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THEORETICAL ANALYSIS AND EXPERIMENTAL INVESTIGATION OF THE DEFECTS IN THE COMPRESSED ZONE OF THE REINFORCED CONCRETE ELEMENTS

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Due to economic trends in the building industry, the investigation of the residual bearing capacity of reinforced concrete elements has been receiving more and more attention in recent years. Studying the effect of damage on the bearing capacity of reinforced concrete elements is one of the main themes of investigation in this field. Results of 4 reinforced concrete beams' testing are proposed, one of which was the control one (tested without damages) and three – typically damaged in the compressed zone at different load levels. As a result, the most crucial effect was detected by the type of damage, load, and neutral axis position change. In addition, research results demonstrate an increase of 3.8% in reinforced concrete beams bearing capacity if they are damaged under the load, compared with the unloaded damaged reinforced concrete beams.

Key words: bending elements, reinforced concrete beam, damages, defects, bearing capacity, corrosion.

Introduction

The primary purpose of the research is to compare the results of three samples' testing and to analyze the influence of damages and defects of reinforced concrete elements on their strength and deformability with preliminary analysis of possible research methods by overviewing existing research in this area and by conducting an own computer simulation test.

A significant number of buildings and constructions are built using reinforced concrete constructions. (Blikhars'kyi and Obukh, 2018; Zhang et al., 2015). Some of them are exploited in damaged conditions. All these encourage research to indicate residual bearing capacity reinforced concrete elements. While considering the issue of residual bearing capacity research, it should be paid attention to the research (Brara and Klepaczko, 2006) where the issues of the influence of dynamic tension on the strength of concrete depending on the time changing, are considered. The primary attention is paid to the factors of the speed of the development of deformation and changes in the humidity of concrete. Understanding this problem can make it more helpful in strengthening construction.

Research of damaged reinforced concrete elements is a complex and relevant topic. Many different factors and their possible combinations caused the significant complication of calculations (Klymenko et al., 2013). The influence of T-beam damage factors on the magnitude of their destructive load is considered. In the operation of the experimental obtained data processing by the method (Voskobiinyk et al., 2011), with the removal of insignificant coefficients of the regression equations, an adequate mathematical model has been obtained, which has good information usefulness and by which the influence of the investigated factors on the initial parameters of beams can be used, like geometric interpretation.

When describing the residual bearing capacity of flexural reinforced concrete elements in damaging, an important place is the classification of damage and defects. The most widespread ones in terms of the loss of the concrete cover, according to Malganov (1990) and Voskobinik (2010), are shaving off the nominal cover of concrete which occurs when: there is mechanical damage during transportation and operation; corrosion of reinforcement; the influence of the fire and the detachment of concrete brushes occurring during a fire, during the pressure of tumors, e.g., salt or ice; or soaked in case of violation of the operation's rules.

The authors (Petrov O. M., 2015) investigated the influence of defects in reinforced concrete structures, which are formed during manufacture, with the displacement of reinforcement and scraping of concrete, with torsion formation. By the action of bending moment in the flexural reinforced concrete elements can occur spatial spiral cracks and a significant reduction in the crack resistance in normal and inclined sections in 4.7 times.

Particularly dangerous is the influence of defects and damage on bending RC elements (Voskobinik, 2011) which cause biaxial bend. In this case, there is a change of work, the nature of the stress-strain state, the strength and deformability of the element as a result of damage or defect. The set of different factors forming the biaxial bend can be divided into endogenous and exogenous (Voskobinik, 2011).

When disclosing the issue of vibration diagnosis of damage, attention should be paid to the comparison of existing algorithms for the detection of damage. Based on the vibration characteristics, the methods of identification for damage are divided into four main categories: natural frequency methods, methods of form based on the mode, the method of curvature based on the form, and methods that use both the form and the of the regime. In Wei's work (2016), the five investigated damage detection algorithms are analyzed. Capabilities of five comparative damage detection algorithms (Wei, 2016, Table 3).

The authors (Blikharskyy, Z 2019) investigated the issue of taking into account cracks. The limiting width of the crack opening was used as a criterion for the exhaustion of the bearing capacity. The result is that about 19–26 % of the bearing capacity remains before the risk of beam failure in shear. With a decrease in the shear span by 25 %, the maximum width of the crack opening decreases only by 7 %, and with a decrease in the span by 50 %, by 40 %.

The method of diagnostics is based on real-time monitoring of the operation of the element based on the impedance using PZT (lead-zirconate-titanate) for reinforced concrete structures (Park, 2006). The method consists of structured monitoring based on the impedance using the electromechanical connection properties) between the PZT overlay and the experimental structure. Experimental setup and PZT patch attached to host structure (Park, 2006, Fig. 2). Test specimen and progressive surface damage simulated by notches (Park, 2006, Fig. 4).

The possibility of using and creating computer-aided design (CAD) should also be noted. The study of the formation of a modular scheme for a highly specialized integrated CAD for the diagnosis of the technical condition of construction objects is disclosed by B. M. Yeremenko (Yeremenko, 2015). FE model of PZT and concrete beam with damage (Park, 2006, Fig. 7).

