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CHAPTER 112

WHAT HAPPENS WITH REINFORCED CONCRETE STRUCTURES WHEN THE REINFORCEMENT CORRODES¹

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ABSTRACT

In the paper, corrosion of reinforced concrete structures is discussed from the point of view of corrosion products. The different types of corrosion products are presented and a detailed study of the important diffusion coefficient is performed. Stochastic modelling of corrosion initiation, corrosion propagation and corrosion cracking is presented.

1. INTRODUCTION

To understand what happens with a reinforced concrete structure when the reinforcement corrodes, it is necessary to have a detailed understanding of the chemical and physical processes that take place during corrosion.

Corrosion of the reinforcement is one of the major reasons for deterioration of reinforced concrete structures. The corrosion process is very complex and the modelling is often based on observations or speculations rather than a clear understanding of the physical and chemical processes. In this paper the effect of corrosion of a structure is considered from the point of view of the rust production.

Shortly, the main effect of the corrosion is in general a reduced strength of the structural element in question and therefore also a reduction of the structural reliability. However, a number of effects are of interest, such as: When is the corrosion initiated? What types of corrosion products are produced? How much corrosion is needed to form

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a corrosion crack? What kind of crack size may be accepted? What is a reasonable definition of service life for a given structure?

Corrosion of the reinforcement is not only a serious problem because of the reduction of the effective reinforcement and the corresponding strength reduction. The corrosion may also be serious, because the volume of the rust products is higher than the volume of the corroded steel. Therefore, in this paper the corrosion process and the different types of corrosion products are discussed. The porous zone around the steel/concrete surface can to some extent absorb the higher volume of the rust products. Some amount of rust products will diffuse into the capillary voids in the cement. However, at a certain time the total amount of corrosion products exceeds the amount of corrosion products needed to fill the porous zone around the steel. The rust products will then create expansive pressure on the surrounding concrete. To estimate these processes a clear understanding of the structure of the concrete near the reinforcement is necessary.

The expansion of the concrete near the reinforcement will, as emphasized by Thoft-Christensen [1], [2], initiate tensile stresses in the concrete. After some time with increasing corrosion the tensile stresses will reach a critical value and corrosion cracks may develop. With further production of rust, the crack width will increase and eventually often result in spalling. This last part of the corrosion process is still not well understood. More research is certainly needed to clarify these important problems for a corroded reinforced concrete structure.

2. THE CORROSION PROCESS

Chloride-induced corrosion has been investigated by e.g. Neville [3]. In principle,

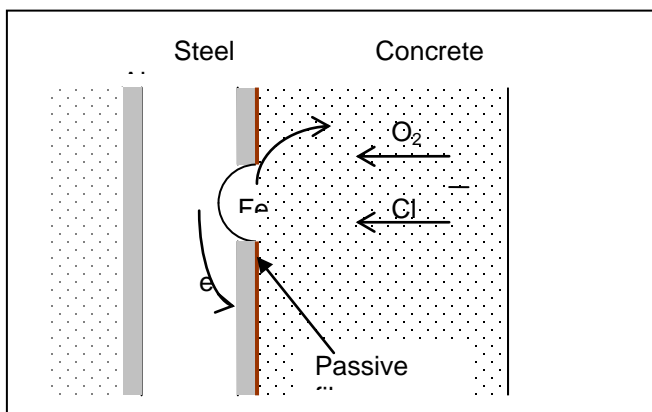
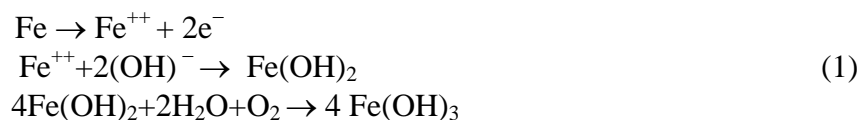


Figure1. Chloride-induced corrosion.

reinforced concrete is an excellent type of structure from a corrosion point of view, since the alkaline environment in the concrete maintains a passive film on the surface of the reinforcement, and this film protects the reinforcement against corrosion. However, if the concrete is penetrated by e.g. water or carbon dioxide, then this passive film breaks down and the reinforcement is open to corrosion.

The chloride-induced corrosion is schematically illustrated in figure 1. An anodic region is established, where the passive film is broken down, whereby an electrochemical cell is formed. The passive surface is the cathode and the electrolyte is the pore water in the concrete. At the anode the following reactions take place:



Chloride ions Cl^- activate the unprotected surface and form an anode. The chemical reactions are



It follows from (1) and (2) that two rust products Fe(OH)_2 (ferrous hydroxide) and Fe(OH)_3 (ferrous hydroxide) are produced.

