Working capacity of direct models of reinforced concrete structures with longitudinal corrosion cracks when exposed to centered and off-center compressive loads

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Abstract. Based on the results of experimental studies of direct models of transport reinforced concrete structures with corrosion longitudinal cracks, the obtained functional dependences of changing their structural behaviors and deformations when exposed of central and off-center compressive load are presented.

1. Introduction
Durability of reinforced concrete structures depends on the corrosion of reinforcing steel [1]. The tensile stress in concrete from the pressure on it of steel corrosion products is 144 kg/cm² [2]. Field surveys of transport load-bearing reinforced concrete structures operating in aggressive environments show the statistical stability of the occurrence of corrosion longitudinal cracks in the protective layer of concrete [3,4].

Appearance of longitudinal cracks in reinforced concrete structures is a harbinger of their Extremum type catastrophe [5]. Maybe that’s one of the reasons why in Russia, one percent of the total number of reinforced concrete bridges that have not reached half of the normative period of operation is collapsed annually [6].

Objective scientific results of deformation and strength characteristics of reinforced concrete structures consisting of multicomponent materials are determined during their experimental tests as compared to theoretical studies [7, 8]. Possibilities of theoretical prediction of damage to reinforcing rods in corrosive longitudinal cracks are very limited due to the difficulty of physical and mathematical modeling of the interaction of an aggressive medium with steel reinforcement [9].

At the same time, in foreign and Russian scientific journals there is no information on conducting experimental studies on reinforced concrete structures with corrosive longitudinal cracks, exposed to central and off-center compressive loads [8].

2. Main part
In long-term full-scale and short-term laboratory tests, reinforced concrete samples of heavy concrete and load-bearing reinforcement with diameter of ϕ = 8 mm of class A400 were used, which, according to the mechanical characteristics of concrete and reinforcement, geometric dimensions, structural design, reinforcement, were direct models of transport reinforced concrete columns [10, 11, 12]. Experimental non-cantilevered prismatic and single-cantilevered columns had geometric dimensions along the length and cross section of 1000 mm and 120:120 mm, respectively, and the thickness of the
concrete protective layer $\delta_{cp} = 15$ mm. One-cantilever columns on one side were kept in the upper and lower part along the height of the cantilever with a length of 100 mm.

To activate the corrosion process on the reinforcement during manufacturing the samples, an additive in the form of 5% NaCl by weight of cement was added into the concrete mixture. There were no additives in test experimental structures.

To obtain objective experimental data, taking into account the requirements of mathematical statistics, thirty-nine single-cantilever and thirty-four non-cantilevered prismatic columns were tested in experimental studies [11, 12].

Field tests of reinforced concrete structures have been carried out in atmospheric conditions in the city of Penza at a test site in the period from 2010 to 2015 [11, 12]. All samples have been periodically moistened at least three times a day with tap water in the warm period of the year.

The average depth of concrete carbonation at the end of field tests was 4 mm, and the classes of concrete in terms of compression strength of non-cantilevered prismatic and single-cantilevered columns having and not having corrosive longitudinal cracks were respectively B49.4 and B50. After five years of full-scale testing, the maximum average width of the opening of longitudinal corrosion cracks on non-cantilevered prismatic and single-cantilevered prototypes containing an aggressive additive was $a_{\text{max}} = 1.1$ mm.

In the regression analysis of the kinetics of changing the geometric parameters of corrosive longitudinal cracks over time, while deriving the functional dependences, the arithmetic mean values of their absolute values were used on the four faces of individual prototypes. Determined linear functional dependences of the geometric parameters of corrosive longitudinal cracks relative to the test time show the absence of influence of the electrical and chemical process products on the steel surface in corrosive longitudinal cracks on reducing the rate of corrosion process on the reinforcement [13].

The variation of the average maximum opening width of the corrosive longitudinal cracks $a_{\text{max}}$ in millimeters over time in years, obtained on non-cantilevered prismatic and single-cantilevered columns, is represented by the corresponding functional dependencies $f a_{\text{max}} = 0.253T - 0.143$ and $f a_{\text{max}} = 0.253T - 0.175$.

The change in the average maximum length of corrosion longitudinal cracks $l_{\text{max}}$ over time in years, obtained from non-cantilevered prismatic columns and from single-cantilevered columns, is depicted by the corresponding functional dependencies $f l_{\text{max}} = 9.0507T - 0.25$ and $f l_{\text{max}} = 8.975 - 3.075$.

Change in time in years of the integral parameter average value of geometric parameters of corrosion longitudinal cracks in the form of $\text{IP} = \sum(a_{\text{max}} l_{\text{max}})$, calculated as the sum of the products of the opening width of corrosive longitudinal cracks $a_{\text{T}}$ for their length $l_{\text{T}}$ within separate differentiated sections with equal values of the opening width of longitudinal cracks, obtained from non-cantilevered prismatic columns and from single-cantilevered columns, is characterized by corresponding functional dependencies $f \text{IP} = 520.35T - 424.75$ and $f \text{IP} = 493.38T - 434.90$.

