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FLEXURAL STRENGTH OF RC-BEAMS WITH CORRODED REINFORCEMENT

Summary

The bearing capacity and serviceability of reinforced concrete structures can severely deteriorate by reinforcement corrosion. The results presented in this paper are a part of author's comprehensive experimental research. Testing the mechanical properties of corroded reinforcement and bearing capacity of beams were a part of the experiment. Yield and tensile strength, ductility and stiffness are lower when compared to non-corroded reinforcing bars. In this paper the correlation between experimentally determinate flexural strengths of beams and extent of steel reinforcement corrosion is presented and the strength verification procedure for RC-beams is proposed.

Key words

Reinforcement corrosion, corrosion rate, flexural strength, ductility

NOSIVOST ARMIRANOBETONSKIH GREDA S KORODIRANOM ARMATUROM NA SAVIJANJE

Rezime

Korozija armature može znatno narušiti nosivost i uporabljivost armiranobetonskih konstrukcija. Rezultati prezentirani u radu su dio opsežnog eksperimentalnog istraživanja provedenog od strane autora. U okviru eksperimenta provedena su i ispitivanja mehaničkih svojstava korodirane armature i nosivosti greda u ovisnosti od stanja korodiranosti armature. Granica popuštanja, čvrstoća, krutost i duktilnost, smanjuju u odnosu na nekorodirane šipke. U radu se prikazuje odnos između eksperimentalno određene nosivosti greda na savijanje i stanja korodiranosti armature i predlaže se postupak provjere nosivosti greda.

Ključne riječi

Korozija armature, brzina korozije, nosivost na savijanje, duktilnost

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1. INTRODUCTION

In the case of the pitting reinforcement corrosion, which are caused by chlorides in the concrete, the shape, size and the lay out of corrosion damages are irregular along the reinforcing bars. It is necessary to know residual mechanical properties of the corroded reinforcement (stress-strain diagrams), which are function to some reliable nominal value which is in good correlation with the real extent of steel reinforcement corrosion. For the nominal value by which the extent of reinforcement corrosion is defined, the corrosion reduction of the diameter of the reinforcement is chosen $\Delta\phi(P_{corr})$, taken from the depth of the reinforcement corrosion P_{corr} determined by the result of measuring the corrosion rate, because it is in good correlation with the experimentally proved reduction of the section of corroded reinforcement [1]. It is known that the pitting corrosion even at the already significant reduction of surface cross-section of the reinforcement often will not cause cracks in the concrete along the reinforcement or spalling of concrete cover, especially in the presence of the transversal reinforcement (hoops) [2], what is commonly the case. It is important to estimate the remaining bearing capacity of the structure also when the outside factors of the reinforcement concrete corrosion are yet not very visible on the surface of the structure. Then the reduction of bearing capacity of reinforced concrete elements is the function of deteriorated properties of corroded reinforcement.

2. SHORT DESCRIPTION OF THE EXPERIMENTAL RESEARCH

All details of a very extensive experimental research are not presented here [1, 3]. In short only significance of the research is discussed which relates to the bearing capacity of the beams with corroded reinforcement. The experimental research has been conducted on samples of RC-beams which were loaded with sustained load and simulatiously exposed to accelerated cycles of moistening by spraying with salted water (NaCl solution) and drying, by which the corrosion of steel reinforcement embedded in beam samples was induced. The loading caused cracks width approximately 0,1 mm, which accelerated the time of the appearance of corrosion and the corrosion process itself.

The dimension of the cross-sections of the beam specimens are 8×12 cm, length 200 cm, reinforced with two bars 8 mm of diameter embedded in tensile zone and with two bars 6 mm of diameter in the compression zone of the cross-section, with hoops 6 mm of diameter spaced out by 8 cm (figure 1). The bars of the nominal diameter of 6 mm are cold worked ribbed reinforcing bars, while those of nominal diameter of 8 mm are hot rolled ribbed reinforcing bars. The mean value of the yield strength obtained by testing the hot rolled bars is 589 MPa, and for the cold worked bars it is 573 MPa. The samples of beams are made of concrete whose mean pressure strength is 35,2 MPa.