3. THE CORROSION PRODUCTS

The different types of rust products are interesting to study because they have great influence on corrosion cracking, since the volume of the rust products corresponding to a given volume of the steel varies a lot. Nielsen [4] has studied this problem and has for several corrosion products obtained the following volumes corresponding to $1 \text{ cm}^3 \text{ Fe}$, see table 1.

Corrosion product	Colour	Volume, cm^3
Fe_3O_4	Black	2.1
Fe(OH)_2	White	3.8
Fe(OH)_3	Brown	4.2
$\text{Fe(OH)}_3, 3\text{H}_2$	Yellow	6.4

Table 1. Volume of corrosion products.

4. CHLORIDE DIFFUSION

Corrosion initiation period refers to the time during which the passivation of steel is destroyed and the reinforcement starts corroding actively. Fick's law of diffusion can represent the rate of chloride penetration into concrete, as a function of depth from the concrete surface and as a function of time

$$C(x,t) = C_0 \left\{ 1 - \text{erf} \left(\frac{x}{2\sqrt{D_c \cdot t}} \right) \right\} \quad (3)$$

where $C(x,t)$ is the chloride ion concentration, as % by weight of cement, at a distance of x cm from the concrete surface after t seconds of exposure to the chloride source. D is the chloride diffusion coefficient expressed in cm^2/sec . The solution of the differential equation (3) is

$$C(x,t) = C_0 \left\{ 1 - \text{erf} \left(\frac{x}{2\sqrt{D_c \cdot t}} \right) \right\} \quad (4)$$

where C_0 is the equilibrium chloride concentration on the concrete surface, as % by weight of cement, erf is the error function.

5. CORROSION CRACK INITIATION

In a real structure, if C_{cr} is assumed to be the chloride corrosion threshold and d is the thickness of concrete cover, then the corrosion initiation period T_{corr} can be calculated.

The time T_{corr} to initiation of reinforcement corrosion is

$$T_I = \frac{(d_1 - D_1 / 2)^2}{4D_c} \left(\operatorname{erf}^{-1} \left(\frac{C_{cr} - C_0}{C_i - C_0} \right) \right)^2 \quad (5)$$

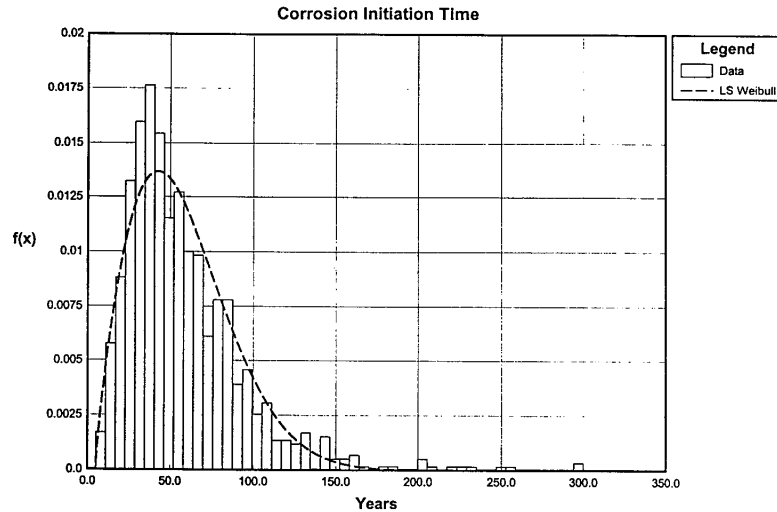


Figure 2. Density function of the corrosion initiation time T_{corr} .

On the basis of equation (5) outcomes of the corrosion initiation time T_{corr} have been performed on the basis of the following data by simple Monte Carlo simulation:

Initial chloride concentration:	0%
Surface chloride concentration:	Normal (0.650 ; 0.038)
Diffusion coefficient:	Normal (30 ; 5)
Critical concentration:	Normal (0.3 ; 0.05)
Cover:	Normal (40 ; 8)

A Weibull distribution can be used to approximate the distribution of the simulated data. The Weibull distribution is $W(x; \mu, k, \varepsilon)$, where $\mu = 63.67$, $k = 1.81$ and $\varepsilon = 4.79$. The corresponding histogram and the density function are shown in figure 2.

6. THE DIFFUSION COEFFICIENT

The diffusion coefficient D is a very important factor in all corrosion estimations. It follows from (5) that the time to corrosion imitation is inversely proportional in D . It is therefore of great interest to get a good estimate of D . The diffusion coefficient D is not a real physical constant for a given concrete structure since it depends of a number of factors.

