Concrete under Severe Conditions: Environment & Loading, B. H. Oh et al. (eds) © *2004, CONSEC'04, Seoul, Korea*

DURABILITY AND PERFORMANCE OF NORWEGIAN CONCRETE HARBOR STRUCTURES

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Abstract

Along the Norwegian coastline there are more than 9.000 harbor structures, most of which are made of concrete, which typically show chloride-induced corrosion within a service period of 5-10 years. As part of the general design, the concrete durability is typically being specified in the form of some prescriptive requirements to maximum w/c-ratio and minimum cement content, which are not easy to verify and control. Even for relatively new concrete structures, where the durability requirements have been in accordance with the new European Concrete Code EN 206-1, premature corrosion of the embedded steel after a short period of time is being observed.

In order to obtain a more controlled durability and long-term performance of concrete structures in chloride containing environments, much research work has been carried out in recent years. In particular, the development of new procedures for probability-based durability design has proved to be very valuable. Although there is still a lack of relevant data, this methodology has already 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 durability data from existing concrete harbor structures, a relatively new Norwegian concrete harbor structure was selected for detailed investigations in the field and subjected to durability analysis. For all new concrete structures in a chloride-containing environment where safety and high long-term performance are important, the present study shows that a probability-based durability design should be an important and integral part of the general design.

1. Introduction

In order to obtain a more controlled durability and long-term performance of concrete structures in chloride containing environments, much research work has been carried out in recent years [1]. In particular, the development of new procedures for probability-based durability design has proved to be very valuable [2-4]. Although there is still a lack of relevant data, this methodology has already been successfully applied to a number of new concrete structures, where strict requirements to safety, durability and long-term performance have been specified.

In order to provide more relevant data and experience with probability-based durability design, a relatively new Norwegian concrete harbor structure, eight years old, was selected for detailed investigations in the field and subjected to durability analysis, some results of which are presented in the following.

2. Field investigation

A relatively new concrete harbor structure was selected for detailed investigations in the field and subjected to a probability-based durability analysis. The structure had a waterfront of 80 m and consisted of an open concrete deck on top of steel tubes filled with concrete. The top of the deck slab was located 3 m above the mean water level.

For concrete quality, a compressive strength of 45 MPa had been specified, while the concrete durability according to the Norwegian Concrete Code [5] included a maximum w/c-ratio of 0.45 and a minimum cement content of 300 kg/m^3. A high performance portland cement in combination with silica fume had been used. A lignosulphonate type of plasticizer had also been used, and the aggregate was mostly of a siliceous type with a maximum aggregate size of 16 mm. Further information about the concrete mixture is given in Table 1.

Table 1. Concrete mix proportions.

Cement (PC)	380 kg/m^3
Silica fume	19,2 kg/m^3
Sand 0-8 mm	1028 kg/m^3
Gravel 11–16 mm	843 kg/m^3
Plasticizer	4,6 kg/m^3
Air Entraining agent	1,62 kg/m^3
Water	187 kg/m^3
W/C	0,45
Effect factor of silica fume	2

The specified concrete cover was 40 mm, while according to NS 3473 [6], the minimum concrete cover in the splash zone should be 50 mm.

In addition to a thorough visual inspection, 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. Since the deck beams were assumed to represent the most exposed and vulnerable parts of the structure, two representative beams (B1 and B2) were selected for a more detailed measurements and analysis. In order to characterize the level of concrete quality, 3 Ø 100 mm concrete cores were also drilled out from the deck slab.

3. Durability analysis

When a reinforcement corrosion starts, the degradation of the concrete structure will develop as schematically shown in Fig. 1.

