Behavior of corrosion-damaged compressed reinforced concrete elements under dynamic loading

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Abstract. The article discusses the issues related to the operation of compressed corroded reinforced concrete elements under dynamic (shock) impacts. The experimental data of the samples subjected to flow-accelerated corrosion are presented. Modeling of such samples was carried out by means of the Ansys software package. In this paper we present a static and dynamic calculation of the experimental samples in the Ansys software package.

The breaking load comparison of the samples obtained during the experimental tests and in the Ansys software package, which has fairly good convergence, is made. The comparison of the experimental and obtained as a result of calculation in Ansys diagrams of the corroded - damaged reinforced concrete element and tensile reinforcement concrete compressed zone deformation is presented. The values of dynamic hardening coefficient were obtained for the first time depending on the corrosion damage section’s length.

Introduction
The problems of ensuring the structural safety of the designed, operated and reconstructed reinforced concrete structures are gaining increasing relevance and importance. The development of new and improvement of the existing methods for modeling and calculating various states and processes in corrosion-damaged reinforced concrete structures is still one of the urgent problems.

Available experimental studies have repeatedly confirmed that the aggressive operating environments action leads to a change in the deformation process [1-5].

The reinforced concrete structures force resistance factors, taking into account the combined action of nonlinearity and nonequilibrium deformation, corrosion damage and dynamic loads, require additional study to solve the statically indeterminate systems [6-9].

The methods for calculating the reinforced concrete structures under the influence of aggressive media were considered in [10-15].

Based on the objectives of the work, namely the study of the stress - strain state of a reinforced concrete corrosion - damaged element with variable stiffness, which is formed as a result of exposure to aggressive environments, various types of damage were provided [16].

Main part
Corrosion damage to concrete and reinforcement in a compressed and stretched zone (under eccentric compression), located at the place where the column body is connected to the consoles, is considered (Figure 1. Type of sample corrosion damage
Reinforcing bars were coated with anticorrosion paint, with the exception of the areas where corrosion damage was required (Figure 1. Type of sample corrosion damage 1). Then the rods were immersed in baths with a solution of concentrated (37%) hydrochloric acid and held for 3-5 days. This amount of time was required to reduce the diameter of the rod from 8 mm to 6 mm. The length of time the reinforcement is in the solution depends on some key factors: medium temperature, volume and concentration of hydrochloric acid, area value to be corroded, distance between the rods.

Finite element models (FEM) were created in the SpaceClaim program, with subsequent export to Workbench Mechanical. Problem solution was carried out using the Newton-Raphson method. The Wilama-Warnke model [17] was used to describe the process of concrete destruction. Two fracture mechanisms were considered - from tension and from compression. Concrete modeling was carried out using FE SOLID 65 CE. This FE type has the ability to take into account the formation and development of cracks in the stretched zone of concrete with the transmission of forces through an open and closed crack. When modeling concrete according to the recommendations [18], a three-line diagram was used $\sigma - \varepsilon$, physical and mechanical characteristics of concrete were taken from experimental data.

Reinforcing bars were modeled using finite elements BEAM 188, the plastic behavior of steel was described by a bilinear dependence $\sigma - \varepsilon$, with little hardening to ensure the solution convergence. The applied diagram was also obtained on the experimental data basis [16].

The stages and speed of static and dynamic loading of the calculation models corresponded to the experimental values.
Figure 2. a) Reinforcing cage and distributing plates of an undamaged sample in Ansys; b) Ansys Crack Pattern

Figure 3. Calculation schemes on the example of centrally compressed samples in Ansys

The comparison of the breaking load of the samples obtained during the experimental tests with the breaking load values obtained in the Ansys software package is given (Table 1).

| Item type | Experimental breaking load, kN | Ansys breaking load, kN | Comparison, % |
|-----------|-------------------------------|------------------------|---------------|

Table 1. Comparison of experimental and numerical breaking load of samples
The obtained values of the breaking load in the Ansys software package have fairly good convergence with the experimental tests results, while there is a clear pattern of an increase in the bearing capacity in numerical calculation.

In addition to a comparative analysis of the breaking load, the purpose of calculating models identical to the experimental samples is to obtain the data on the concrete compressed zone strains, tensile and compressed reinforcement at various loading stages for further comparison with the strain values of strain gauges obtained during the experimental tests.

The destruction of all undamaged NP samples and damage to the P1 samples during eccentric and central application of dynamic and static loads occurred at the interface between the upper console and the column body. The strain values obtained by numerical calculation were compared with the strains recorded in the same places where the strain gages were glued on the experimental samples (Table 2).