According to extensive experimental investigations by Jensen [5] and by Jensen, Hansen, Coats & Glasser [6], it can be concluded that the most important factors are the water/cement ratio w/c , the temperature Φ , and the amount of e.g. silica fume (s.f.). The data presented in this section are all based on Jensen [5] and Jensen, Hansen, Coats and Glasser [6]. In figure 3 is shown the diffusion coefficient D as a function of the water-cement ratio w/c and the temperature Φ °C for cement pastes with 0% silica fume. It is clear from figure 3 that the diffusion coefficient D increases significantly with w/c as

well as the temperature Φ . In the example illustrated in figure 2 the minimum value of D is $0.31 \times 10^{-12} \text{ m}^2/\text{s}$ corresponding to $w/c = 0.2$ and the temperature $\Phi = 4^\circ\text{C}$. The maximum value of D is $80.00 \times 10^{-12} \text{ m}^2/\text{s}$ corresponding to $w/c = 0.70$ and $\Phi = 35^\circ\text{C}$. In figure 4 the contour lines for the same data are shown.

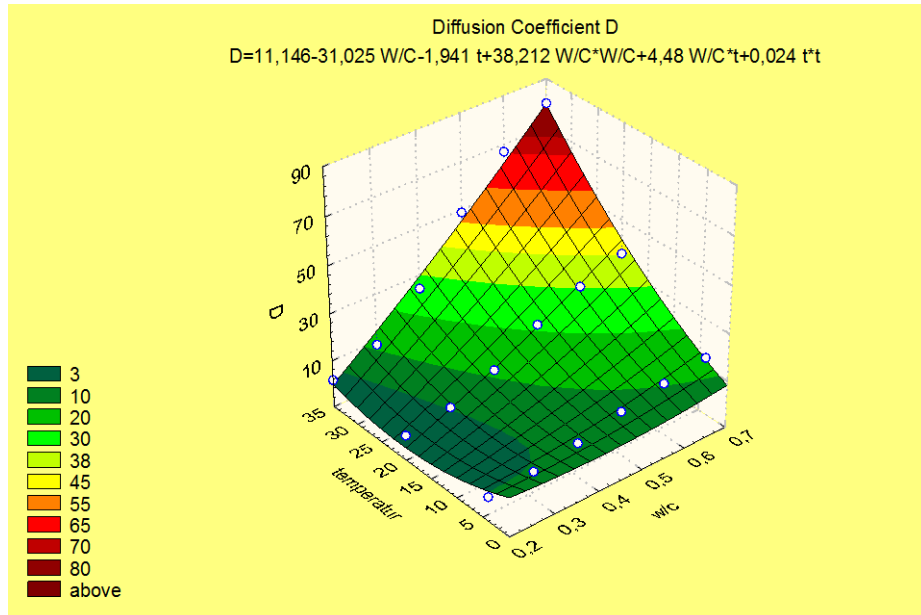


Figure 3. The diffusion coefficient D ($10^{-12} \text{ m}^2/\text{s}$) as a function of the water-cement ratio W/C and of the temperature t $^\circ\text{C}$ (Celsius).

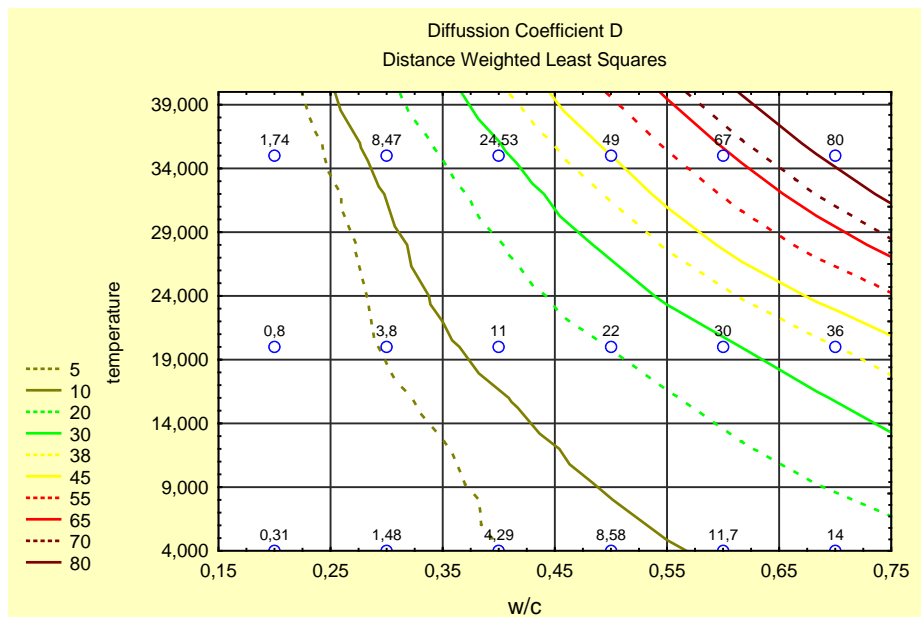


Figure 4. The diffusion coefficient D ($10^{-12} \text{ m}^2/\text{s}$) as a function of the water-cement ratio W/C and the temperature Φ $^\circ\text{C}$ (Celsius).