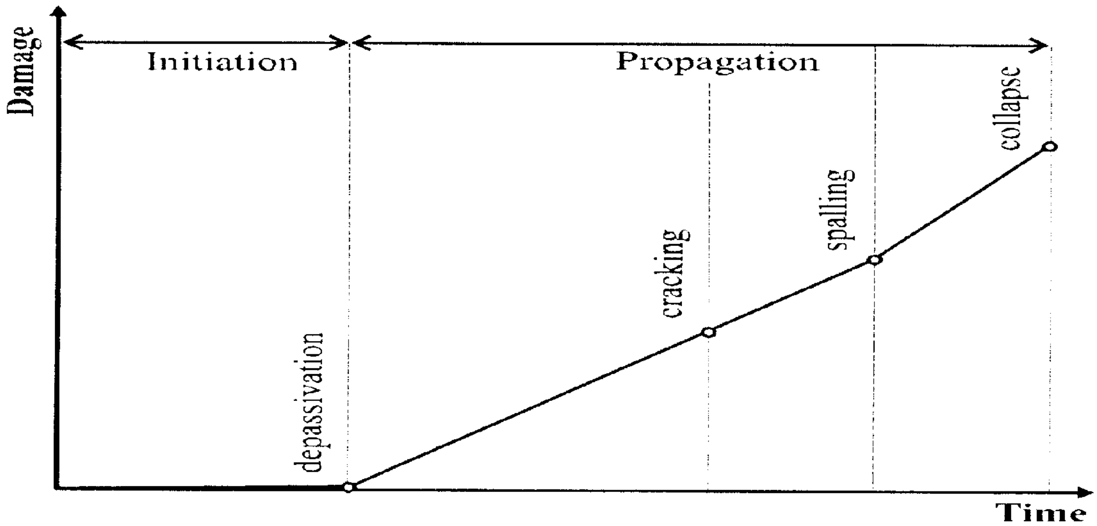

Fig. 1. Degradation development of a concrete structure with reinforcement corrosion.

While the depassivation of the embedded steel represents a well-defined stage of the degradation process, both cracking and spalling of the concrete cover do not necessarily reflect the degree of corrosion. Therefore, it appears appropriate to define the stage of depassivation or onset of steel corrosion 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 [7,8].

4. Results and discussion

4.1 Condition assessment

At the time of inspection, the general condition of the concrete structure appeared to be very good without any visual sign of reinforcement corrosion. However, for both beams investigated, the critical level of chloride concentration (0.07 % by weight of concrete) had already reached the depth of embedded steel. Average chloride profiles from the side of Beam B1 (Beam 1s) and the bottom face of Beam B2 (Beam 2b) are shown in Fig. 2.

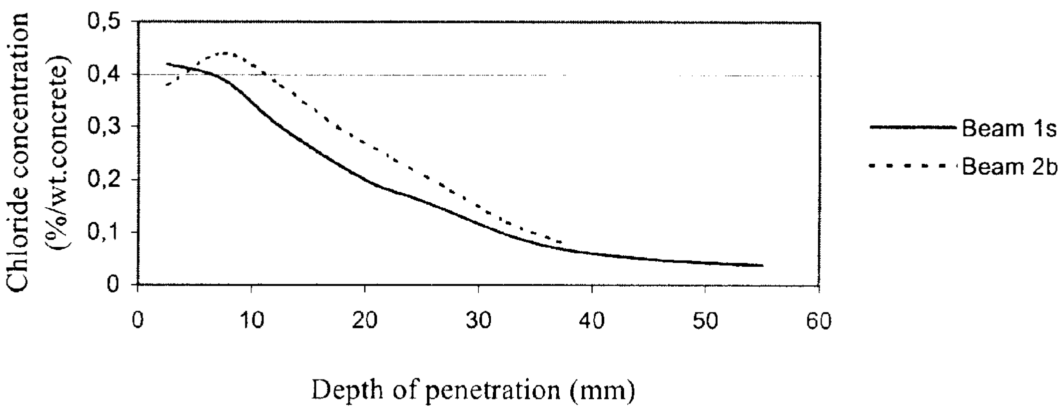

Fig. 2. Average chloride penetration in the beams investigated.

Based on the three concrete cores drilled out from the deck, accelerated chloride diffusivity (D) was determined by use of non-steady state migration testing [9], the results of which are shown in (Table 2). Based on previous experience [10], these test results indicate that the concrete quality in question only had a moderate resistance against chloride penetration.

Table 2. Chloride diffusivity of concrete in the deck.

Parameter	Average value	Standard deviation
D (10^{-12} m^2/s)	10,7	1,1

As shown in Fig. 3, the electrochemical surface potential mapping did not reveal any ongoing steel corrosion in Beam B2 [11].

