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CHAPTER 127

SAFETY AND CORROSION CRACKING OF CONCRETE STRUCTURES [1]

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ABSTRACT

Deterioration of reinforced structures due to reinforcement corrosion is one of the main reasons for unsatisfactory safety of many concrete structures. The first sign of safety problems is often discoloring of the concrete surface or cracking/spalling due to corrosion of the reinforcement. In the present study it is investigated how to assess the reduction of the rebar section due to corrosion based on observation of the width of the corrosion crack.

1. INTRODUCTION

It is of great interest to investigate whether it is possible to estimate the reliability of a given structure observations of corrosion crack on the surface of the concrete structure. In the paper recent progress in modelling of the deterioration of reinforced concrete structures is presented with special emphasis on the corrosion crack width propagation. Important developments have taken place in the field of deterioration of reinforced concrete structures during the last 20 years; see e.g. Thoft-Christensen [1].

Modelling of corrosion cracks has been treated in recent years by several researchers. Experiments and 2-dimensional FEM analysis seem to support that the function between the reduction of the rebar diameter ΔD_{bar} and the corresponding increase in crack width Δw_{crack} in a given time interval Δt measured on the surface of the concrete specimen can be approximated by a linear function; Thoft-Christensen [2].

[1] Proceedings 4th Int. Workshop on Life-Cycle Cost Analysis and Design of Civil Infrastructures Systems, Cocoa Beach, Florida, May 8-11, 2005, pp. 135-142.

More recently the parameter $\gamma = \Delta w_{crack} / \Delta D_{bar}$ is further studied with respect to its dependency on the diameter of the reinforcement bar and the concrete cover; Thoft-Christensen [3].

In the paper it is shown that the above-mentioned work can be extended to more realistic beam configurations when a 3-dimensional FEM modelling is used. The parameter $\gamma = \Delta w_{crack} / \Delta D_{bar}$ may then be evaluated for a 3-dimensional beam by assuming a concentrated corrosion area of the reinforcement. In this way it is possible not only to investigate homogeneous corrosion, but also pit corrosion. A framework for further research in this area including realistic stochastic modeling of reinforced concrete beams is presented.

2. SAFETY ESTIMATION BASED ON CORROSION CRACK WIDTH

The proposed procedure for estimating the safety of a corroded reinforced concrete bridge consists of 3 steps:

- Step 1: Visual observations of corrosion cracks.
- Step 2: Estimation of the amount of corrosion products.
- Step 3: Estimation of the safety of the beam.

These 3 steps are described in the next 3 chapters with special emphasis on the crucial step 2.

3. STEP 1: VISUAL OBSERVATIONS OF CORROSION CRACKS

The first sign of corrosion of the reinforcement in a reinforced concrete beam may be one or several cracks parallel to the reinforcement at the underside (near the rebars) of thr beam. This is illustrated in figure 1. For a strongly corroded conrete beam with spalling the procedure resented in this paper cannot be used to estimate the safety of the beam since the loss of reinforcement section is not the major factor regarding loss of strength. In such a case a more important factor will be the loss of bond; see e.g. Lundgren [4].

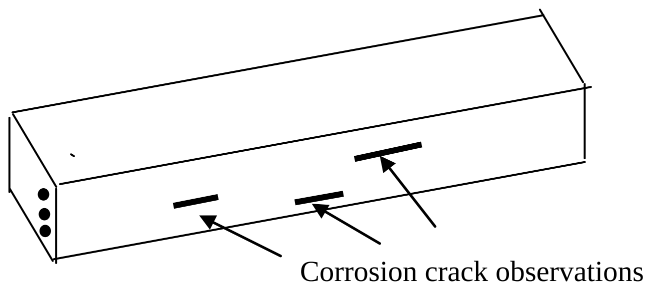

Figure 1. Corrosion cracks observations parallel with the reinforcement at the underside af the concrete beam.

The proceedure presented here is therefore only applicable in cases where the strength (safety) of the concrete been is sensitive to the loss of reinforcement section. This is usually the case in the beginning of the corrosion process.

During the visual observation the position, length and crack width of all corrosion cracks are registred so that the critical beam sections are identified. By the procedure presented below the reduction of the rebar section in all the critical beam sections is assessed. The effect of this loss of rebar section on the strength of the critical sections can then be calculated. The safety reduction of the concrete beam may then be estimated using a systems approch.

4. STEP 2: ESTIMATION OF THE AMOUNT OF CORROSION PRODUCTS

Corrosion cracks in reinforced concrete beams are due to the increased volume of corrosion products. Initially, the rust products from the corroded reinforcement will fill the porous zone near the reinforcement but then result in an expansion of the concrete near the reinforcement. As a result of this, tensile stresses are initiated in the concrete near the reinforcement. With increasing corrosion the tensile stresses will at a certain time reach a critical value and cracks will be developed.