The influence of w/c and the temperature Φ may be explained by the chloride binding. Only the free chloride is important for the diffusion coefficient D . With increased w/c ratio less chloride is bound and D therefore increased. The strong

influence of the temperature is mainly caused by thermal activation of the diffusion process but may also be due to a reduced chloride binding when the temperature is increased. Taking into account the chloride binding also improves the modelling of the chloride ingress profiles.

It is clearly of great importance to get good estimates of w/c and Φ . The w/c value to be used is the original w/c value when the concrete was produced. If the original value of w/c is not available, then it can be estimated by testing of the concrete. The temperature Φ is more complicated to estimate, since the temperature usually varies a lot. As a first estimate it is suggested to use an equivalent value based on information of the variation of the temperature during the year at the site of the structure. When relevant values of W/C and Φ are obtained, then an estimate of D may be obtained from figure 3 or figure 4.

The addition of silica fume is of great importance for the chloride ingress. Silica fume additions reduce the chloride ingress because of changes in the pore structure. This is illustrated in table 2, see Jensen [5].

w/c	% s.f.	D (10^{-12} m ² /s)
0.3	0	3.8
	3	2.0
	6	0.42
	10	0.12
	20	0.05
0.5	0	22
	3	13
	6	4.2
	10	1.6
	20	0.30

Table 2. The diffusion coefficient D as a function of % s.f. for two values of w/c and $\Phi = 20$ °C:

7. CORROSION CRACK INITIATION

When corrosion has started the diameter $d(t)$ of the reinforcement bars at the time t is modelled by

$$d(t) = d_0 - c_{corr} i_{corr} t \quad (6)$$

where d_0 is the initial diameter, c_{corr} is a corrosion coefficient, and i_{corr} is the rate of corrosion. Based on a survey, three models for chloride penetration have been proposed (the initial chloride is assumed to be zero): low and high deterioration, Thoft-Christensen & Jensen [7].

It is assumed that there is a porous zone around the steel/concrete surface caused by the transition from paste to steel, entrapped/entrained air voids, and corrosion products diffusing into the capillary voids in the cement paste. When the total amount of corrosion products exceeds the amount of corrosion products needed to fill the porous zone around the steel, the corrosion products create expansive pressure on the surrounding concrete.

Close to reinforcement bars the concrete has some porosity. Very close to the bars the porosity is close to 1, but the porosity decreases with the distances from the bars. The porosity is typically of the order of 0.5 about 10-20 μ m from the bars so the

porous zone is very narrow. Let t_{por} be the thickness of an equivalent zone with porosity 1 around a steel bar. Then the amount of corrosion products necessary to fill the porous zone can be written

$$W_{porous} = \pi \rho_{rust} t_{por} d \quad (7)$$

where d is the diameter of the reinforcement bar and ρ_{rust} is the density of the corrosion products.

For illustration, let t_{por} be modelled by a lognormal distribution with the mean $12.5 \mu\text{m}$ and a standard deviation of $2.54 \mu\text{m}$. Further, let ρ_{rust} and d be modelled by normal distributions $N(3600,360) \text{ kg/m}^3$ and $N(16,1.6) \text{ mm}$, respectively.

Then it can be shown by Monte Carlo simulation that W_{porous} with a good approximation can be modelled by a shifted lognormal distribution with a mean $2.14\text{e}-03 \text{ kg/m}$, a standard deviation $0.60\text{e}-03 \text{ kg/m}$ and a shift of $0.82\text{e}-03 \text{ kg/m}$, see figure 5.

