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MODELING OF REINFORCEMENT CORROSION IN CONCRETE

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Abstract: *Chloride-induced steel corrosion is one of the major deterioration problems for steel reinforced concrete structures. The accumulated corrosion products on the bar surface cause longitudinal cracking of the concrete cover. Loss of concrete cover leads to reduction in bond strength at the interfacial zone between the two materials. In addition, the deterioration of the ribs of the deformed bars causes a significant reduction of the interlocking forces between the ribs of the bars and the surrounding concrete keys. This deteriorates the primary mechanism of the bond strength between deformed bars and concrete, and hence, the bond strength decreases significantly. In this paper the effect of reinforcement corrosion on the bond strength between reinforcement and concrete was investigated for different corrosion levels. The effect of corrosion was simulated by the nonlinear numerical analysis with the FEM program using the 3D models.*

Keywords: Concrete, reinforcement, corrosion, bond, numerical analysis.

1. Introduction

It is known that, in good quality concrete the embedded reinforcing steel is protected against corrosion due to the formation of a sub-microscopically thin film. The corrosion of reinforcements in the construction of a transport infrastructure (especially bridges), parking areas, etc., is primarily initiated by chlorides from de-icing salts. In prestressed concrete structures the reinforcing steel elements are subjected to high mechanical stresses, therefore corrosion of the tendons can lead to consequences far more serious than in the case of conventionally reinforced concrete structures. This may result in failure of the steel and consequently of structure, or part of it, with a great potential for life losses, life disruption, and a huge economic impact. When corrosion is initiated, active corrosion results in a volumetric expansion of the corrosion products around the reinforcing bars against the surrounding concrete. Higher corrosion rates can lead to the cracking and spalling of the concrete cover. Continued corrosion of reinforcement causes a reduction of total loss of bond between concrete and reinforcement.

2. Experimental measurements

Numerical modeling is based on data obtained from previous experimental investigation of the effect of reinforcement corrosion on bond behavior. A total number of 48 reinforced concrete specimens were made. The dimensions of specimens were 200 x 200mm, height 130mm, Fig 1. The specimens were divided into 6 groups (types A to F), depending on the diameter of the reinforcement (Ø8 - types A, C, E, and Ø10 - types B, D, F), the thickness of concrete cover (30 and 40 mm respectively), and with or without stirrups, Tab.1. In the next part of paper, results for specimens with Ø10 diameter of reinforcement are discussed.

To accelerate the reinforcement‘s corrosion, the impressed current technique was used. The actual degree of corrosion, (corrosion level C_L) was measured as the loss in weight of the reinforcement steel bar to that of the bond length before corrosion, and thereby representing an average corrosion level along the bond length. The bond strength has been calculated using the initial (un-corroded) cross-sectional dimension of the bars.

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Tab. 1: Geometrical parameters of specimens.

Type	**main rebar d_{sl}** [mm]	**stirrups d_{ss}** [mm]	**main rebar cover c** [mm]	**c/d_{sl}** [-]
A1-A8	***8***	***6***	***40***	***5.0***
B1-B8	***10***	***6***	***40***	***4.0***
C1-C8	***8***	***6***	***30***	***3.75***
D1-D8	***10***	***6***	***30***	***3.0***
E1-E8	***8***	***-***	***30***	***3.75***
F1-F8	***10***	***-***	***30***	***3.0***

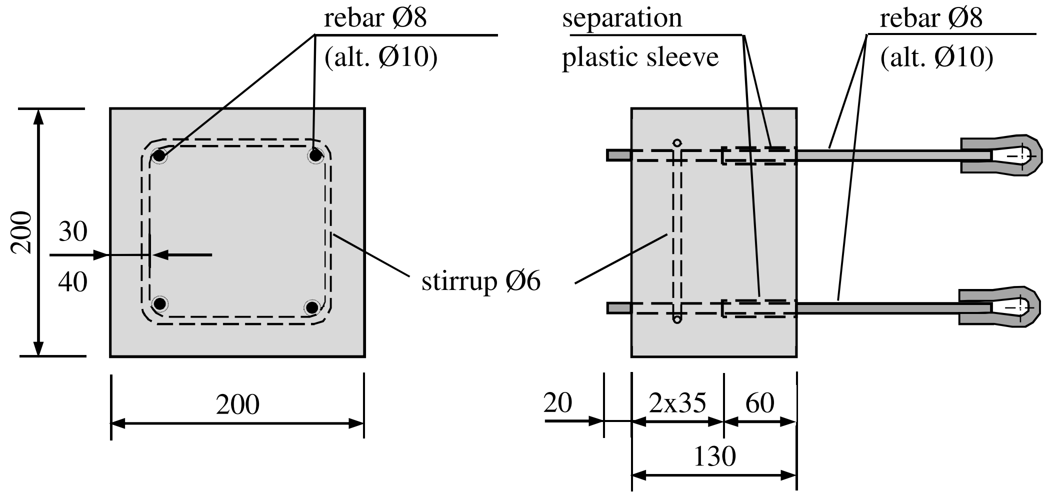
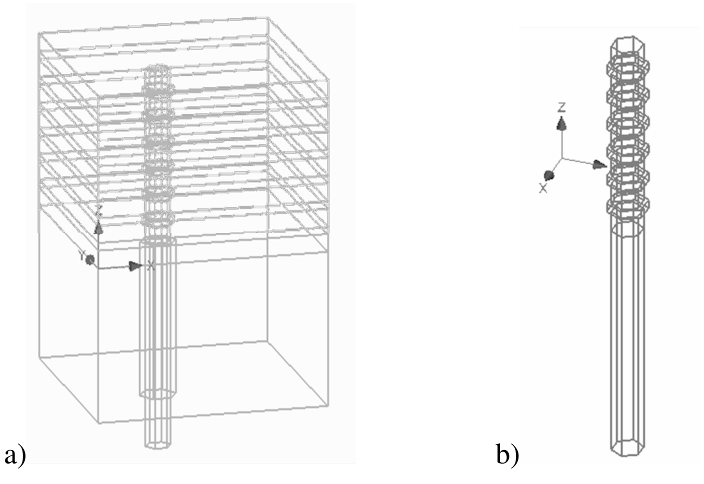


