Calculation residual strength of reinforced concrete beams with damages, which occurred during loading

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Abstract. The article presents the development of a method of experimental study of reinforced concrete beams with damaged steel reinforcement. In addition, the purpose is to conduct experimental tests of undamaged samples with steel reinforcement of 20- and 16-mm diameter. Also, the 20 mm steel bars were damaged to the area equal to 16 mm samples, experimental tests of such samples were performed and corresponding analysis and comparison of the results of both tests was conducted. According to the study program, 6 beam samples were tested. Two of them were undamaged control samples with single load bearing reinforcement of Ø20 mm diameter; 2 samples with Ø20 mm reinforcement had about 36% damages (which corresponds to area of the 16 mm diameter samples) and 2 samples with Ø16 mm single reinforcement, which corresponds to 36% load bearing reinforcement damage of control samples (the area of 36% damages of 20 mm samples corresponds to 16 mm diameter). The experimental study identified the strength and strain parameters of reinforced concrete beams with damages in the load bearing stretched reinforcement due to the action of the bending moment, which causes the exhaustion of the bearing capacity.

1. Introduction
Reinforced concrete structures are the most widely used load-bearing elements of buildings and structures [1-4]. The most common are the structures, subjected to bending, which are used in the form of beams, slabs, frame crossbar, girders, etc. [5-7]. Reinforced concrete structures are often subjected to the action of aggressive environment [8]. In addition, according to the commonly used classification the considerable variety of environments could be identified, depending on the factors which cause their action [9]. The most intense aggressive environment is the one, caused by chemical industry. Herewith the reinforced concrete, as the construction material, is one of the best in terms of its exploitation in aggressive environments. Steel reinforcement, which is the most susceptible to corrosion, is securely protected by the concrete layer. If the concrete composition is properly selected, steel reinforcement will be relatively non-susceptible to corrosion [10]. However, significant number of buildings and structures has been in operation for decades, often without the selection of high-quality concrete and proper corrosion protection of reinforced concrete structures [11-14]. As the result, the corrosion or mechanical damages of concrete take place [15-17] and, subsequently, after destruction of protective concrete layer, the corrosion of steel bars begins. This process could result in decreasing of reinforced concrete elements bearing capacity and
serviceability [18-20]. If the corresponding strengthening and reconstruction measures are not implemented, the accidental destruction of the building or its separate elements could occur. Corrosion could be the reason for decrement of steel bar cross-section in reinforced concrete elements. Therefore, as the result, the stress-strain state of construction changes and its serviceability characteristics are reduced. In addition, it is important to note that corrosion process take place under the load action and reinforced concrete elements have corresponding stress-strain state. These factors could cause certain specific features of the corrosion processes proceeding, which is related to initial existing stresses in both concrete and steel reinforcement, possible cracks, etc.

Nowadays the great number of studies is devoted to the issue of reinforced concrete structure strengthening with the use of composite materials [21], steel and reinforced concrete cages [22], various modern materials in order obtain better protection of such constructions [23-28].

In order to conduct the optimal calculations of such structure strengthening, the real stress-strain state should be identified, taking into consideration damages of reinforcement. Therefore, the study of influence of damages on stress-strain state of reinforced-concrete structures is really topical. In particular steel reinforcement damages need to be considered.

2. **Purpose of the article**

The main purpose of the article is to develop the method of experimental research of reinforced concrete beams with damaged steel reinforcement. In addition, the aim is to conduct experimental tests of undamaged samples with steel reinforcement of 20- and 16-mm diameter. Also, the 20 mm steel bars were damaged to the area equal to 16 mm samples, experimental tests of such samples were performed and corresponding analysis and comparison of both test results was conducted.

3. **Materials and method of experimental research**

The following legend and marking are used: C – control; B – beam; D – damaged. When the corrosion or mechanical damages of the reinforcement occurs, the reinforcement cross-section is reduced and, correspondingly the bearing capacity of reinforced concrete elements is decreased. In experimental studies the widely spread practice is to simulate the decrease of cross-section area of beam reinforcement by drilling holes in steel bars. Herewith, depending on the drilled hole diameter the level of reinforcement damage and cross-section area reduction of steel bars are simulated. In the tests the diameter of drilled holes was gradually increased, for example the area of Ø20-sample cross-section was reduced to the area of Ø16-samples.

The first number means the beam series. In our case there are two series: 1-st series- beams with steel reinforcement of 20 mm diameter; 2-d series- beams with steel reinforcement of 16 mm diameter. Second number is the sequence number of the sample.

Experimental samples used in the research had the length of 2100 mm, 100 mm weight and 200 mm height. The beam concrete composition: C: S: R =1:1.16:2, 5 with W/C=0.375. The cement used - M-500, sand quartz without impurities with a size module $M_k=2.00$, granite rubble of fractions 5 to 10 mm – 66%, 10 to 20 mm – 33%.