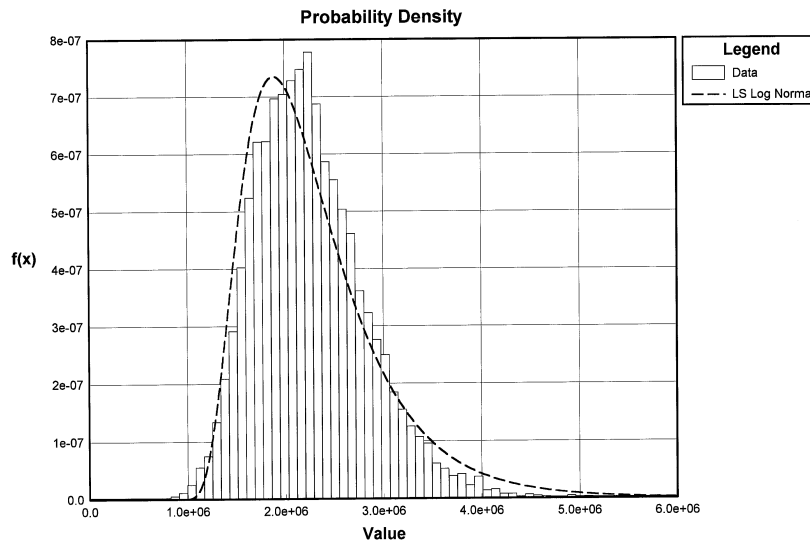


Figure 5. Stochastic modelling of W_{porous} .

After corrosion initiation the rust products will initially fill the porous zone and then result in an expansion of the concrete near the reinforcement. As a result of this, tensile stresses are initiated in the concrete. With increasing corrosion the tensile stresses will reach a critical value and cracks will be developed.

During this process the corrosion products at initial cracking of the concrete will occupy three volumes, namely the porous zone, the expansion of the concrete due to rust pressure, and the space of the corroded steel. The corresponding total amount of critical rust products W_{crit} to fill these volumes is

$$W_{crit} = W_{porous} + W_{expan} + W_{steel} \quad (8)$$

where W_{expan} is the amount of corrosion products needed to fill in the space due to the expansion of the concrete around the reinforcement, and W_{steel} is the amount of corrosion products that generate the cracking.

Let the expansion of the concrete around the reinforcement have the thickness t_{expan} , then W_{expan} can be written

$$W_{\text{expan}} = \rho_{\text{rust}} \pi (D + 2t_{\text{por}}) t_{\text{crit}} \quad (9)$$

where t_{crit} is the thickness of the expansion at crack initiation.

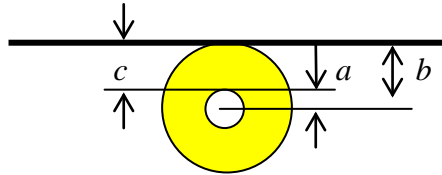


Figure 6. Idealization of the concrete around the reinforcement by a thick-walled cylinder.

Liu & Weyers [8] have estimated t_{crit} by assuming that the concrete is a homogeneous elastic material and can be approximated by a thick-walled concrete cylinder with inner radius $a = (d + 2t_{\text{por}})/2$ and outer radius $b = c + (d + 2t_{\text{por}})/2$ where c is the cover depth, see figure 4. Then the approximate value of the critical expansion t_{cr} is

$$t_{\text{crit}} = \frac{cf'_t}{E_{ef}} \left(\frac{a^2 + b^2}{b^2 - a^2} + \nu_c \right) \quad (10)$$

where E_{ef} is the effective elastic modulus of the concrete and f'_t is the tensile strength of the concrete. ν_c is Poisson's ratio of the concrete. In this paper E_{ef} , ν_c , and c are considered deterministic with values 10 GPa, 0.25, and 60 mm, respectively. The tensile strength f'_t is modelled as a normally distributed variable with the mean value 4MPa and the standard deviation 0.6 MPa.