In Klymenko's study (2012), the stress-strain state of beam reinforced concrete elements was simulated using PC "Lear 9.6", based on isotopes, using a piecewise linear dependence. According to the author, a consistent analysis of voltage isopods in actual construction materials allows to reliably estimate the influence of constructive factors on the bearing capacity to predict the nature of further deformation and physical destruction. To determine the residual bearing capacity of the damaged, bent reinforced concrete elements were carried out on the T-beams in work (Klymenko, 2014). As shown in the paper's conclusion, the simulation of damages of bent reinforced concrete elements in software complexes based on the finite element method is a way to determine the residual bearing capacity, but this is a rather laborious process.

Therefore, research in the field of residual bearing capacity indication are highly topical for Ukraine as well as for other countries (Sykora, 2015; and Tigeli, 2013).

Materials and Methods

In order to investigate the priority of factors in the research, it was divided into two parts the previous simulation in the software Femap and testing of four samples. So during the prior simulation in the software Femap formed the matrix of the dependence impact of each factor on the bearing capacity with the subsequent determination of coefficient of influence and the regression equation. Analyzing the regression equation, we obtained results of the impact of each factor, and their interaction, on the bearing capacity of the element.

To determine each factor's influence, the definition of the concept "factor" must be considered. A factor is an independent measured variable, which at a particular time acquires a specific value. During operation, every factor, denoted by x_i, may become one of several values. Such values are called levels. So, the totality of combinations of factors levels is the number of experiments (Vozniak and Zhelykh, 2003) what we can be determined by the formula:

$$N = p^{(k)}. \tag{1}$$

Where p is the number of levels of factors, k is the number of factors. In analyzing the priority of two main factors, the methodology of planning experiment 22 with the effect of the interaction of factors is described in (Vozniak and Zhelykh, 2003). Where the regression equation looks like:

$$y = b_0 + b_1 x_1 + \ldots b_k x_k. \tag{2}$$

The coefficients are calculated according to the equation:

$$b_0 = \frac{\sum_{j=1}^{N} x_{ji} x_{ji}}{N}; j = 0, 1, ..k. \tag{3}$$

Particularly, for $b1$ and $b2$:

$$b_1 = \frac{-y_1 + y_2 - y_3 + y_4}{4}, \tag{4}$$

$$b_2 = \frac{-y_1 - y_2 + y_3 + y_4}{4}. \tag{5}$$

Then the coefficient $b0$ is determined by the dependence of:

$$b_0 = \frac{\sum y_1}{4}. \tag{6}$$

According to this method, factors $x1$ and $x2$ are considered, where $x1$ is the initial load level which is 0.3 from the bearing capacity, and $x2$ is damage which carries the loss of the cover in the compression area in the size of 30 mm. It is considered that these factors as the most widespread in practice. Consequently, $y = b_0$, where b_0 is the arithmetic mean of the optimization parameter. To perform this operation, we introduce a vector-column of a fictitious variable $x0$, which acquires the value of +1 in experiments.

While forming a matrix of the interaction of two factors, we assume that in the presence of the factor xi or xj, the factors have a "+" value in the absence of the "–" value. For example, if there is a load and no damage, get the value in the lines $+x_1$ and $-x_2$. The value of y_i is the bearing capacity of the beam at various combinations of factors in Table 1. For example, in case 1, y_i is defined as bearing capacity in the presence of load (loss of protective layer in the size of 30 mm) and loading equal to 8.786 kN (load level 0.3 from the bearing capacity of regular undamaged samples).

The following dimensions of the coefficients for the regression equation are obtained: $b0 = 13.993$; $b1 = -2.866$; $b2 = -2.049$; $b12 = 0.055$. The regression equation will have the following form:

$$y = 13.993 - 2.866x_1 - 2.049x_2 + 0.255x_1x_2. \tag{7}$$

Also, this equation indicates the simultaneous action of two factors. The obtained results indicate a decrease in the bearing capacity with an increase in factors x_1 and x_2, where the factor x_1 is more influential. Consequently, the critical factor is the level of loading.

Table 1

The planning experiment's matrix 22 with the effect of the interaction of factors

No.	x_0	x_1	x_2	$x_1 x_2$	y
1	+	+	+	+	9.133
2	+	–	+	–	14.756
3	+	+	–	–	13.12
4	+	–	–	+	18.964

The modeling results were obtained in different variations with the results of the total displacements of the model obtained: regular beam without any damages, beam with damages without the initial level of loading, and with damages taken with initial loading 0.3 from bearing capacity from the regular beam.