After formation of the initial crack the rebar cross-section is further reduced due to the continued corrosion, and the width of the crack w_{crack} is increased. The function between the reduction of the rebar diameter ΔD_{bar} and the corresponding increase in crack width Δw_{crack} in a given time interval Δt measured on the surface of the concrete specimen is discussed in this chapter.

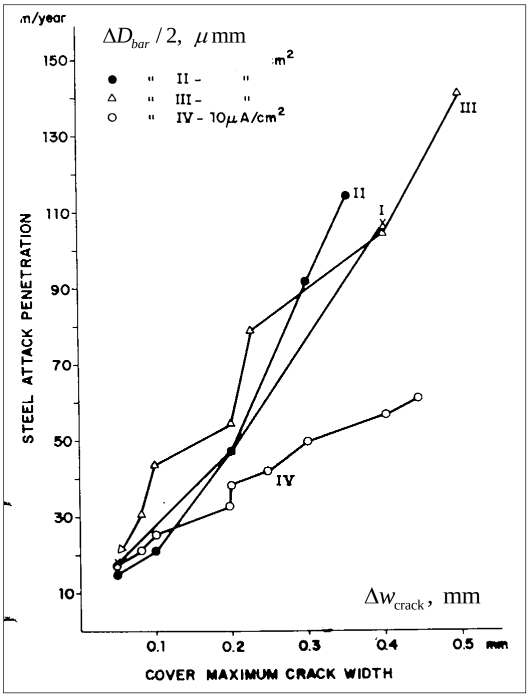

Figure 2. Loss in rebar diameter ΔD_{bar} versus the crack width Δw_{crack}; Andrade, Alonso & Molina [5].

The evolution of corrosion cracks in reinforced concrete beams has been experimentally investigated; see Andrade, Alonso & Molina [5]. Four simplified small reinforced concrete beams with only a single rebar and 2 or 3 cm of cover have been tested. 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 on the surface of the concrete specimen can be approximated by a linear function

$$\Delta w_{crack} = \gamma\, \Delta D_{bar} \qquad (1)$$

where γ is of the order 1.5 to 5, see figure 2.

A simple approximate estimation of the coefficient γ in equation (1) may be obtained by the geometrical approach presented below; see Thoft-Christensen (2001). For illustration, assume that the diameter of the rebar at the time of crack initiation is D = 16 mm and that the cover is c = 30 mm; see figure 3.

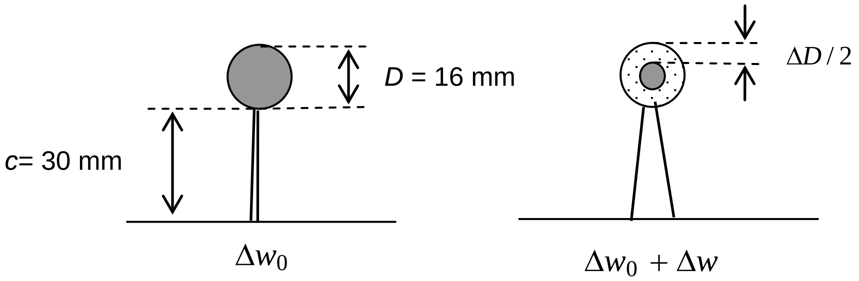

Figure 3. Illustration of the crack evolution in a given time interval Δt.

The procedure is then based on the assumption that the increase in the volume (area) of the crack is equal to the volume (area) of the corrosion products produced when the diameter is reduced to $D - \Delta D$. The relationship between Δw and ΔD can then be obtained approximately by

$$\frac{1}{2}\left(\frac{D/2}{D/2+c}+1\right)c\,\Delta w = (\alpha - 1)\pi D \frac{\Delta D}{2} \tag{2}$$

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 for $\nu = 1/6$ are 2 to 4. In the example shown in figure 2 one obtains $\gamma = 1.4$ to 4.2 in good agreement with the experimental results described in Andrade, Alonso & Molina [5].

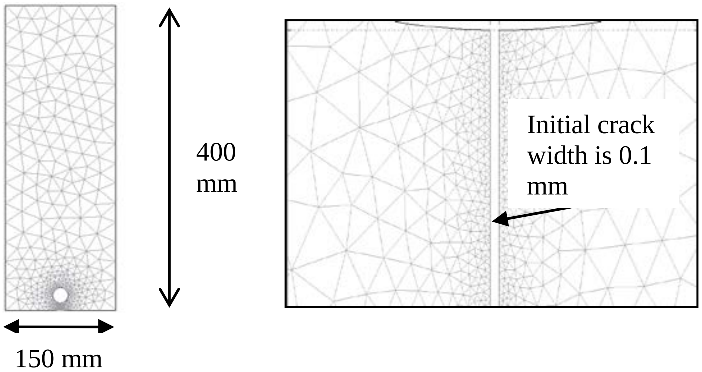

Figure 4. FEM net. The total net to the left and the local net near the crack to the right.