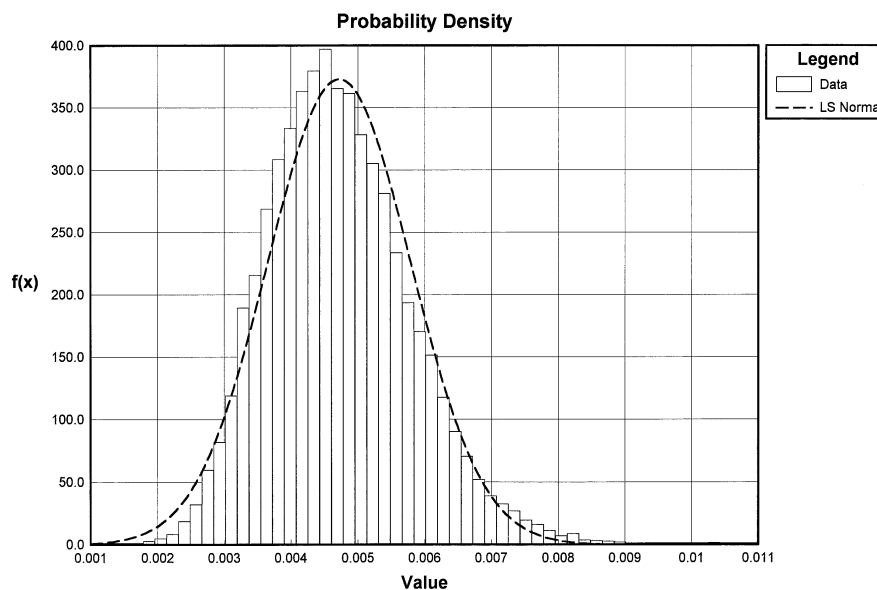


Figure 7. Stochastic modelling of W_{expan} .

Then by Monte Carlo simulation it can be shown that W_{expan} with a good

approximation can be modelled by a normal distribution $N(0.0047, 0.0011)$ kg/m, see figure 7.

Finally, W_{steel} can be written

$$W_{steel} = \frac{r_{rust}}{r_{steel}} M_{steel} \quad (11)$$

where ρ_{steel} is the density of steel and M_{steel} is the mass of the corroded steel. Clearly, M_{steel} is proportional to W_{crit} . Liu & Weyers, 1998 have calculated the factor of proportionality for two kinds of corrosion products as 0.523 and 0.622. For simplicity, it will be assumed that $M_{steel} = 0.57W_{crit}$. Therefore, equation (9) can be rewritten

$$W_{crit} = \frac{\rho_{steel}}{\rho_{steel} - 0.57\rho_{rust}} (W_{porous} + W_{expan}) \quad (12)$$

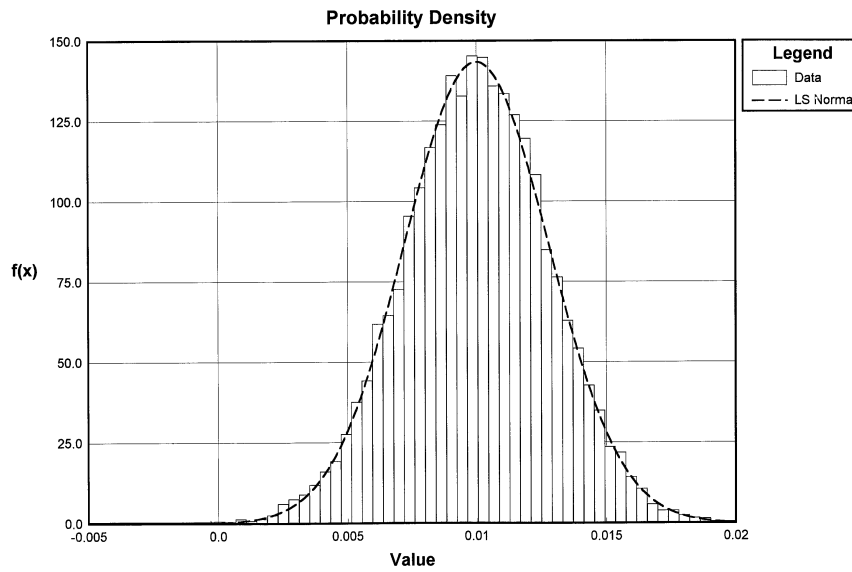


Figure 8. Stochastic modelling of W_{crit} .

Let ρ_{steel} be modelled by a normal distribution $N(8000; 800)$ kg/m³. Then by Monte Carlo simulation it can be shown that W_{crit} with a good approximation can be modelled by a normal distribution $N(0.010; 0.0027)$ kg/m, see figure 8.

The rate of rust production as a function of time t (years) from corrosion initiation (Liu & Weyers [8]) can be written

$$\frac{dW_{rust}(t)}{dt} = k_{rust}(t) \frac{1}{W_{rust}(t)} \quad (13)$$

i.e. the rate of corrosion is inversely proportional to the amount of rust products W_{rust} (kg/m). The factor $k_{rust}(t)$ (kg²/m²year) is assumed to be proportional to the annual mean corrosion rate $i_{cor}(t)$ (μ A/cm²) and the diameter d (m) of the reinforcement. The proportionality factor depends on the types of rust products, but is here taken as $0.383e-3$.

$$k_{rust}(t) = 0,383 \times 10^{-3} di_{corr}(t) \quad (14)$$

By integration

$$W_{rust}^2(t) = 2 \int_0^t k_{rust}(t) dt \quad (15)$$

Let $i_{cor}(t)$ be modelled by a time-independent normally distributed stochastic variable $N(3 ; 0.3)$ (μ A/cm²) then the time from corrosion initiation to cracking Δt_{crack} can be estimated by (16) by setting $W_{rust}(\Delta t_{crack}) = W_{crit}$.

$$\Delta t_{crack} = \frac{W_{crit}^2}{2k_{rust}} = \frac{W_{crit}^2}{2 \times 0.383 \times 10^{-3} di_{corr}} \quad (16)$$

Then it can be shown by Monte Carlo simulation that Δt_{crack} with a good approximation can be modelled by a Weibull distribution $W(3.350 ; 1.944 ; 0)$ years, see figure 9. The mean is 2.95 years and the standard deviation 1.58 years.