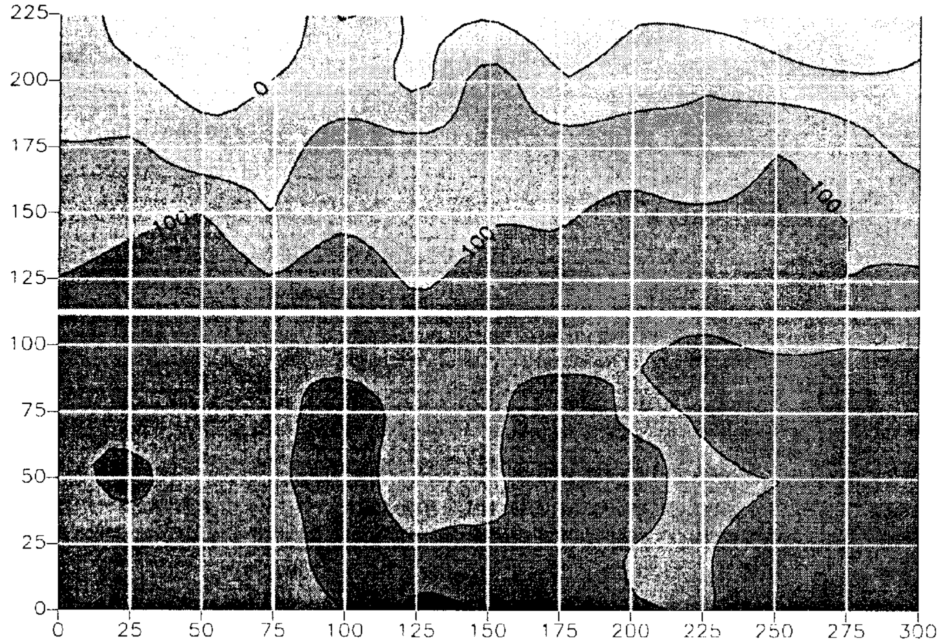

Fig. 3. Electrochemical surface potentials on the bottom face and east side of Beam B2 (CSE).

4.2 Durability analysis

In order to determine the surface chloride concentration (C_S) and the apparent diffusion coefficient (D_A), the chloride penetration curves were fitted with the error-function solution to Fick's Second Law, the results of which are shown in Table 3, together with some other parameters for the durability analysis

In order to carry out the probability-based durability analysis, it was necessary to determine the statistical parameters which define the probability density curves of the model variables shown in Table 3. The concrete cover (X_c) for the Beams B1 and B2 was determined on the basis of a large number of concrete cover measurements. The apparent diffusion coefficients (D_A) were determined from the curve fitting of a large number of chloride penetration profiles. 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 α, which expresses the time-dependence of the diffusion coefficient, was also adopted based on current experience. The parameter for the model uncertainty takes into account the uncertainties, which arise due to the simulation of the real degradation process [12].

Based on the statistical parameters shown in Table 3, the probability of failure (depassivation) versus time of exposure was analysed for a period of up to 50 years as shown in Fig. 4.

Table 3. Statistical parameters for the durability analysis.

Beam	B1	B2
x_C (mm)	N(50.0; 10,0)	N(48,7; 5,5)
D_A (10^{-12} m^2/s)	LN(0,37;0.13)	N(1.1;0.27)
c_{CR} (%/wt. conc.)	N(0.07;0.007)	
c_S (%/wt conc.)	N(0.55; 0.13)	N(0.71; 0.03)
α (-)	N(0.37;0.07)	
t_0 (years)	D(8.0)	
t (years)	D(50.0)	
Model uncertainty	N(0.0;0.1)	

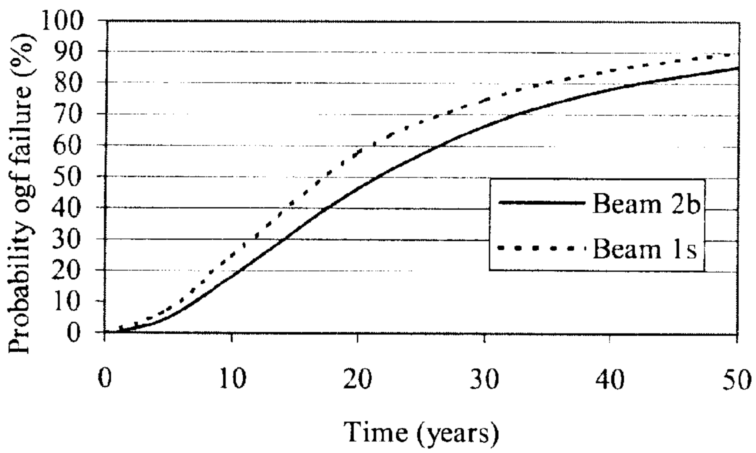

Fig. 4. Probability of failure versus time of exposure for the beams investigated.

From Fig. 4 it can be seen that the beams showed a difference in performance, due to a difference in exposure conditions. Contrary to Beam B1 which is sheltered from rain, the exposed edge of Beam B2 is also subjected to "wash-off" effects on the rain exposed faces.