Three degrees of the reinforcement corrosion are estimated by the programme of experiments, after which approximate reach acceded to testing of beams samples (table 1). For each degree of corrosion a series of four samples of reinforced concrete beams were provided. Four control samples of beams were also taken without being subjected to the reinforcement corrosion. In Table 1 the mean depth of reinforced corrosion is marked P_{corr}.

For the measuring of the corrosion rate the Galva Pulse© device was used whose work is based on galvanostatic impulse method [1, 4].

Table 1 The number of beam specimens

Degree of corrosion	**0** Control specimens (not exposed to corrosion)	**I** P_{corr} = 0,05 mm	**II** P_{corr} > 0,1 mm	**III** P_{corr} > 0,2 mm
Number of samples	1 specimen at the age 28 days were testing till the collapse	1 specimen each in a environmental chamber for testing the conditions of reinforcement and the penetration of chlorides		
	3 specimens loaded in laboratory conditions (20±2°C, RH 65%) to which deflections are measured till the end of the experiment, and then tested till the collapse	3 specimens each in a environmental chamber exposed to: - sustained static loading, - cycles of spraying with chloride solution and drying (reinforcement corrosion), after reaching the predicted degree of corrosion (I,II,III,) were tested to the collapse		

To each degree of reinforcement corrosion, on whose samples of corroded reinforcement taken from the beams tensile testing was conducted, the corresponding size of corroded reduction diameter of reinforcement $\Delta\phi(P_{corr})$ was added, defined from the result of measuring the corrosion rate in the elapsed period [1, 4, 5] according to these expressions:

$$P_{corr} = \int_0^{\tau} 11{,}6 \cdot i_{corr}(t)dt = 11{,}6 \cdot \int_0^{\tau} i_{corr}(t)dt \tag{1}$$

$$\phi = 12{,}74 \cdot \sqrt{m_0 - 0{,}00785\left(\phi_{nom} P_{corr} - P_{corr}^2\right)\pi}\ , \tag{2}$$

$$\Delta\phi(P_{corr}) = \frac{(\phi - \phi_0)}{\phi_0} \cdot 100\ , \tag{3}$$

where

P_{corr} - the mean corrosion depth in measuring area of sensors, i.e. corrosion depth calculated on the basis of the results of measuring the corrosion rate of the reinforcement in the period in which the progression of the reinforcement corrosion is monitored (according to expresssions (1) in microns, and in the expression (3) introduced in mm),

$i_{corr}(t)$ - corrosion rate in μA/cm^2 obtained by periodic measuring on beam samples, t is the lasting time of reinforcement corrosion in years,

τ - time (years) in which the mean depth of corrosion is calculated P_{corr},

m_0 - length mass of non-corroded reinforcement (g/mm), 0,00785 is the steal density (g/mm^3),

ϕ_{nom} and ϕ_0 - the nominal and original diameters of the non-corroded bars (mm) and $\Delta\phi(P_{corr})$ is reduction of the diameter of corroded bars in relation to original diameter of the non- corroded bars (%).