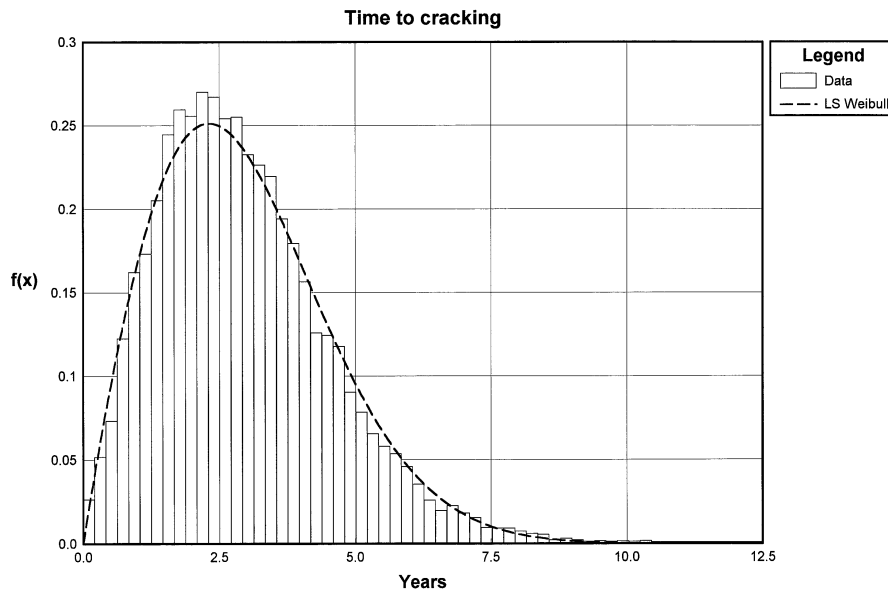


Figure 9. Stochastic modelling of Δt_{crack} .

The mean value of T_{crack} is of the same order as the experimental values (and the deterministic values) obtained by Liu & Weyers [8].

8. EVOLUTION OF CRACKS IN THE CONCRETE

Andrade, Alonso & Molina [9] have investigated experimentally the evolution of corrosion cracks in reinforced concrete beams. After formation of the initial crack the rebar cross-section is further reduced due to the continued corrosion, and the width of the crack is increased. In the paper four simple test specimens have been investigated. The specimens are small, simplified reinforced concrete beams with only a single rebar and 2 or 3 cm of cover. An impressed current artificially corrodes the beams. The loss of bar sections is monitored and the corresponding crack evolution is measured by strain gauges attached to the surface of the beams. In all four experiments the function between the reduction of the rebar diameter and the maximum crack width measured in

the surface of the concrete specimen can be approximated by a linear function, see figure 10.

Let Δw be the increase in crack width in the time interval Δt and let the corresponding loss of rebar diameter be Δd . Then, see figure 11,

$$\Delta w = \gamma \Delta d \quad (17)$$

where γ is of the order 1.5 to 5 in the experiments reported by Andrade et al. [10]. The factor γ depends on the applied current and on the cross-sectional data.

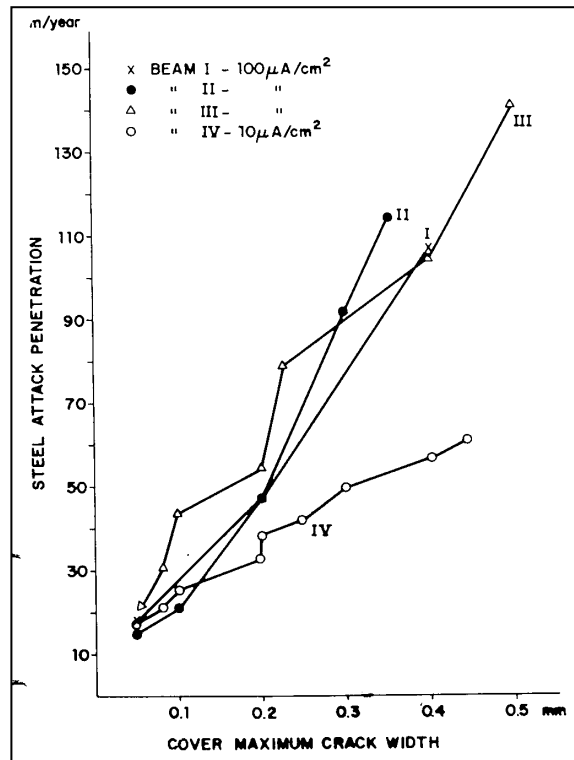


Figure 10. Loss in rebar diameter versus the crack width. Andrade et al. [10].