Under laboratory conditions, samples were exposed to short-term compressive central and off-center loads. Under off-center compression, there was studied the working capacity of single-cantilevered columns with small ($e_1 = 40$ mm), medium ($e_2 = 80$ mm) and large ($e_3 = 120$ mm) eccentricities.

In the regression analysis of the effect of corrosive longitudinal cracks and the magnitude of eccentricity of the applied compressive load on the absolute indices of the deformative, stiffness and strength properties of the non-cantilevered prismatic and single-cantilevered columns, the arithmetic mean values of their absolute values were used for individual prototypes with the same eccentricity values.

Figure 1 shows the change in the relative values of absolute deformations on non-cantilevered prismatic and single-cantilevered samples, both with and without corrosion longitudinal cracks, depending on the relative values of the destructive short-term compression load with different eccentricities.
Figure 1. Change in relative values of absolute deformations of samples.

Figure 1 shows the following conventions: ■, □ respectively, experimental and calculated, according to the obtained functional dependence \( f\left(\frac{\delta}{\delta_c}\right) \cdot 100 = 85.3 \) the values related to samples loaded with a centrally applied compressive load with an eccentricity \( e = 0 \) cm; ●, ○ respectively experimental and calculated, according to the obtained functional dependence \( f\left(\frac{\delta}{\delta_c}\right) \cdot 100 = 102.7 \), the values related to the samples loaded with an eccentricity \( e = 4 \) cm; ▲, Δ, respectively, experimental and calculated, according to the obtained functional dependence

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f\left(\frac{\delta_8}{\delta_c}\right) \cdot 100 = 110 + 140 \cdot e^{-\frac{2}{3}n},
\]

data related to samples loaded with an eccentricity \( e = 8 \) cm; ■, □ respectively, experimental and calculated, according to the obtained functional dependence

\[
f\left(\frac{\delta_{12}}{\delta_c}\right) \cdot 100 = 110 + 160 \cdot e^{-3n},
\]

numerical results related to samples loaded with an eccentricity \( e = 12 \) cm.

Increase of eccentricity contributes to increase of relative values of absolute deformations \( \delta / \delta_c \) over the whole line of relative values of destructive compressive load (Fig. 1).

Figure 2 shows the change in relative absolute deformations at the relative value of the destructive compressive load \( P/P_{des} = 1 \) for non-cantilever prismatic and single-cantilever samples, respectively, having and not having corrosive longitudinal cracks, depending on the eccentricity magnitude.

In the figure 2 the following conventions are used: ●, ○ - respectively data from Fig.1 and calculated results on functional dependence \( f\left(\frac{\delta}{\delta_c}\right) \cdot 100 = 85.3 + 4.35 \cdot e \). Expression \( (\delta / \delta_c) \cdot 100 \) with a relative value of the destructive load \( P/P_{des} = 1 \) for eccentricities \( e = 0 \) cm, \( e = 4 \) cm, \( e = 8 \) cm and \( e = 12 \) cm, respectively, is 85.3%, 102.7%, 110.3% and 148.0% with the resulting functional dependence \( f\left(\frac{\delta}{\delta_c}\right) \cdot 100 = 85.3 + 4.35 \cdot e \). Assuming a value of 85.3% per unit, in the case of considering the centrally applied compressive load with \( e = 0 \) cm, the value of the expression \( (\delta / \delta_c) \cdot 100 \) for eccentricities \( e = 4 \) cm, \( e = 8 \) cm and \( e = 12 \) cm, respectively, increases by 1.20; 1.29 and 1.74 times.
Figure 2. Change in relative values of absolute compressive deformations on non-cantilever prismatic and single-cantilever samples depending on eccentricity magnitude.

Figure 3 shows a change in the relative stiffness of samples both with and without corrosion longitudinal cracks, loaded with a compressive load with corresponding eccentricities $e = 4$ cm, $e = 8$ cm, $e = 12$ cm, depending on the stress state.

Figure 3 shows the following conventions: ●, ○ – respectively, analytical experimental data and calculated values determined by functional dependence $D_4^c/D_4 = 0.98 - 16n$, obtained from samples loaded with compression load with eccentricity $e = 4$ cm; ▲, △ - accordingly, analytical experimental data and calculated values determined by functional dependence $D_8^c/D_8 = 0.82 - 0.35n$, obtained from samples loaded with a compressive load with eccentricity $e = 8$ cm; ■, □ - accordingly, analytical experimental data and calculated values determined by functional dependence $D_{12}^c/D_{12} = 0.97$ at $n \geq 0.1$. 
n < 0.4, as well as by functional dependence $\frac{D_\Delta}{D_{12}} = 1.21 - 0.617n$ at $n \geq 0.4$, $n \leq 1$, obtained from samples loaded with a compressive load with eccentricity $e = 12$ cm.