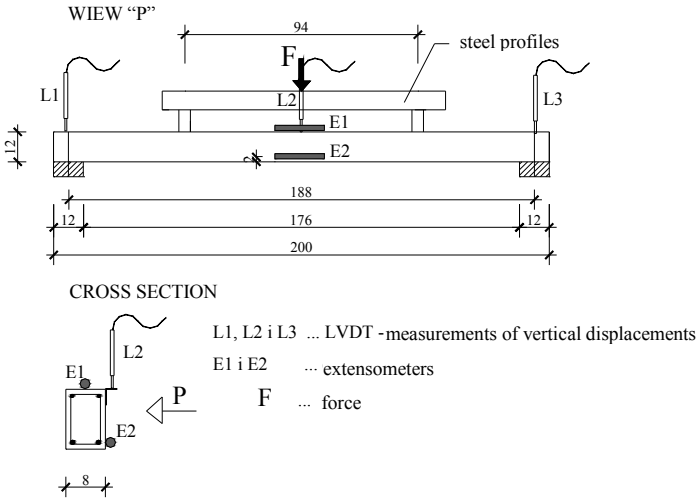

Figure 1. Testing scheme and the measuring places at the testing of the beams

3. THE FELXURAL STRENGTH OF THE BEAMS AND THE EXTENT OF REINFORCEMENT CORROSION

The condition of the corroded reinforcement is defined by other mechanical properties of the corroded reinforcement presented by the idealised diagrams of mean values of stress and strain in Figure 2. They are used in calculating the flexural strength of the beam specimens.

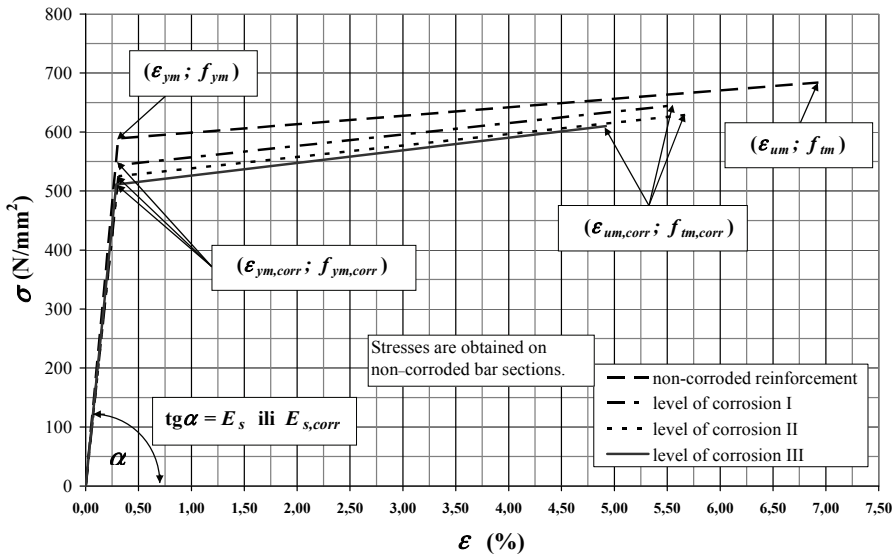

Figure 2. Ideaised stress-strain diagrams for corroded tensil reinforcement

The calculation of the bearing capacity of the cross-section to bending is conducted on the basis of the standardised procedure according to Eurocode 2 [6]. The calculation of stress-strain diagram for the concrete consists of the parabola and straight line (Figure3). The mean measured pressure strenght f_{cm} = 33,17 N/mm^2 is used [1].

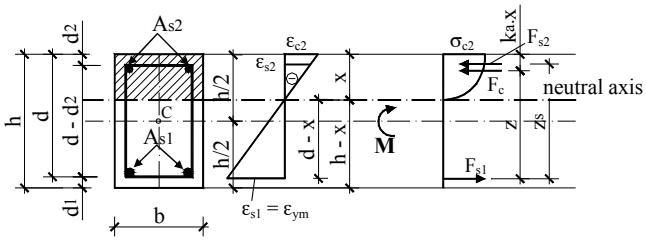

Figure 3. Diagrams of stress and strain in the section of the beam sample

The magnitude which is analysed is the bending moment at which the stress in tensile reinforcement reaches the yield strength. For the mean value of the yielding strength of the corroded reinforcement $f_{ym,corr}$ to which the deformation $\varepsilon_{ym,corr}$ meets and the mean concrete strength pressure f_{cm}, the values of the bending moment at the beginning of yielding of the corroded tensile reinforcement $M_{ym,corr}$ are calculated, which are then compared with the measured mean values of the bending moment at the beginning of the yielding of tensile reinforcement (ε_{ym}, f_{ym} and M_{ym} for non-corroded reinforcement). Since the influence of ties to enhancement of concrete strength in the compression zone and to deviation from Bernouli's hypothesis on straight crosss-sections, and the influence of the pressure reinforcement to stress and deformation of concrete in the compression zone, the caculation of the moment $M_{ym,corr}$ is conducted using the numerical procedure with finate elements (FEM) on the analysis model shown in figure 4. At the modeling the rule of symmetry of the system was used. The beam has two planes of symmetry; longitudinal and transversal, so the quarter of the beam was modeled, using adequate boundry conditions.