According to NS 3490 [13], the probability of failure for a serviceability limit state should not exceed 10 %, while according to Eurocode 1 [14], the probability of failure should not exceed 7 %. For the two beams investigated, it can be seen from Fig. 4 that the probability of failure in the form of depassivation, exceeds 10 % within a period of

10 years, while the field investigations revealed that the chloride front already had reached a depth varying from 40 to 50 mm after a period of 7 to 8 years.

If a probability-based durability design had been carried out as an integral part of the original design of the structure, such a poor durability would probably not have been accepted. A probability-based durability design would also have provided a basis for a performance-based quality control during concrete construction, and hence also, a basis for documentation of obtained construction quality [15].

5. Conclusions

Although the structure investigated is representative for relatively new concrete structures in Norwegian harbors, the present investigation was only based on one structure and a limited amount of field measurements. For the probability analysis, it was also necessary to make a certain number of assumptions. On the basis of the results obtained, however, the following conclusions appear to be warranted:

1. For the beams investigated, the durability analysis showed that a 10 % probability of failure in the form of onset of steel corrosion would be exceeded already within a period of 10 years, while the field investigations revealed that the chloride front had already reached a depth varying from 40 to 50 mm after a service period of 7 to 8 years.

2. For all new concrete structures in a chloride-containing environment where safety and high long-term performance are important, a probability-based durability design should be an important and integral part of the general design.

6. Aknowledgement

The second author would 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

1. Gjorv, O.E., "Durability and Service Life of Concrete Structures", *Proceedings, The First fib Congress 2002*, Session 8, V. 6, *Japan Prestressed Concrete Engineering Association*, Tokyo, 2002, pp. 1-16.
2. DuraCrete, "Modelling of degradation" The European Union – Brite EuRam III, Project No. BE95-1347, Probabilistic performance based durability design of concrete structures, Report No. R 4-5, 1998.
3. DuraCrete, "General guidelines for durability design and redesign", The European Union – Brite EuRam III, Project No. BE95-1347, "Probabilistic performance based

durability design of concrete structures", Report No. R15, 2000.
4. McGee, R., "Modelling of durability performance of Tasmanian bridges", *Proceedings, The 8th International Conference on the Application of Statistics and Probability*, Sydney, Australia, 1999.
5. Norwegian Standard NS 3420, "Specifications for buildings and construction", Oslo, 1986.
6. Norwegian Standard NS 3473, "Concrete Structures – Design and detailing rules", Oslo, 1989.
7. Ferreira, M., Årskog, V., Jalali, S. and Gjorv, O. E., "Probability-based Durability Design of Concrete Harbor Structures", *Proceedings, Fourth International Conference on Concrete Under Severe Conditions – Environment and Loading*, Seoul, Korea, June 2004.
8. Ferreira, M., Jalali, S. and Gjørv, O. E., "Software for Probability-based Durability Analysis of Concrete Structures", *Proceedings, Fourth International Conference on Concrete under Severe Conditions – Environment and Loading*, Seoul, Korea, June 2004.
9. Nordtest Method NT Build 492, "Determination of chloride diffusion coefficient from non-steady state migration experiments".
10. Nilsson, L., Ngo, M.H. and Gjorv, O.E., "High-Performance Repair Materials for Concrete Structures in the Port of Gothenburg", *Proceedings, Second International Conference on Concrete Under Severe Conditions – Environment and Loading*, ed. by O.E.Gjorv, K. Sakai and N. Banthia, *E & FN Spon*, London and New York, V. 2, 1998, pp. 1193-1198.
11. Broomfield, J.P., "Corrosion of Steel in Concrete Understanding, investigation and repair", *E & FN Spon*, London and New York, 1997, pp. 40-50.
12. Leira, B. J., Hynne, T., Lindgård, J., "Marine Concrete Structures Subjected to Chloride Attack: Probabilistic Lifetime Assessment", *Proceedings, The ETCE/OMAE2000 Joint Conference: Energy for the New Millennium. American Society of Mechanical Engineers (ASME)*, New Orleans, USA, 2000.
13. Norwegian Standard NS-3490, "Design of structures – Requirements to reliability", Oslo, 1999.
14. EN 1991, "Eurocode 1: Basis of design and actions on structures", *CEN*, 2000.
15. Gjorv, O.E., "Durability Design and Construction Quality of Concrete Structures", *Proceedings, Fourth International Conference on Concrete Under Severe Conditions – Environment and Loading*, Seoul, Korea, June 2004.