a quality which is typical for offshore structures.

# Test location, placing of specimens

A test site was located in the skerries outside Bergen, satisfying the following reqirements:

- close to the road
- continuous replenishment of seawater
- calm water
- availability of electricity
- overhang (see fig. 4)
- short transit-time from Bergen

The specimens were placed by means of boat and divers,

208

and the system worked so well that no landbased equipment will be installed unless there is an increase in our activity on the site.

## Survey and Removal

Once the specimens were placed, they were monitored intermittently by electrochemical methods (see below). The timeschedule was made out with the aim of removal of specimens for laboratory examination after 1,3 and 5 years.

Due to outside conditions the first removal was made after 18 months. The experience from that examination and the interpretation of the electrochemical data have resulted in an extension of the duration of the exposure tests to at least 10 years.

# ELECTROCHEMICAL METHODS

The electrochemical methods most commonly applied in corrosion research are potential and polarization measurements.

Measurement of corrosion potential is illustrated in fig. 5. The electrochemical potential of a metal or a galvanic coupling is measured, via a high-impedance millivoltmeter, (here a 3<sup>1</sup>/<sub>2</sub> digit digital multimeter), against a reference electrode; in our case a silver/silver-chloride electrode is used. This is by far the most common measuring method, but in the interpretation of potential readings it should be noted that even if a potential reading shows that corrosion is possible, - it will not tell anything about the rate of the corrosion.

To determine this, potentiostatic or dynamic testing is needed. The experimental set-up is shown in fig. 6. Potentiostatic testing will tell about the current flow required in a circuit in which the metal (working electrode) to be tested is forced to a preset potential.

In potentiodynamic testing the preset potential is varied within a range and the current flow between counter- and working electrode is recorded along with the potential.

The final output consists of potential/log-current diagram (as in fig. 15).

In the present tests a Wenking PGS77 potentio/galvanostat was used.

#### OBSERVATIONS AND RESULTS

#### Ambient conditions

Temperature and oxygen content of the seawater has been checked. The temperature has varied from 4 to  $15 \stackrel{\circ}{\text{C}}$  dependent on the time of year, while the oxygen content at all times has been at saturation level, about 9 to 7 ppm. The current in the sound

is strong, and the difference between high and low tides is small.

# Marine growth

Marine growth was present on two levels, as macro and as micro growth. The macro species were the most visible; and the tendency has been towards more and more growth. However, there are seasonal and directional differences in the amount of growth. Microgrowth is present as a slimy film covering the surface and

penetrating some millimeters into cracks.

In September 1979 marine biologists were cataloguing the species which were to be found on the specimens.

#### Potential readings

Figs. 7-15 show readings for several single specimens and groups of such. As the figures show, the trend is consistently negative. At the first reading (30 days) a slightly lower potential could be measured on the cracks, but this difference was not measurable at later readings.

Specimens with galvanized reinforcement started at a very negative potential, but positive trends appeared in several specimens after app. 2 years of exposure.

Fig. 7 shows a typical potential vs. time curve for an uncracked beam, while fig. 8 shows the corresponding curve for a specimen which has longitudinal cracks along the 8 mm stirrups. Fig. 9 illustrates the negligible effects of cover in uncracked specimens, while fig. 10 shows that there is no systematic effect from varying the steel area, i.e. bar diameter. Figs. 11 and 12 show that after a time there is no significant effect from the conditions of the concrete cover, i.e. state of cracking. A notable exception is that some uncracked specimens at -1 m seem to show positive trends at the last survey (after app. 950 days).

This is demonstrated in figs. 9 and 11.

The hot dip galvanized specimens showed behaviour as illustrated in fig. 13. The two long-term behaviour trends are characteristic.

The within-test variations are illustrated in fig.14. It is seen that curves showing the mean necessarily have a large margin of error even though the general trend is significant. This shows that both the number of companion specimens and the minimum size of specimens should be considered seriously when planning corrosion tests on reinforced concrete.