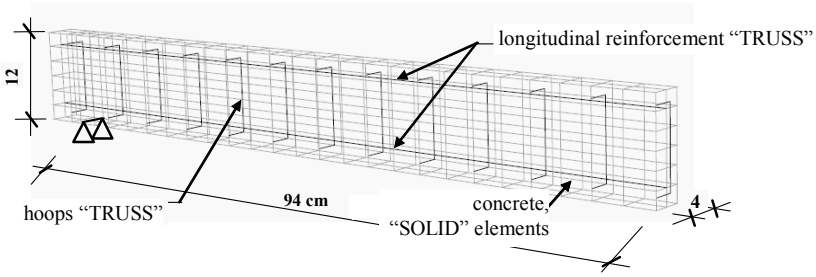

Figure 4. Calculating model for numerical calculation of the beams

Numerical calculations are conducted using the finite elements method (ABAQUS©) programme, taking in consideration the nonlinear behaviour of the materials (nonlinear calculation, material nonlinearity). As the constitutive model of steel for reinforcement the idealised diagrams are used (in Figure 2), and the constitutive models of concrete in pressure and tension are described in work [1]. In Figure 5, the value of bending moments are shown at the beginning of yielding of tensile reinforcement obtained by calculation using both calculating models (on the basis of standardised procedure according to Eurocode 2 and FEM) compared to experimental results (measured values [1]).

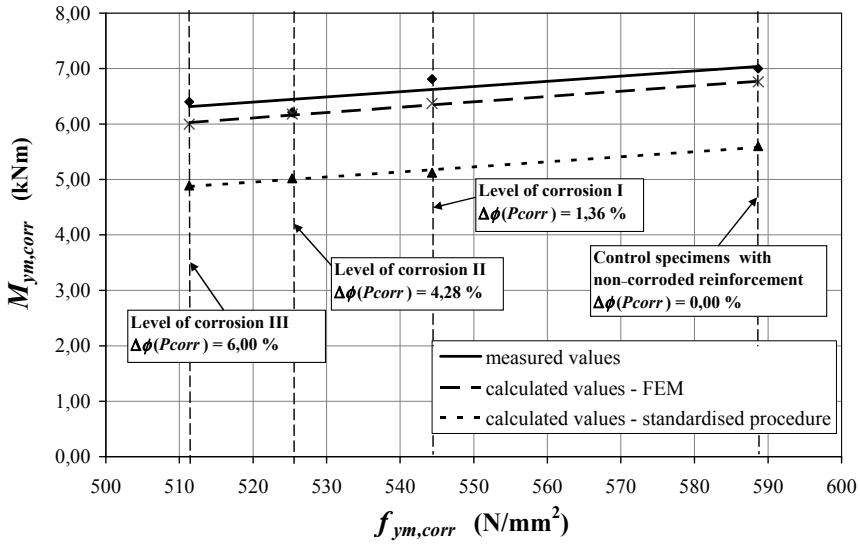

Figure 5. Calculated and experimenatall mean values of of bending moment $M_{ym,corr}$

4. CONCLUSION

Since the calculated and measured values are proportional throughout the monitored period, the conclusion is that the size of the moment of bending at the beginning of yielding of the tensile reinforcement at the beam specimens, lineary depend on the extent of reinforcement corrosion. To verify the flexural strength of the beams with corroded reinforcement the standard calculating method according to Eurocode 2 is suitable, using the stress-strain diagrams for corroded reinforcement.

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