

Influence of corrosion longitudinal cracks on rigidity and strength of reinforced concrete structures

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Abstract. The article deals with the experimental study of the influence of corrosion longitudinal cracks in a protective layer of concrete on the change of deformation and strength properties of central and eccentric compressed reinforced concrete structures. The results of a long-term full-scale experimental study of the kinetics development of the opening width, length, and the integral parameter of corrosion longitudinal cracks are presented. Much attention is given to the functional dependences of change in short-term rigidity and strength of the compressed experimental reinforced concrete structures, both with corrosion-resistant longitudinal cracks, and without corrosion longitudinal cracks, on the value of the eccentricity. The functional dependences of the change of the relative values of rigidity and strength on eccentricity are shown. The results are obtained during a short-term test on the compressive load of the direct models of reinforced concrete pillars with corrosion longitudinal cracks and without them.

1. Introduction

The structural design of bridge structures determines a widespread use of reinforced concrete structures as load-bearing elements. The most common aggressive influence of environment for reinforced concrete structures is a chloride-containing medium, which causes corrosion of steel rods and promotes the formation of corrosion longitudinal cracks in a protective layer of concrete, leading to a reduction of binding steel rods to the concrete.

The actual durability of reinforced concrete structures used in liquid chloride-containing environment is several times less than the standards because of the corrosion of steel rods [1,2].

Reinforced concrete structures of bridge spans have become emergency structures as a result of steel rods corrosion and destruction of the protective layer of concrete aged up to 15 years, at an increase in deflections by 35%, stress in concrete by 26% and stress intensity in steel rods by 86% [3,4].

At a reduction of binding of corrosive steel rods with concrete in bent reinforced concrete structures by 30%, the load-bearing capacity of normal sections perpendicular to the longitudinal axis of steel rods is reduced to 30% with a mass loss of 7.4%, while the durability of reinforced concrete



structures depends not so much on reducing of the cross-section area of steel rods, much more from the reduction of binding of steel rods with concrete [5,6].

2. Actuality, scientific significance

Despite the determining influence of binding of steel rods with concrete on strength and durability of reinforced concrete structures, the coefficients of binding of steel rods with concrete aren't included into the calculation for the limited data of reinforced concrete elements in state standard specifications [5].

At present the quantitative analysis of change in the binding of corrosive steel rods with concrete has not been studied because of lack in regular control of steel rods corrosion, changes in the mechanical properties of concrete as a result of the chloride penetration into concrete, as well as the available experimental results of changing the binding of corrosive steel rods with concrete. The results are received not on the direct models of reinforced concrete structures, and on reinforced concrete elements with artificial breaking of binding of steel rods with concrete [6,7]. Therefore, actually the beginning of process of steel rods corrosion in reinforced concrete structures is considered as the loss of durability of reinforced concrete structures [8].

Metal oxide formations are formed in the bent reinforced concrete structures in the areas of influence of the calculated normal cracks perpendicular to the longitudinal axis of the bearing reinforcement, as a result of corrosion on the surface of steel rods.

The volume of corrosion materials of steel is exceeded in one and a half - three times the volume of the metal (depending on the amount of oxygen contained in the metal oxides) [9-15].

The pressure of steel rods corrosion products upon the concrete of the protective layer causes the formation of corrosion longitudinal cracks. The decay of the electrochemical process does not occur because of the continuing increasing pressure on concrete of steel products corrosion and the increasing width of the corrosion longitudinal cracks opening. [16].

Objective results of the analysis of the effect in binding changing of corrosive steel rods with concrete on the deformation and strength properties of load-bearing reinforced concrete elements can be obtained only on direct models of reinforced concrete structures testing at least six test specimens. [17-19].

3. Problem formulation

The task of the experimental investigation is to study the kinetics development from the point of view of the geometric parameters of the corrosion longitudinal cracks of unloaded reinforced concrete elements and to determine the effect of the eccentricity of the short-time compressive load acting on reinforced concrete elements with corrosion longitudinal cracks in the protective layer of concrete to change their rigidity and destructive loads.