The reinforcement of samples: A500C steel bars, diameter was different, depending on series: Ø20 mm (1-st series, Figure 2.4), 16 mm (2-d series, Figure 1). Reinforcement of compressed zone and transverse reinforcement are made of Ø5 B 500 bars. Transverse reinforcement Ø5 B500C has 75 mm spacing. Connection of the reinforcement in the spatial frame was performed with the use of factory contact welding. To the longitudinal reinforcement were welded 4 metal holders with 200 mm spacing, intended for fastening mechanical devices for determining deformations. The samples were manufactured at the factory on the current production vibrating platforms.

During the experiment, samples were subjected to bending under short-term loading. Load level was controlled using K1 and K2 ring dynamometers, which simultaneously served as the hinge support on one side and a fixed support on the other side of the 1900 mm beam.

Load was applied in the form of two concentrated forces in the thirds of the beam span with the use of a hydraulic jack and the distribution beam. The scheme of device location is shown on Figure 3.
Figure 1. Construction and reinforcement of experimental samples of first series.

Deformations of the load-bearing reinforcement were measured with the use of clock-type micro-indicators Аi1 and Аi2 with the division value of 0.001 mm. The i1 and i2 micro-indicators with the division value of 0.001 mm were located on the beam upper face in order to measure the deformation of the most compressed concrete fibres. The i3 to i10 micro-indicators were located on the side face of the beam with 20 mm spacing increments and did not extend beyond the bending zone.

Figure 2. The scheme of location of devices.

The 1 series sample openings (load-bearing reinforcement of 20 mm diameter) were performed with their gradual incrimination: 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5 and 5.6 mm. For the 2 beams of the 1st series (BD-1.3 and BD-1.4), the openings were single (Figure 3).

Beam samples were concreted in single mix with appropriate control tests of cubes, prisms and cylinders. The compressive strength of concrete was determined by testing of cubes with 100 mm edge and cylinders with 100 mm diameter and 200 mm height. Prism strength and initial modulus of elasticity were determined with the use of prisms of 400 mm length and 100×100 mm cross-section and cylinders with 300 mm length and 150 mm diameter.

After the research the following results were obtained:
- prism strength fcd - 33.8 MPa,
• cubic strength of f_{cube} - 48.7 MPa.

**Figure 3.** The general view of the single opening in load-bearing reinforcement of damaged samples.

Before the beginning of the experimental research, 3 samples of A500C class reinforcement were previously tested under tension in order to determine the mechanical properties of steel bars [17] (Figure 4).

![Strain diagrams of the continuous initial A500C steel bar](image)

**Figure 4.** Strain diagrams of the continuous initial A500C steel bar [17].

The results of continuous load-bearing reinforcement of the 1st series beams are presented in Table 1.

| Material                        | Yield strength $\sigma_{0,2}$, MPa | Ultimate strength $\sigma_{u}$, MPa | Specific elongation $\delta$, % |
|---------------------------------|-----------------------------------|------------------------------------|--------------------------------|
| A500C reinforcement of 20 mm diameter | 570                               | 650                                | 15,3                           |

### 4. Results of the experimental research

According to the research program 6 beam samples were tested. Among them were 2 undamaged control samples with single load bearing reinforcement of $\varnothing 20$ mm diameter- BC-1.1 and BC-1.2; 2 samples with $\varnothing 20$ mm reinforcement with damages about 36% (which corresponds to area of the 16 mm diameter samples)-BD-1.3 and BD-1.4 and 2 samples with $\varnothing 16$ mm single reinforcement - BC-2.5 and BC-2.6, which corresponds to 36% load bearing reinforcement damage of control samples (the area of 36% damages of 20 mm samples corresponds to 16 mm diameter).

The strain characteristics of compressed concrete and stretched load bearing reinforcement of non-damaged control samples with $\varnothing 20$ mm reinforcement (BC-1.1 and BC-1.2) and samples with load bearing $\varnothing 16$ mm reinforcement (BC-2.5 and BC-2.6) are given in Figure 5. Herewith, it is important to note that graphs in Figure 5 and others show averaged values of both strains and bending moments of twin-beams.
Figure 5. Averaged strain graphs of stretched reinforcement (left) and compressed concrete (right) of 1st series non-damaged beams BC-1.1 and BC-1.2 (a); 3d series beams BC-2.5 and BC-2.6 (b).

In samples with undamaged reinforcement, physical destruction occurs as the result of brittle fracture of the compressed concrete zone (Figure 6).