All the curves illustrate what might be called the three phases of reinforcement corrosion:

1. Initation phase, Corrosion potential:
>-500 mV Ag/AgC1

- 2. Transient phase, Corrosion potential: -700 < e < -500 mV</pre>
- 3. Final (permanent) phase; Corrosion potential: <-700 mV, typically -800 to -900 mV Phase 3 is reached after 6 to 18 months.

#### Potentio-dynamic tests

Several curves similar to fig. 15 have been obtained. (The first readings were taken after approximately 20 months of exposure). The curves consistently show low corrosion current and steep polarization curves, and when calculated from fig. 15 the rate of corrosion is approximately 4. 5  $\mu$ m/year, based on the assumption that the whole area of steel is active.

### Visual examination of specimens

In the cracks of specimens removed after 18 months a white (greyish) deposit was found. In most cases this deposit seemed to close most of the crack. It was found to be in evidence to a depth of approximately 20 mm below the surface; covering the crack surface and spanning the crack. On microscopic examination the deposit appeared crystalline in structure and very dense. Chemical analysis showed it to consist of mixture of CaCO<sub>3</sub> and Mg(OH<sub>2</sub>).

#### Reinforcement

The amount of corrosion discovered when the reinforcement was laid bare, was insignificant ( $\sim$  nil). Small spots of corrosion products were in a few instances visible in crack tips and where there were large voids directly adjacent to the reinforcement. However, there were no discernible attacks on the steel. The pH on the embedded steel surface was approximately 12.0; measured with indicating paper.

#### Galvanized reinforcement

The zinc-coating was heavily corroded and in several places bare steel was found.

DISCUSSION

### General corrosion

The major discovery in these tests is the negative trend of the corrosion potential in all specimens with normal reinforcement; whether they are cracked or not. They all went through the three characteristic potential phases mentioned earlier; i.e. the initial, transient and final phases. This phenomenon is believed to be the result of lack of oxygen as oxygen is consumed on the steel surface at a higher rate than it can be replenished from the ambient seawater.

The small oxygen flux is due to:

- The very small diffusivity of oxygen in watersaturated concrete.
- Oxygen consumption by micro-organisms on the concrete surface.
- 3. Deposits of CaCO<sub>3</sub> and Mg(OH)<sub>2</sub> in cracks and pores gradually blocking the concrete, possibly making it almost impervious to O<sub>2</sub>-diffusion.
- 4. Continuing hydration reducing porosity.

Fig. 16 shows an idealized oxygen concentration profile; identifying some principal zones. In the figure the effect of changing either no. 2, 3 or 4 (above) is plotted. It is important to note that in marine concrete all processes will add up, since they all are time-dependant.

In the initial phase one reason for oxygen consumption on the steel surface is the cathodic current needed to maintain a passive oxide layer at the high pH.

Chloride ions penetrating to the surface of passivated steel may destroy the passivating oxide-layer locally with strong, very local attacks as a result (pitting).

As seawater contains a lot of chlorides, in various forms, a possible form of corrosion attack on the reinforcement in the initial phase pitting. However, there is good reason to assume that the number of pits is fairly high, and since the amount of available cathodic current is constant, regardless of the number of pits, the average anodic current will be small. Thus the most important consequence of pitting is that oxygen is consumed in the process. As oxygen is consumed, the steel potential drifts towards negative, with the final result that active general corrosion takes place on the whole surface of the steel at a very low potential and at an extremely low rate.

This final, general corrosion is probably the end result of a myriad oscillating active/passive-cells on the steel. surface. As fig. 15.shows, the process is highly unstable. A small change (increase) in oxygen availability may increase the potential by up to 1000 mV.

#### GALVANIC CORROSION AND CRACKS

## Initial phase

Steel directly exposed to seawater has a free corrosion potential of about -670 mV vs. Ag/AgCl, while the reinforcement in its initial state is at about -200 mV. Thus, initially, exposed steel will be the anode in an exposed-embedded steel corrosion cell. Steel "exposed" in a crack, however, will not usually become anodic at first, since the fluid inside the crack will normally be highly alkaline. As the corrosion potential of the embedded reinforcement goes negative, it will, when its potential becomes less positive than that of the exposed steel, become the anode in the circuit; thus the polarity changes. Any galvanic corrosion of exposed steel due to embedded steel will end.