4. Methodology of experimental study

Experienced reinforced concrete samples according to geometric dimensions and reinforcement, mechanical characteristics of concrete and steel rods are direct models of reinforced concrete pillars.

The experimental structures were made of heavy concrete of portland cement of brand 400 "Mordovcement" with water-cement ratio $v/c = 0.45$ and granite crushed stone of 5-10 mm fraction. Quartz sand with a modulus of fineness $M_{cr} = 2.2$ was used as a fine aggregate. Tap water was added to the concrete mixture.

The uncantilever prismatic pillars with geometric dimensions along the length and cross-section, respectively 1000mm and 120 x120mm and the thickness of the protective layer of concrete $\delta_{zsb} = 15$ mm. They are reinforced with a reinforcement framework with load-bearing reinforcement in the form of 4 rods having a diameter $\phi = 8$ mm of A400 class and distributive steel rods having diameter $\phi = 4$ mm class Bp500.

One-cantilever pillars have geometric dimensions along the length and cross-section in the central part, respectively 1000mm and 120 x110mm with a thickness of the protective layer of concrete 15

mm. There are cantilevers with a length of 100 mm in the upper and lower part of the height on one side of the pillars. One-cantilever pillars are reinforced with a reinforcement framework with four bearing steel rods of A4 class having diameter $\phi=4\text{mm}$ and distributive steel rods of B500 class having diameter $\phi=5\text{mm}$. Steel rods of Vr500 class having diameter $\phi=5\text{mm}$ is used in the cantilevers.

There were 39 one-cantilever pillars in the experimental study. Among them 26 samples were affected with aggressive influence of environment and 13 samples were affected with nonaggressive influence. 34 uncantilever prismatic pillars also took part in the experimental study. 23 samples were affected with aggressive influence of environment and 13 samples were affected with nonaggressive influence.

NaCl additive in the amount of 5% of the cement mass was added to the concrete mixture during their manufacture to neutralize the alkali of steam moisture in the concrete and to activate corrosion process on the steel rods for the purpose of producing corrosion longitudinal cracks in the protective layer of concrete during the long-term full-scale testing of reinforced concrete samples. The additive is absent in the control reinforced concrete samples.

Models of reinforced concrete pillars were tested at an experimental ground in the atmospheric conditions of Penza. All samples were moistened with tap water at least three times a day in the warm period of the year. In terms of the intensity of corrosion damage to steel rods, these test conditions for reinforced concrete samples are characterized as highly aggressive [20].

In the process of full-scale tests at least once a month, geometric parameters of corrosion longitudinal cracks were measured: the width of the opening and the length of cracks on the surface of the four sides of reinforced concrete samples formed as a result of corrosion of the bearing longitudinal steel rods.

Some areas with certain numerical values of the opening width of corrosion longitudinal cracks ℓ_T , followed by the determination of their length a_T were determined before measuring the geometric characteristics of corrosion longitudinal cracks. The width of crack opening was measured using a Brinell microscope tube with an accuracy of 25 μm .

The test results were presented in the form of an integral parameter (IP), defined as the sum of multiplication of the width of the opening of corrosion longitudinal cracks a_T by their length ℓ_T within certain areas on the surface of concrete samples.

After the completion of long-term full-scale experimental studies in the laboratory all samples were tested for definition of central and eccentric compression up to failure on the PMM-125 hydraulic press to determine rigidity and strength.

The rigidity D which is the common integral characteristic of deformation properties of eccentrically compressed elements, was calculated through the bending moment M and the curvature of the element K with radius R according to the formula:

$$D = \frac{M}{R} = \frac{M}{1/R} \quad (1)$$

The radius of curvature R was determined according to the increments of linear deformations on the compressed and stretched sides [21].

The values of concrete deformation on stretched and compressed sides were measured with the help of mechanical tensometers of the Hugenberger during laboratory short-term tests of the samples.

The strength of concrete was determined by the method of nondestructive testing of concrete strength using an electronic strength meter of concrete IPS-MG4.03 after the end of long-term tests of experimental structures.