For a given beam cross-section the coefficient γ in equation (1) can be estimated using FEM analysis; Thoft-Christensen (2003). For illustration, consider the rectangular beam cross-section shown in figure 4. The cover is c = 10 mm. The initial crack width is 0.1 mm. In the FEM modelling the rectangular cross-section is assumed to have a hole at the site of the reinforcement and a crack from the hole to the boundary as shown in figure 4. The number of constant strain elements is 5580 and there are 3066 nodes. The FEM analysis is made using FEMLAB/MATLAB. The material is assumed to be linear elastic with the elasticity modulus E = 25×10^9 Pa, Poison's ratio $\nu = 1/6$, and the pressure from the increasing corrosion products is modelled as a uniform loading (pressure) p = 1×10^8 N/m at the boundary of the hole.

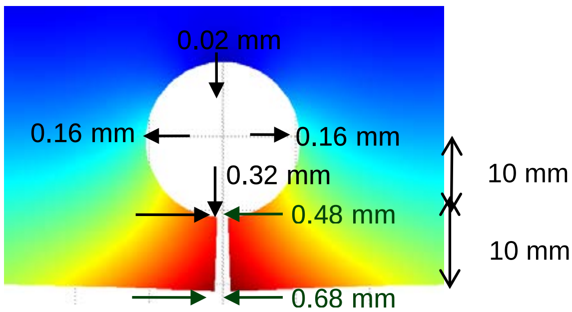

Figure 5. Displacement at four points of the circle and at the crack opening.

The displacements obtained by the FEM analysis are shown in figure 5. The increase in the crack width is Δw_{crack} = 0.67 mm and the average increase in the hole diameter is ΔD_{hole} = 0.31 mm. Therefore,

$$\gamma = \Delta w_{crack} / \Delta D_{bar} \approx \Delta w_{crack} / \Delta D_{hole} = 2.2 \tag{3}$$

The coefficient γ as a function $\gamma(D,c)$ of the bar diameter D and the concrete cover c has recently been investigated using FEM analysis assuming linear elasticity. The analysis is performed by a procedure similar to the one used above; Thoft-Christensen [3]. 30 combinations of the diameter D and the cover c are used in the FEM analysis and the results are shown in figure 6.

Diameter D, mm			Cover a,mm		
	20	25	30	35	40
10	3.72	3.53	3.39	3.30	3.25
12	3.93	3.76	3.63	3.55	3.50
14	4.09	3.94	3.83	3.75	3.71
16	4.20	4.08	3.99	3.92	3.88
18	4.26	4.19	4.11	4.06	4.03
20	4.28	4.27	4.21	4.18	4.15

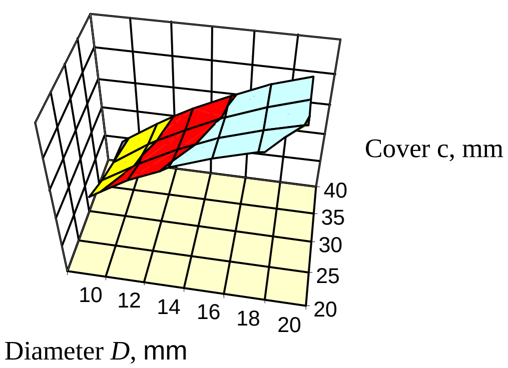

Figure 6. Estimates of $\gamma(D,a)$.

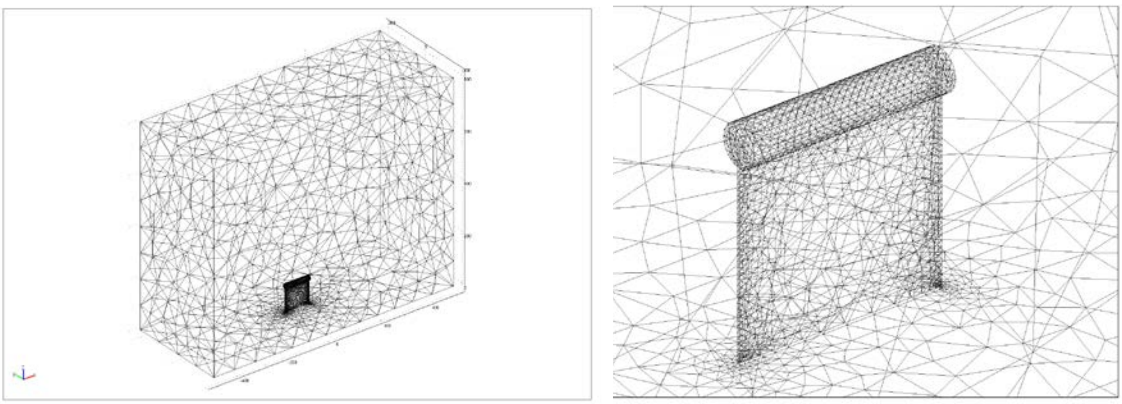

Figure 7. 3-D FEM modelling of concrete beam with localised corroded reinforcement and the associated crack.