In the <u>final</u> phase, all available oxygen is used for general corrosion of the reinforcement at a low potential, and the change of polarity will give at least some measure of cathodic protection to the exposed steel.

### Cracks

If seawater was allowed to <u>flow</u> through cracks in the concrete cover, reserve alkalinity would be removed from the crack and the immediately surrounding concrete. This would make the behaviour of the steel in a crack tip analogous to that of directly exposed steel, with the consequences mentioned above.

A "normal" crack in concrete does not behave in this manner. Studies (see fig. 18) (2) show that cracks penetrating to the steel do that in a very complex manner. It is probable that the fluid in the crack will have a composition very similar to that of gel water, and ion-exchange between crack- and seawater will have to take place as diffusion and/or migration processes. Subsequently, it will take a long time before seawater is able to change the alcalinity significantly. In fact, because solid deposits after a time will block the cracks, the cracks will end up being no weaker than the bulk of the concrete as far as corrosion is concerned.

# Effect on cathodic protection systems

Since the reinforcement normally is in electric (metallic)contract with exposed steel on the exterior of the structure, it will also be in contact with cathodic protection systems designed to protect this exposed steel. The large area of reinforcing steel will initially drain a large amount of additional current in the oxygen reduction process. If cathodic protection is by sacrificial anodes, the increased drain will be reflected in much higher rate of anode-consumption than would be expected in order to protect the exposed steel alone.

A cathodic protection system is designed to polarize the protected steel to approximately -800 mV. As this is approximately the free corrosion potential of reinforcing steel in the final phase, and since this steel, as shown in fig. 16, is very easy to polarize, the current drain to this reinforcement will be very low or nil.

In practice these effects will be most obvious if cathodic protection systems are designed to protect only the external steel on marine structures. Then current consumption will take place at a totally unexpected high rate during the first year or two, then the current will stabilize at a lower value.

As far as has been possible to ascertain, this is what actually has taken place on offshore structures with cathodic protection of exposed steel. This may be regarded as an indirect proof that the process observed on our admittedly small test specimens also take place in large, real-life, structures.

# CONCLUSIONS

From the results obtained the following may be concluded regarding submerged concrete:

- Reinforcement embedded in sound, high quality concrete which is completely sumberged in seawater will, after 6-18 months of exposure, reach a very negative corrosion potential (typically vs. Ag/AgC1 -900 mV).
- The negative trend is the result of lack of oxygen in that the oxygen originally present is consumed, while solid deposits in concrete matrix and cracks reduce the cover diffusivity. The organic film on the concrete surface adds to this reduction of oxygen transport.
- Through the lack of oxygen, the final, permanent state of the steel is active corrosion.
- The rate of active corrosion is so low (< 10  $\mu m/year)$  that the steel exhibits a quasi-passive behaviour.
- The anodic polarization curve is very steep, showing the conditions to be highly unstable. A small increase in activity (oxygen availability) can make the potential change considerably (up to 1000 mV).
- Through lack of oxygen, the potential may be depressed until the cathodic reaction is hydrogen evolution.
- In the active state, the danger of pitting due to penetrating choride ions breaking down passivity is not present as the steel is far more negative than the pitting potential.
- Crack sizes appear to have minor importance as long as the crack is within a "normal" range and loading is static. However, the influence of variable loading remains to be studied for the specific purpose of corrosion behaviour.
- Galvanic corrosion of exposed steel in contact with the reinforcement will cease after about 1 year of exposure.
- Cathodic protection systems for exposed steel will be virtually unaffected by the reinforcement after the final phase has been reached.
- Tests such as these should be performed in natural seawater and have a duration which is significant

when compared to the lifetime of an actual structure. Attempts at accelerating or idealizing tests in the laboratory may easily lead to incorrect conclusions since the interaction between the multiphase material concrete and the supersaturated solution seawater is both concentration and time dependent.

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