5. Experimental studies results

Long-term experimental studies of the kinetics as the development of geometric parameters of corrosion longitudinal cracks in the protective layer of concrete were carried out for five years from 2010 to 2015.

The period from the beginning of the testing to the appearance of corrosion longitudinal cracks in the protective layer of concrete on the samples was 15 months, which is equal to 20 years in the event of periodic exposure of reinforced concrete structures in a liquid chloride-containing highly aggressive environment in the given climatic conditions [22].

Concrete classes for compressive strength of uncantilever prismatic and one-cantilever pillars with and without corrosion longitudinal cracks were B49.4 and B50 respectively.

Dependences of the average maximum opening width of the of corrosion longitudinal cracks on the test time, obtained from the experimental data of twenty-three uncantilever prismatic pillars and of twenty-six one-cantilever pillars are presented in the form and (Figure 1).

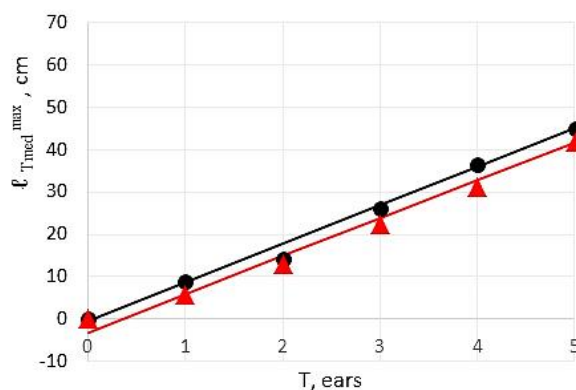


Figure 1. Dependence of the average maximum opening width of corrosion longitudinal cracks on uncantilever prismatic pillars (circles) and one-cantilever pillars (triangles) on the test time.

Dependences of the average maximum length of corrosion longitudinal cracks on the test time, obtained from experimental data of twenty-three uncantilever prismatic pillars and twenty-six one-cantilever pillars, have the form and (Figure 2).

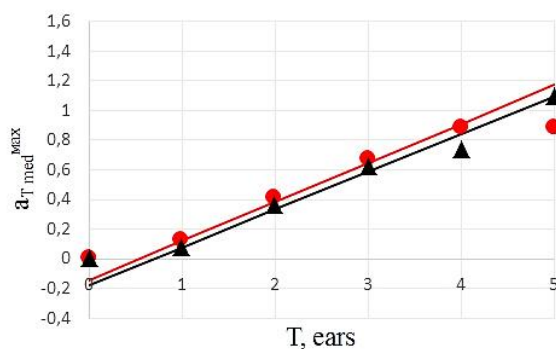


Figure 2. Dependence of the average maximum length of corrosion longitudinal cracks on uncantilever prismatic pillars (circles) and one-cantilever pillars (triangles) on the test time.

Dependences of the average value of the integral parameter on the test time, obtained during the experiments of twenty-three uncantilever prismatic pillars and twenty-six one-cantilever pillars have the form.

In the laboratory thirty-four uncantilever prismatic pillars including eleven control samples without corrosion longitudinal cracks were tested for central short-term compression. Thirty-nine one-cantilever pillars including thirteen control samples without corrosion longitudinal cracks were subjected to eccentric short-term compression.

When testing one-cantilever pillars for short-term eccentric compression, the bending moment was created by setting the eccentricity $e = 40$ mm, $e = 80$ mm and $e = 120$ mm between the geometric

center of the cross section of the central part of the column and the point of application of the resultant compressive load.

Dependence of the variation of rigidity average values of eccentrically bent one-cantilever reinforced concrete pillars with corrosion longitudinal cracks on the eccentricity of the applied short-time compressive load with the corresponding number of specimens $e_1 = 4$ cm (12 samples), $e_2 = 8$ cm (9 samples), $e_3 = 12$ cm (6 samples) has the form.