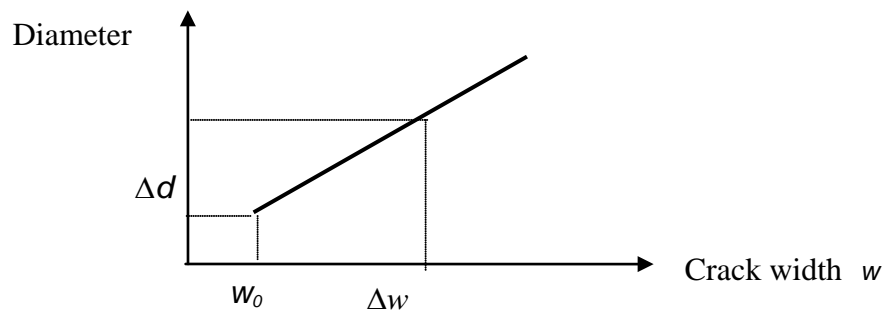


Figure 11. Relation between reduction in diameter and the crack width.

A simple approximate estimation of γ for a given beam cross-section may be performed as shown below. For illustration, assume that the diameter of the rebar at the time of crack initiation is 16 mm and that the cover is 30 mm, see figure 12.

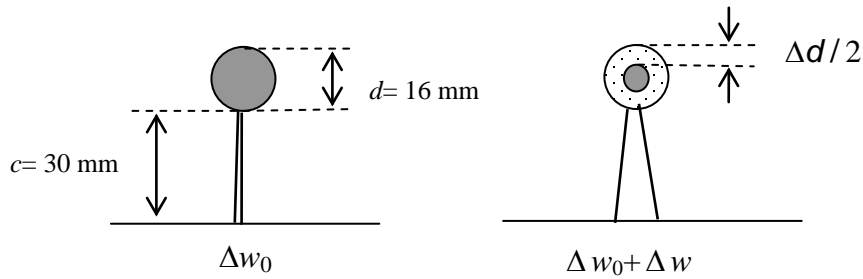


Figure 12. Evolution of cracks.

To the left in figure 12 the crack at the time of the initial crack forming is shown. The initial crack width is Δw_0 . To the right the assumed crack configuration is shown at the time when the diameter loss is Δd . The crack width is then $\Delta w_0 + \Delta w$. Assuming that the increase in the volume of the crack is equal to the volume of the corrosion products produced when the diameter is reduced to $d - \Delta d$, the relationship between Δw and d can be obtained approximately by

$$\frac{1}{2} \left(\frac{d/2}{d/2 + c} + 1 \right) c \Delta w = (\alpha - 1) \pi d \frac{\Delta d}{2} \quad (18)$$

where $\alpha = \rho_{rust} / \rho_{steel}$ (the relation between the densities of the rust product and the steel) depends on the type of corrosion products. Typical values are 2 - 4. By inserting the above-mentioned data one obtains for this case $\gamma = 1.4 - 4.2$ in good agreement with the experimental results described by Andrade et al. [9].

9. SPALLING

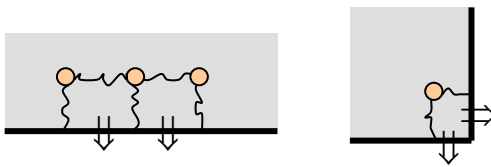


Figure 13. Typical examples of concrete spalling.

Using FEM the procedure presented above can be extended to estimating the time for corrosion based spalling of concrete for e.g. slabs and beams; see figure 13.

A severe example of corrosion spalling is shown in figure 14.



Figure 14. Corrosion cracking and spalling.

10. CONCLUSIONS

In the paper, corrosion of reinforced concrete structures is discussed from the point of view of corrosion products. The different types of corrosion products are presented and a detailed study of the important diffusion coefficient is performed. The aim is to use a sound modelling of the corrosion process. The total corrosion process from corrosion initiation to corrosion cracking and spalling is considered.

11. ACKNOWLEDGEMENT

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