DURABILITY ANALYSIS AND PERFORMANCE OF CONCRETE BARGES

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Abstract

Along the Norwegian coastline, an increasing number of reinforced concrete barges are being produced for the local fish farming industry. Since these concrete barges both are being used as living quarters and storage units for equipment and fish feed, there are strict requirements to safety and performance.

So far, the requirements to durability and long-term performance have almost exclusively been based on conventional, prescriptive requirements to concrete composition and construction procedures. Since this approach frequently has shown to yield unsatisfactory results for concrete structures in marine environment, much research work has been carried out over recent years in order to develop a better basis for obtaining a more controlled durability and long-term performance. In particular, the introduction of a probability-based durability analysis has proved to be very valuable.

In order to provide more relevant durability data from existing concrete barges, an existing concrete barge was selected for detailed investigations in the field and subjected to a probability-based durability analysis. The results demonstrate that the requirements based on current concrete codes are not adequate for providing appropriate durability and long-term performance of such concrete structures.

1. Introduction

In recent years, much research work has been carried out in order to obtain a more controlled service life of concrete structures in chloride containing environments [1]. In particular, probability-based durability analysis has proved to be very valuable [2-4]. Although there is still a lack of relevant data, this methodology has been successfully applied to a number of new concrete structures, where strict requirements to durability and long-term performance have been specified.
In order to provide more relevant data and experience with probability-based durability analysis, an existing concrete barge in Norwegian waters was selected for a detailed investigation in the field and subjected to durability analysis, some results of which are presented in the following.

2. Field investigation

The concrete barge was located in one of the fiords on the Norwegian west coast. The barge was 22 m long, 15 m wide, and the thickness of the top- and bottom slabs as well as the outer walls was 180 mm. The payload was 90 tons, and the average draught and freeboard was 1.4 m and 1.1 m, respectively.

For concrete quality, a compressive strength of 45 MPa had been specified, while the durability requirements according to NS 3420 [5], included a maximum w/c- ratio of 0.45, a minimum cement content of 300 kg/m³ and a minimum concrete cover of 50 mm. A blended portland cement with 20% fly ash in combination with silica fume was used, and the aggregate was mostly of a siliceous type with a maximum aggregate size of 16 mm. A lignosulphonate type of plasticizer in combination with a naphthalene-based superplasticizer were also used. Further information about the concrete mixture is given in Table 1.

<table>
<thead>
<tr>
<th>Table 1. Concrete mixture.</th>
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<tr>
<td>Cement (PC with 20 % fly ash)</td>
<td>420 kg/m³</td>
</tr>
<tr>
<td>Silica fume</td>
<td>8 kg/m³</td>
</tr>
<tr>
<td>w/b-ratio</td>
<td>0.44</td>
</tr>
<tr>
<td>Sand 0-8 mm</td>
<td>1000 kg/m³</td>
</tr>
<tr>
<td>Gravel 8-16 mm</td>
<td>790 kg/m³</td>
</tr>
<tr>
<td>Superplasticizer</td>
<td>4.5 litres/m³</td>
</tr>
<tr>
<td>Plasticizer</td>
<td>4.0 litres/m³</td>
</tr>
</tbody>
</table>

The concrete barge which was constructed in 1991, had been in service for about 12 years at the time of investigation. The condition assessment was primarily based on a large number of chloride penetration measurements in combination with electrochemical surface potential mapping. Extensive concrete cover measurements were also carried out. The field measurements were concentrated on the most exposed side of the barge, where the chloride penetration measurements were carried out at two different elevations of 300 mm and 700 mm above the water line. In addition, some chloride penetration measurements were also carried out from the inside of the concrete barge, partly on the top surface of the bottom slab and partly on the outer walls below the water line. Fig. 1 shows the locations of all samples taken.
3. Durability analysis

For concrete structures subjected to reinforcement corrosion, a development of degradation as schematically shown in Fig. 2 will take place.

After depassivation or onset of steel corrosion, it may take several more years before any visual sign of corrosion such as cracking or spalling will occur (e.g. 3-5 years), and it may still take a very long time before the structural capacity of the structure becomes significantly reduced. In the following, however, the stage of depassivation or onset of steel corrosion has been defined as the serviceability limit state.

The rate of chloride penetration into concrete as a function of time is normally modelled by use of Fick’s Second Law of Diffusion in combination with a time dependent diffusion coefficient. For the durability analysis, the solution to this equation for predefined boundary conditions was used in combination with a Monte Carlo simulation, where further details about the durability analysis are given elsewhere [6,7].
Fig. 2. Development of degradation of a concrete structure subjected to reinforcement corrosion.