Fig. 1: Geometry of experimental specimens with stirrups

3. Numerical analysis

The Atena 3D software was used for numerical modeling. A total of 3 models, depending on geometrical parameters of specimens were developed. Due to symmetrical shape and for decrease of numerical solution, only 1/4 of specimens were modeled (Fig. 2). The reinforcement ribs were also modeled due to effect of mechanical interlock of the reinforcement ribs into concrete. The reinforcement cross-section was modeled as hexagon with the same cross-section area as original the circle, because the 3D version of Atena does not allow to model circular cross-sections.



a) b)

Fig. 2: a) Geometry of 3D model without stirrups, b) Modeling of reinforcements ribs.

The reinforcement cross-section area is decreasing due to corrosion, while the volume of the corrosion products increases. Due to this phenomenon, it was necessary to recalculate the reinforcement diameter *d*(t) at time *t* and also the percentage loss of reinforcement area, (Fig. 3). The value of percentage loss of reinforcement area was calculated depending on the generated corrosion products (Fe_2O_3, Fe_3O_4...) during the accelerated corrosion.

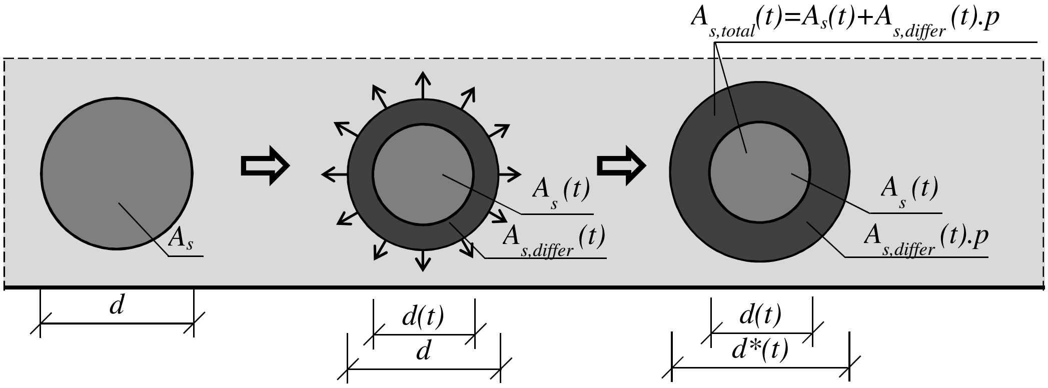


Fig. 3: Change of reinforcement cross-section area due to corrosion – theoretical approach.

The contact between concrete and reinforcement was modeled with material characteristic “3D interface”, which is based on Mohr-Coulomb criterion with tension cut off. The constitutive relation for a general three-dimensional case is given in terms of tractions on interface planes and relative sliding and opening displacements and it is given by Eq. (1).

$$\begin{Bmatrix} \tau_1 \\ \tau_{2.} \\ \sigma \end{Bmatrix} = \begin{bmatrix} K_{tt} & 0 & 0 \\ 0 & K_{tt} & 0 \\ 0 & 0 & K_{nn} \end{bmatrix} \begin{Bmatrix} \Delta v_1 \\ \Delta v_2 \\ \Delta u \end{Bmatrix} \tag{1}$$

Where τ is the shear stress in the x and y directions, σ is the normal stress, Δv is the relative displacement on surface, Δu is the relative opening of contact, K_{tt} is the initial elastic shear stiffness and K_{nn} is the initial elastic normal stiffness.