**Table 2.** Comparison of the obtained strains’ values in numerical calculation with the experimental data under dynamic loading

| Item type | Load, kN | Experiment | Ansys | Comparison |
|-----------|---------|------------|-------|------------|
|           | $\varepsilon_{b, \text{op}} \cdot 10^3$ | $\varepsilon_{s, \text{op}} \cdot 10^3$ | $\varepsilon_{b, \text{max}} \cdot 10^3$ | $\varepsilon_s \cdot 10^3$ | $\frac{\varepsilon_{b, \text{op}} - \varepsilon_{b, \text{s}}}{\varepsilon_{b, \text{op}}} \cdot 100\%$ |
| Dynamic loading | Eccentric compression | | | |
| NP-VS | 10 | -0.5 | 0.1 | -0.43 | 0.07 | 14.0 | 24.0 |
| | 20 | -0.9 | 0.25 | -1.01 | 0.22 | -12.2 | 12.0 |
| | 30 | -1.3 | 0.41 | -1.38 | 0.37 | -6.2 | 9.8 |
| | 52.33 | -2.3 | 0.87 | -2.45 | 0.91 | -6.5 | -4.6 |
| P1-VS | 5 | -0.6 | 0.5 | -0.47 | 0.62 | 21.7 | -24.0 |
| | 10 | -0.9 | 1.05 | -0.69 | 1.23 | 23.3 | -17.1 |
| | 15 | -1.1 | 1.53 | -0.93 | 1.73 | 15.4 | -13.0 |
| | 28.16 | -2.8 | 9.2 | -3.01 | 8.45 | -7.5 | 8.2 |
| P2-VS | 5 | -0.2 | 0.8 | -0.24 | 0.62 | -20.0 | 22.5 |
| | 10 | -0.51 | 1.7 | -0.36 | 1.54 | 29.4 | 9.4 |
| | 15 | -0.8 | 2.6 | -0.87 | 2.75 | -8.7 | -5.8 |
| | 19.32 | -1.1 | 9.4 | -1.17 | 8.65 | -6.4 | 8.0 |
The convergence of the relative strains’ experimental values with those obtained as a result of numerical calculations in Ansys at the last stages of loading is quite good, the discrepancies were from -7.5% to 9.0%.

The reinforcement deformations value during the experimental tests of corrosion-damaged reinforced concrete centrally compressed samples is $\varepsilon_{sc} = -9.2 \times 10^{-3}$. This value is characterized by the loss of stability of compressed reinforcement at the time of the sample fracture. But at the same stage of loading the samples in the Ansys software package, the deformations of the compressed reinforcement are much less and are determined by the maximum value $\varepsilon_{sc} = -2.33 \times 10^{-3}$, which is caused by the greater bearing capacity of the samples in numerical calculation (Table 1). Therefore, the comparison of the compressed reinforcement strain values at the last loading stage was not performed.

In figure Figure 4.4 the experimental and obtained as a result of calculation in Ansys, diagrams of concrete compressed zone deformation and tensile reinforcement of a corroded - damaged reinforced concrete element under dynamic loading are compared.
Figure 4. Comparison of the concrete compressed zone deformation experimental values and tensile reinforcement with the calculation results in Ansys for a corrosion-damaged sample under dynamic loading.

As it can be seen from Figure 4, the nature of the computational model strain diagrams corresponds to the experimental data.

Results

The performed comparative analysis of the bearing capacity and the resulting strains in the experimental samples with the results of numerical calculation has fairly good convergence, on the basis of which, models with different damage zones were calculated in the Ansys software package relative to the experimental sample with damage (figure 5) to determine the dynamic hardening coefficient depending on the corrosion - damaged sections’ length. The corrosion - damaged areas’ length is expressed as a percentage, relative to the height of the element. In this case, the area of the damaged cross section remains constant and is 80%.

Figure 5. Types of corrosion - damaged reinforced concrete elements relative to the experimental sample

Figure 5 shows several types of samples with different lengths of corrosion damage. So, Figure 5a shows an experimental sample No. 1 with a corrosion damage plot 14%, Figure 5b shows type No. 1.1 with a damage section 7%, Figure 5c shows type No. 1.2 with a damage section 21% and Figure 5d Type No. 1.3 is presented with 28% damage area. As well as in the experimental samples having damage type No. 1 on other models, in the local zones of corrosion damage, a decrease in the reinforcement cross section was simulated from a diameter of 8 mm to 6 mm.

The corrosion damage percentage value relative to the height of the element was taken into account only in the stretched zone of the element, since the destruction of all calculated models occurred in the upper part of the sample at the column body junction with the console.

The calculation results of the samples with different percentages of corrosion damage under central and eccentric compression on static and dynamic loads are presented in the Table 3.

Table 3. The dynamic hardening coefficient values depending on the corrosion damage section length
### Summary

Based on the data of Table 3, as well as on the experimental values of the dynamic hardening coefficient, not damaged centrally and eccentrically compressed reinforced concrete elements 1.19 and 1.18, respectively, graphs of the dynamic hardening coefficient dependence on the corrosion-damaged section’s length (Figure 6).

**Figure 6.** Graphs of the Kd dependence on the corrosion - damaged section’s length of centrally and eccentrically loaded elements

From the graphs presented, it can be seen that when the corrosion - damaged section’s length is more than 20%, dynamic hardening practically does not change.

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