The compressive load with eccentricity $e = 4$ cm causes more minimal values of the relative value of the difference between the stiffness values of samples without corrosive longitudinal cracks and samples with corrosion longitudinal cracks compared to loads differing with eccentricity values at all relative values of the destructive compressive load. With a relative value of the destructive compressive load $P/P_{des} = 1$, the relative values of the difference between the stiffness values of samples without corrosive longitudinal cracks and samples with corrosive longitudinal cracks loaded with eccentricities $e = 4$ cm, $e = 8$ cm and $e = 12$ cm, respectively, are 18.1%; 55.4% and 42.2%.

Figure 4 shows the change in the relative value of the difference in stiffness values of the respective samples both without corrosive longitudinal cracks and with them, having the corresponding eccentricities $e = 4$ cm, $e = 8$ cm, $e = 12$ cm, loaded with a compressive load, starting with $P/P_{des} = 0.4$ and ending with $P/P_{des} = 1$, depending on the eccentricity values.

![Figure 4](image-url)

**Figure 4.** Change of relative value of difference of stiffness values of samples depending on eccentricity values.

Conventions: ●, ○ - respectively analytical experimental data and calculated values obtained by functional dependence

\[
f\left[\frac{\left(\Delta D - \Delta D' / \Delta D\right)}{100}\right] = 3.863 \cdot e^{-4.55}
\]

Index C refers to samples with corrosive longitudinal cracks.

The kinetics of increasing values of the relative stiffness difference between samples without corrosive longitudinal cracks and samples with corrosive longitudinal cracks has a directly proportional dependence on the eccentricity value and for eccentricity values with $e = 4$ cm, $e = 8$ cm and $e = 12$ cm, this increment is respectively 10.9%, 25.0% and 41.8%.

Figure 5 shows the change in the absolute value of the destructive compressive load applied to samples both with and without corrosion longitudinal cracks, depending on the eccentricity values.
Figure 5. Change of absolute value of destructive compressive load applied to samples depending on eccentricity values.

Figure 5 shows the following conventions: ●, ○ - respectively analytical experimental data and calculated values determined by the functional dependence $f_{P_{des}} = 6 + 2.718^{-0.21 \cdot e}$, obtained from samples without corrosive longitudinal cracks; ▲, Δ - respectively analytical experimental data and calculated values determined by functional dependence $f_{P_{des}^C} = 3 + 37 \cdot 2.718^{-0.22 \cdot e}$, obtained from samples with corrosive longitudinal cracks. Index C refers to samples with corrosive longitudinal cracks.

The arithmetic-mean absolute values of the destructive compressive load for individual groups of samples, both having corrosive longitudinal cracks and not having them, loaded with corresponding eccentricity values, were used when displaying functional dependencies in Fig.5.

Figure 6 shows the change in the relative value of the destructive compressive load of prototypes with corrosion longitudinal cracks in relation to experimental structures without them depending on the eccentricity values of the applied compressive load.

Figure 6. Change of relative value of destructive compressive load to samples depending on eccentricity values of applied compressive load.

Figure 6 shows the following conventions: ●, ○ - respectively analytical experimental data and calculated values obtained by functional dependence $f\left(\frac{P_{c}}{P_{des}}\right) \cdot 100 = 87 - 2.175 \cdot e$. Index C means that the breaking load refers to samples with corrosive longitudinal cracks.
The change in the relative value of the destructive compressive load between the samples with corrosion longitudinal cracks and experimental structures without them varies according to inversely proportional functional dependence with respect to eccentricity values and makes for eccentricities $e = 0$ cm, $e = 4$ cm, $e = 8$ cm and $e = 12$ cm corresponding values 87.0%, 78.5%, 69.6 and 60.9%.

3. Conclusions
1) corrosion process on reinforcement in corrosion longitudinal cracks of non-loaded reinforced concrete structures does not slowdown in time;
2) stiffness of samples without corrosion longitudinal cracks has higher values than the rigidity of experimental structures with corrosion longitudinal cracks for all relative values from a destructive compressive load with a tendency to increase this quantitative indicator with an increase in eccentricity;
3) increment kinetics of increasing values of the relative stiffness difference between samples without corrosive longitudinal cracks and samples with corrosive longitudinal cracks has a directly proportional dependence on the increase in eccentricity;
4) absolute value of destructive compressive load of samples with and without corrosion longitudinal cracks varies exponentially relative to eccentricity values with presence of lower numerical values for samples with corrosion longitudinal cracks;
5) relative value of destructive compressive load between samples with and without corrosion longitudinal cracks makes for eccentricity magnitudes of $e = 0$ cm, $e = 4$ cm, $e = 8$ cm and $e = 12$ cm corresponding values of 87.0%; 78.5%; 69.6% and 60.9%.

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