Figure 6. Brittle fracture of the concrete of the most compressed fibre of the BC-1.1 (a) and BC-3.5 samples

In the samples BP-1.3 and BP-1.4 with 20 mm reinforcement without applying a load in the in the steel bars was made a hole of 5.6 mm diameter, which resulted in a cross-sectional area of the steel bar equal to the sample of 16 mm diameter. However, it should be noted that hole mostly reduces the core zone of the steel bar, leaving the thermally-strengthened part of the rebar almost undamaged. It was identified according to the results of experimental testing of samples with holes. Therefore, no exact yield zone could be identified, which is shown by the experimental results [17]. The gradual increase in deformation of stretched reinforcement and the most compressed fibre of concrete could be clearly identified.

It is important to note the changes in the destruction characteristics of the samples, which are the result of damages mostly in non-strengthened steel-bar layer and insufficient damages in thermally-strengthened reinforcement layer. In addition, no destruction of compressed concrete and achievement of the strain limit values by most compressed fibre took place. Destruction was caused by the load-bearing reinforcement rupture. It could be explained by the fact that damages of the stretched armature were mostly local, which corresponds to the drilled hole. This could be affirmed by the absence on the graphs (Figure 7) exact yield zone of the steel bars.

Summary results of test samples without initial load level are shown in Table 2. In samples BD-1.3, BD-1.4, BC-2.5 and BC-2.6, the area of the load-bearing reinforcement, as well as all other parameters (concrete strength, frames location, etc.) are the same. However, according to table, 2, the strength of samples with 20 mm diameter damaged reinforcement (BD-1.3 and BD-1.4) is higher than the strength of samples with 16 mm load bearing reinforcement (BC-2.5 and BC-2.6).
Figure 7. Averaged strain graphs of stretched reinforcement (left) and compressed concrete (right) of damaged beams of the 1st series BP-1.3 and BP-1.4 (a) and the destruction nature of the BD-1.3 sample (b).

Table 2 Bearing capacity of experimental samples

| Sample mark | Bearing capacity, kNm | Physical destruction, kNm | Deviation in the bearing capacity values, % | Deviation in physical destruction, % |
|-------------|-----------------------|---------------------------|-------------------------------------------|------------------------------------|
|             | sample average sample average | sample | average | sample | average | sample | average |
| BC-1.1      | 24.9 24.2             | 32.9 31.1                  | - -                                            | - -                                |
| BC-1.2      | 23.5 29.3             | 22.9 23.5                  | 21.5 25.2                                     | 26.4 22.5                          |
| BD-1.4      | 19 18.1               | 24.1 23.5                  | 28.9 32.6                                     | 35.7 28.6                          |
| BC-2.5      | 16.3 16.9             | 20 21.1                     | 27.7 30.2                                     | 28.6 32.2                          |
| BC-2.6      | 17.5 16.9             | 22.2 21.1                  | - -                                            | - -                                |

Note: deviations were identified according to control samples KB-1.1 and KB-1.2

This could be explained by the fact that in the damaged samples the main load-bearing reinforcement zone is the thermally-strengthened outer layer. Therefore, the deviation of the bearing capacity of the damaged specimens was in average 24%, and of the non-damaged with the same reinforcement area - 31%.

5. Conclusion

In the article, by the experimental study the strength and strain parameters of reinforced concrete beams with damages in the load bearing stretched reinforcement due to the action of the bending moment, which causes the exhaustion of the bearing capacity were identified.

With the gradual reduction of the stretched reinforcement cross-section, certain increase in the deformation of both the reinforcement and the concrete of the most compressed fibre occurs; herewith if further increase in the load takes place the final bearing capacity of the reinforced concrete beams decreases in comparison with the samples with non-damaged reinforcement. The final bearing capacity decreases almost proportionally to the reduction of the load bearing reinforcement area.

Exhaustion of the load-bearing capacity of reinforced concrete beams without damages of reinforcement was due to reaching the yield strength of the steel bars and, after gradual load increase – reaching of the limit strain in the concrete fibre and its destruction. In reinforced concrete beams with damaged reinforcement if the load was increased the bearing capacity was exhausted due to reaching of the yield strength in the reinforcement. After further load increasing the rupture of the reinforcement occurs without fragmentation of the compressed zone concrete. It could be explained by
the fact that the reinforcement damages were performed locally in one particular place by drilling of the hole, which, in addition, was the stress concentrator.

Reinforced concrete beams with ø20 mm load-bearing reinforcement, which area by damaging was decreased to the area of the ø16 mm steel bars had the final bearing capacity higher than reinforced concrete beams with non-damaged ø16 mm reinforcement. It could be explained by the fact that when of ø20 mm steel bars were damaged by hole drilling, the most damaged zone of the bar cross-section had lower mechanical properties; the outer thermally-strengthened layer with higher mechanical properties was damaged insignificantly.

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