For eccentricities $e_1 = 4$ cm, $e_2 = 8$ cm and $e_3 = 12$ cm, the average rigidity values of eccentrically bent one-cantilever reinforced concrete pillars with corrosion longitudinal cracks are $D_1 = 2.44 \text{ kg} \cdot \text{cm}^2$, $D_2 = 1.62 \text{ kg} \cdot \text{cm}^2$ and $D_3 = 1.30 \text{ kg} \cdot \text{cm}^2$, for which the relative rigidity values for eccentricities $e_1 = 4$ cm, $e_2 = 8$ cm and $e_3 = 12$ cm, respectively are 1; 0.67 and 0.53.

Dependence of the variation of rigidity average values of eccentrically bent one-cantilever reinforced concrete pillars without corrosion longitudinal cracks from eccentricity with the corresponding number of test specimens $e_1 = 4$ cm (4 samples), $e_2 = 8$ cm (5 samples), $e_3 = 12$ cm (3 samples).

For eccentricities $e_1 = 4$ cm, $e_2 = 8$ cm and $e_3 = 12$ cm, the rigidity average values of eccentrically bent one-cantilever reinforced concrete pillars without corrosion longitudinal cracks are equal $D_1 = 3.55 \text{ kg} \cdot \text{cm}^2$, $D_2 = 2.54 \text{ kg} \cdot \text{cm}^2$ and $D_3 = 2.193 \text{ kg} \cdot \text{cm}^2$, for which the relative rigidity values for eccentricities $e_1 = 4$ cm, $e_2 = 8$ cm and $e_3 = 12$ cm, respectively are 1; 0.72 and 0.68.

Dependence of relative value change of reduction in the rigidity average values of eccentrically bent one-cantilever reinforced concrete pillars, having and not having corrosion longitudinal cracks on the eccentricity, with the corresponding number of test specimens $e_1 = 4$ cm (4 samples without longitudinal cracks and 12 samples with longitudinal cracks); $e_2 = 8$ cm (5 samples without longitudinal cracks and 9 samples with longitudinal cracks); $e_3 = 12$ cm (3 samples without longitudinal cracks and 6 samples with longitudinal cracks) has the form (Figure 3).

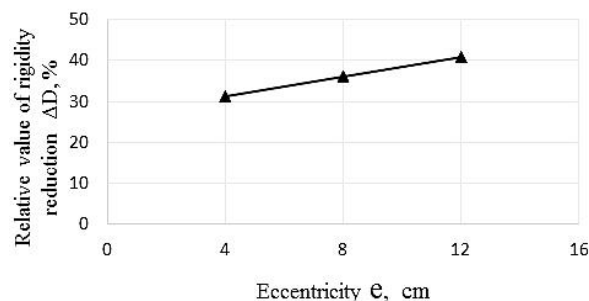


Figure 3. Dependence of relative value change of reduction in the rigidity average values of eccentrically bent one-cantilever reinforced concrete pillars, having and not having corrosion longitudinal cracks on the eccentricity.

Dependence of the average value change of the destructive compression load for uncantilever prismatic pillars and one-cantilever pillars with corrosion longitudinal cracks on the eccentricity value corresponding to the number of test specimens $e_1 = 0$ cm (23 samples), $e_2 = 4$ cm (11 samples), $e_3 = 8$ cm (11 samples), $e_4 = 12$ cm (4 samples) is presented in the form.

The average values of the destructive load of compression for uncantilever prismatic pillars and one-cantilever pillars with corrosion longitudinal cracks depending on the eccentricity for $e_1 = 0$ cm, $e_2 = 4$ cm, $e_3 = 8$ cm and $e_4 = 12$ cm respectively have relative values: 1; 0.51; 0.26; and 0.13, for which the values of the destructive load of compression for eccentricities $e_2 = 4$ cm, $e_3 = 8$ cm and $e_4 = 12$ cm, respectively are in 1.96; 3.85 and 7.69 times less for the same value than for eccentricity $e_1 = 0$ cm.