4. Results and discussion

4.1 Condition assessment
At the time of investigation, the condition of the concrete barge appeared to be very good without any visual sign of reinforcement corrosion. From Fig. 3 it can be seen, however, that a deep chloride penetration had already taken place. From the lower elevation of chloride measurements (Elevation 1), two of the 12 chloride profiles revealed that a chloride concentration of more than 0.07 % by weight of concrete had reached the embedded steel at a depth of 50 mm, while for the highest elevation (Elevation 2), the assumed critical chloride concentration of 0.07 % by weight of concrete had not yet reached the embedded steel.

From the inside of the concrete barge, an increased chloride content towards the wet side and a slight increasing chloride content towards the dry side of the bottom slab were also observed (Fig. 4). These results indicate that the chloride front had reached a depth of approximately 140 mm into the bottom slab. From the inside of the outer wall, however, no increased chloride content at a depth of 80 mm, 0.5 m below water level, was observed.

As can be seen from Fig. 5, the electrochemical surface potential mapping showed potentials more negative than −350 mV (CSE) in the lower part of the concrete barge, which indicate that a partial depassivation of the reinforcing steel had taken place.
Fig. 3. Average of 12 chloride profiles from the outside of the concrete barge.

Fig. 4. Average of 6 chloride profiles from the inside of the bottom slab.
Fig. 5. Electrochemical surface potential mapping (CSE) on the outside of the concrete barge.

4.2 Durability analysis
For the probability-based durability analysis, only the observed chloride penetration from Elevation 1 was used, while all the statistical parameters needed for the further analysis are shown in Table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Distribution</th>
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<tbody>
<tr>
<td>$X_s$ (mm)</td>
<td>N(49.9;2.0)</td>
</tr>
<tr>
<td>$D_A$ ($10^{-11}$ m$^2$/s)</td>
<td>N(6.3;1.4)</td>
</tr>
<tr>
<td>$C_{CR}$ (% wt. of concrete)</td>
<td>N(0.07;0.007)</td>
</tr>
<tr>
<td>$C_S$ (% wt. of concrete)</td>
<td>N(0.90;0.16)</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>N(0.52;0.06)</td>
</tr>
<tr>
<td>$t_0$ (years)</td>
<td>D(12.0)</td>
</tr>
<tr>
<td>$t$ (years)</td>
<td>D(60.0)</td>
</tr>
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</table>

The concrete cover ($x_c$) was determined on the basis of a large number of concrete cover measurements, the results of which were calibrated by drilling holes to the embedded steel. The apparent diffusion coefficient ($D_A$) was determined from Fick’s Second Law of Diffusion and curve fitting of the 12 chloride profiles at Elevation 1. A critical chloride content ($C_{CR}$) of 0.07% by weight of concrete with a CoV of 10% was adopted based on current experience. The surface chloride concentration ($C_s$) was determined from the curve fitting of the chloride profiles. The exponent $\alpha$, which expresses the time-dependence of the diffusion coefficient, was also adopted based on current experience.

On the basis of the above statistical parameters, the probability of corrosion in the form of time to depassivation was analysed for a period of up to 60 years, the results of
which are shown in Fig. 6.

![Graph showing probability of failure versus time](image)

Fig. 6. Probability of corrosion versus time for the concrete barge investigated.

According to the Norwegian Standard NS 3490 [8], the probability of failure for a serviceability limit state should never exceed 10%, while according to Eurocode 1 [9] the probability of failure for this limit state should not exceed 7%. From Figure 5 it can be seen that the probability of failure in the form of depassivation exceeds 10% within a period of approximately 15 years, while the field investigations revealed that a critical chloride concentration had already reached the embedded steel. If a probability-based durability design originally had been carried out as an integral part of the general design of the structure, such a poor durability would probably not have been accepted. A probability-based durability design would also have provided a valuable basis for a performance-based quality control during the concrete construction, and hence also, a basis for documentation of obtained construction quality which would have been of great importance for the future facility management of the structure [10].

5. Conclusions

Although the structure investigated is typical for concrete barges currently being produced in Norway, the present investigation was only based on one barge and a limited number of field measurements. The probabilistic analysis was also based on a certain number of assumptions. On the basis of the results obtained, however, the following conclusions appear to be warranted:

1. For the most exposed part of the concrete barge, the durability analysis showed that a 10% probability for steel corrosion to occur would be exceeded within a period of approximately 15 years, while the field investigation revealed that a critical chloride concentration had already reached embedded steel after a service period of 12 years.

2. For new concrete barges with strict requirements to safety and long-term
performance, the present investigation shows that a probability-based durability design should be an important and integral part of the general design.

6. Acknowledgements

The authors would like to thank Mr. Kjell Borgund of Ålesund University College for all valuable assistance during the field investigations. The second author would also like to express his gratitude for the fellowship received from The Research Council of Norway during his staying at the Norwegian University of Science and Technology, NTNU, in Trondheim.

References