In an ongoing research project, a more acceptable 3-D modelling is being tested using 3-D modelling of a reinforced concrete beam with a single reinforcement bar, see figure 7. Figure 7 shows a section of a reinforced concrete beam with a cylindrical hole and a narrow crack (0.1 mm) from this hole to the underside of the beam. The material is assumed to be linear elastic and the pressure from the increasing corrosion products is modelled as a uniform loading (pressure) at the boundary of the cylindrical hole.

The preliminary results from this analysis are presented by Thoft-Christensen [6]. In figure 8 the displacements in the beam cross-section through the midpoint of the cylindrical hole (corroded part of the reinforcement9 is shown. The undisturbed beam section is shown to the left and the displacements when the uniform pressure on the surface of the hole is 10^5 MPa are shown to the right. More details are given in Thoft-Christensen [6].

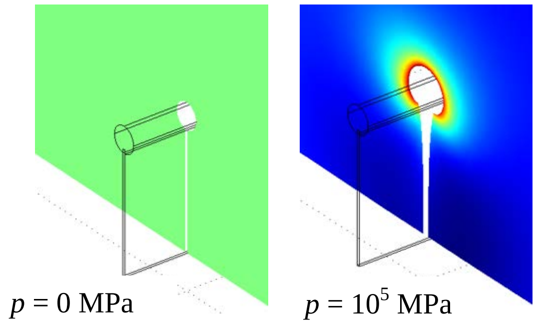

Figure 8. The displacements in the cross-section through the midpoint of the cylindrical hole.

5. STEP 3: ESTIMATION OF THE SAFETY OF THE BEAM

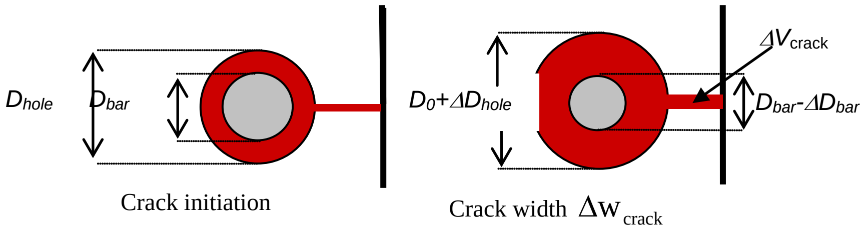

Figure 9. Crack width increase from crack initiation (0.1 mm) to Δw_{crack}.

An approximate relation between the decrease in the steel bar ΔD_{bar} and the increase in the hole ΔD_{hole} may be obtained easily by considering the volume of the produced rust products $\pi \Delta D_{bar}\ D_{bar}\ \alpha$ ($\alpha = \rho_{steel}/\rho_{rust}$ is the relation between the densities of the steel and the rust product) and the volume due to the expansion of the hole $\pi \Delta D_{bar}\ D_{bar} + \pi \Delta D_{hole}\ D_{hole}\ + \Delta V_{crack}$; see figure 9. By equalizing these two volumes and assuming that $D_{bar} \approx D_{hole}$ one gets

$$(\alpha\text{-}1)\Delta D_{bar} \approx \Delta D_{hole} + \Delta V_{crack}/\pi D_{hole} \tag{4}$$

and

$$\gamma = \Delta w_{crack}/\Delta D_{bar} \approx (\alpha\text{-}1)\Delta w_{crack}/(\Delta D_{hole} + \Delta V_{crack}/\pi D_{hole}) \tag{5}$$

where the relation $\alpha = \rho_{\text{steel}} / \rho_{\text{rusr}}$ between the densities of the corrosion products and the steel is of the order 2.1 to 6.4 depending of the type of corrosion products; Nielsen [7]. The reduced safety of a corroded reinforced concrete beam may then be estimated on basis of crack width observations by using the above mentioned FEM analysis and equation (4).

6. CONCLUSIONS

A new methodology, by which the relation between the width of a corrosion crack and the corresponding reduction of the rebar section is obtained, is presented in this paper. The methodology may be used to relate safety of the beam to observed corrosion cracks in cases where the rebar sections are significant for the safety of the beam. The methodology is based on FEM analysis of corrosion crack propagation.

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