Dependence of average value change of the destructive compression load for uncantilever prismatic pillars and one-cantilever pillars without corrosion longitudinal cracks on the eccentricity value with the corresponding number of test specimens $e_1 = 0$ cm (11 samples), $e_2 = 4$ cm (5 samples), $e_3 = 8$ cm (5 samples), $e_4 = 12$ cm (3 samples) has the form.

The average values of the destructive load of compression of uncantilever prismatic pillars and one-cantilever pillars without corrosion longitudinal cracks, depending on the eccentricity value $e_1 =$

0 cm, $e_2 = 4$ cm, $e_3 = 8$ cm and $e_4 = 12$ cm respectively have relative values : 1; 0.56, 0.29 and 0.18, for which the values of the destructive load of compression for eccentricities $e_2 = 4$ cm, $e_3 = 8$ cm and $e_4 = 12$ cm, respectively decrease in 1.79; 3.45 and 5.56 times compared with the same value at eccentricity $e_1 = 0$ cm.

Dependence of relative value decrease of the short-time destructive load of compression applied to uncantilever prismatic pillars and one-cantilever pillars, both with corrosion and without corrosion longitudinal cracks, on the value of the eccentricities $e_1 = 0$ cm, $e_2 = 4$ cm, $e_3 = 8$ cm and $e_4 = 12$ cm, is represented in the form (Figure 4).

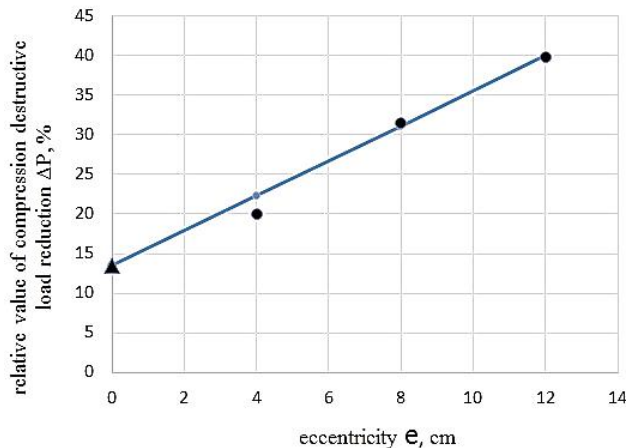


Figure 4. Dependence of relative value decrease of the short-time destructive load of compression applied to uncantilever prismatic pillars and one-cantilever pillars, both with corrosion and without corrosion longitudinal cracks, on the value of the eccentricities.

The depth of concrete carbonization is about 4 mm after five years of full-scale testing of reinforced concrete samples.

6. Conclusion

- width average values of corrosion longitudinal cracks with maximum opening, the longest length of corrosion longitudinal cracks and the value of the integral parameter are directly proportional to the test time;
- the resulting products of steel electrochemical corrosion in corrosive longitudinal cracks do not slow down the corrosion process on the surface of steel rods during time;
- rigidity average values of eccentrically bent test specimens, both with corrosion longitudinal cracks, and without them, decrease according to the exponential dependence on the value of eccentricity;
- relative values of reduction of rigidity average values of eccentrically bent test specimens both having and not having corrosion longitudinal cracks, increase in direct proportion with the increase of eccentricity and are for the values $e_1 = 4$ cm; $e_2 = 8$ cm; $e_3 = 12$ cm, respectively, $\Delta D_1 = 31.3\%$; $\Delta D_2 = 36.2\%$; $\Delta D_3 = 40.8\%$;
- value of compression destructive load for test samples, both with corrosion and without corrosion longitudinal cracks, decreases according exponential dependence with increasing eccentricity;
- relative values of reduction in the destructive load of compression for test specimens having and not having corrosion longitudinal cracks vary in direct proportion with the increase of eccentricity and are $e_1 = 0$ cm, $e_2 = 4$ cm, $e_3 = 8$ cm and $e_4 = 12$ cm, respectively, $\Delta P_1 = 13.5\%$, $\Delta P_2 = 20.1\%$, $\Delta P_3 = 31.5\%$ and $\Delta P_4 = 40.0\%$.

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