The reinforcement volume increase due to the corrosion from experimental research was put into the model as load using the shrinkage function, with the opposite sign so as to cause increase of reinforcement volume. This load was evenly distributed within the cross-section and incrementally increases with the load steps. Subsequently, the reinforcement was loaded with a tension force with a value of 1 kN per one step. The monitor was added on free end of reinforcement for the measurement of the displacements.

4. Comparison of results

Comparison of results obtained from experimental and numerical analysis for specimens with rebars Ø 10mm, are presented on Fig.4. The general trend of bond strength curves for all specimens is similar: the bond strength decreases with increases corrosion level. Also, results from numerical solution confirmed the results from experiments. A good match of both methods is shown. The regression functions for results from numerical analysis are line, but for results from experiment are curve. Comparison of results obtained from experimental and numerical analysis for specimen type B and D, are presented on Fig.4. The curve shows that the bond strength obtained from experiment was higher than the numerical analysis (Atena 3D software). But, for specimens without stirrup (series F), the results from experiment were lower than the numerical analysis. However, the relative differences between the both methods are small and within the range of acceptable variation (approximately 2 MPa). Comparison results for specimens with stirrups (series B and D) and without stirrups (series F) also showed that the transverse reinforcement (stirrups) provides positive effect on bond strength. For example, for corrosion revel of reinforcement CL= 6%, the decrease on bond strength for specimens with stirrups are approximately 20%, but for specimens without stirrups are more than 35%.

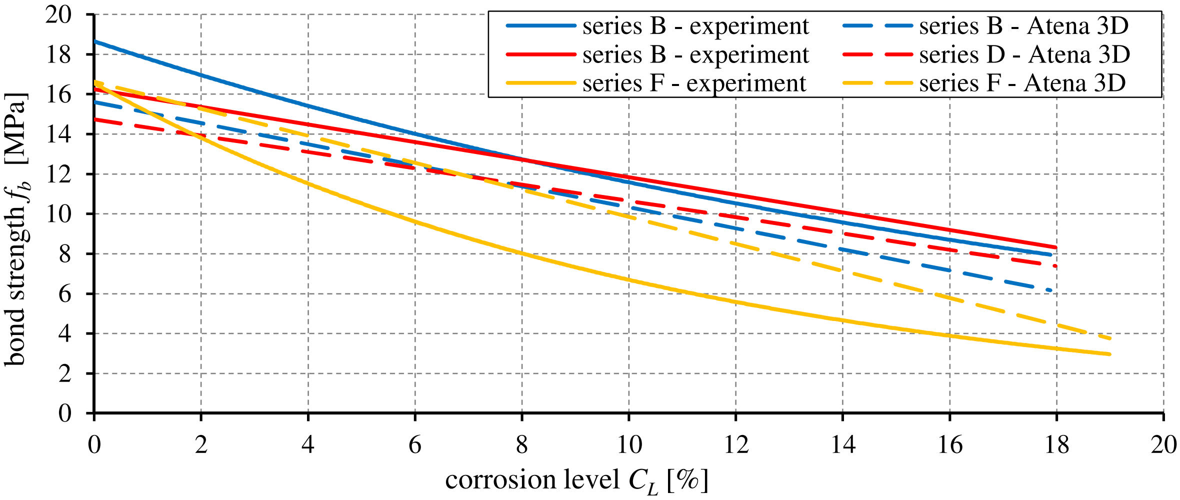


Fig. 4: Comparison of experimental and numerical results (rebars Ø 10mm)

5. Conclusions

The paper analyses the effect of steel corrosion on bond behavior between a reinforcement and concrete. The experimental and numerical results confirmed that:

1. The corrosion of the reinforcing steel adversely affects the bond strength. The loss of bond strength is potentially more severe than the loss of the bar's cross section. The results demonstrated that due to the reinforcement corrosion, the bond strength can be reduced by 50% while the loss of the reinforcement area is only 12%.

2.Compared to specimens without stirrups, specimens with stirrups show higher residual bond strength and less influence of corrosion on bond resistance. The numerical and experimental results lead to the conclusion that for specimens with stirrups, the bond strength of specimens with stirrups is much less sensitive to the corrosion of main reinforcement.

3.For the given degrees of corrosion rate, the risk for cracking, spalling and decrease in bond strength mainly depends on the geometry of the cross section (concrete cover) and the transverse rebars (links).

4.By comparing numerical and experimental results, regarding the bond strength dependency on the corrosion level, good results are obtained. The results obtained from experiment were higher than numerical analysis results circa 12.40 % for the specimen series B, 8.97 % for the specimen series D respectively. For specimen series F, the results obtained from numerical analysis were higher than experiment results circa 29.43 %.

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