Table 2

Comparison of simulation results with different combinations of factors

No.	Type of test	Maximum total displacement of the model, mm	Divergence with regular sample
1	Regular sample	0.758	–
2	Sample with damaged compressed cover layer by 30 mm without initial load	1.127	1.48
3	Sample with damaged compressed cover layer by 30 mm with initial load of 30 % of bearing capacity	0.898	1.18

We can conclude that the initial load level substantially affects the residual bearing capacity based on the above. Reinforced concrete beams damaged without an initial load level showed deformability of 1.48 times greater than the regular. Samples that received similar damage at a load level of 0.3 from the bearing capacity of the regular showed a minor increase in deformability (1.18 times) than the regular beam. This means that for researching the influence of defects and damage on the bearing capacity of the bending reinforced concrete elements, it is necessary to take into account the initial stress-strain state.

The research was conducted for test samples – one-span reinforced concrete beams. Reinforcement was performed by working stretched rebar of Ø14 mm, compressed rebar in the zone of maximum shear force action – Ø10 mm. Transverse reinforcement was introduced by smooth rebar of Ø8 mm, located in supporting zones. During the experiment, physic-mechanical characteristics of materials were indicated: concrete – C35/45; reinforcement introduced by A500C class.

For concrete deformation measurements, clock-type indicators I1–I8 were used with the basis of 20 cm in the zone between the loads applied and spacing of 40 mm (see Figs. 1 and 2). Indicators I11–I14 were located in the zone of concrete stresses concentration. These indicators indicate the highest strains and include in the basis the damaged concrete zone. On the stages previous to load application and after, maximum compression deformation was identified by I15 and I16. Strain measures for reinforcement were made with the use of indicators I9 and I10. Aistov deflection meters P2–P4 measured beams' deflection (Figs. 1 and 2), and subsidence is on supports were indicated by P1 and P5.

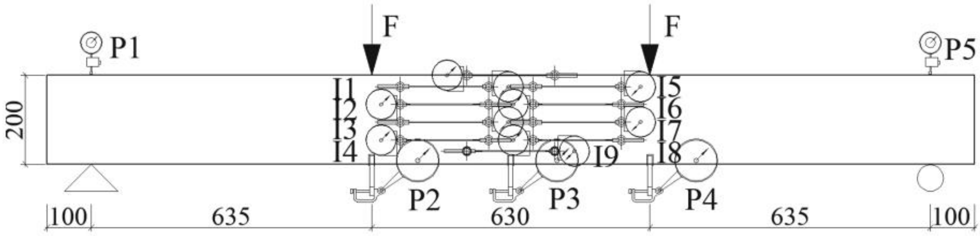


Fig. 1. Scheme of devices' location

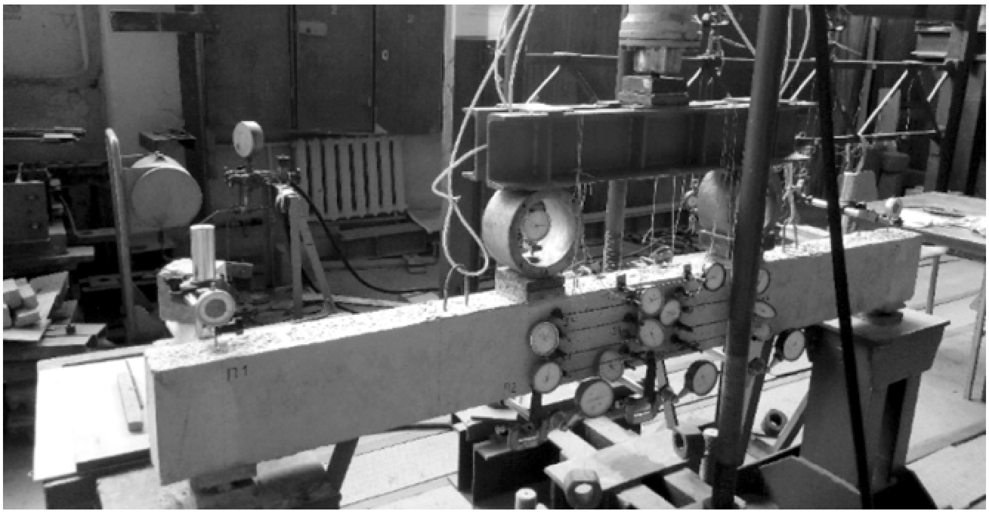


Fig. 2. General view of devices location on the research sample

The experiment was conducted in stages with loading increases of 0.05 $P_{max.c}$ (where $P_{max.c}$ – is the loading at which the bearing capacity of the control sample was depleted). This increase was used until the loading had reached the value of 0.3 $P_{max.c}$ or until the first cracks appeared. Further increases of loading were equal to 0.1 $P_{max.c}$. At the load level equal to 0.8–0.9 of the limit strength of the sample, the increase was equal again to 0.05 $P_{max.c}$. Observation of the formation and development of the cracks was conducted using microscope MPB-2 with the division price of 0.05 mm. For reinforced concrete beams damaged before the load application, the damages were done without additional stages at impairments of 10, 20, 30 mm. For experimental samples, BD 2.6.1-0-20 and BD 1.1.2-0-20 damages were done in one stage using two disks (Fig. 3).

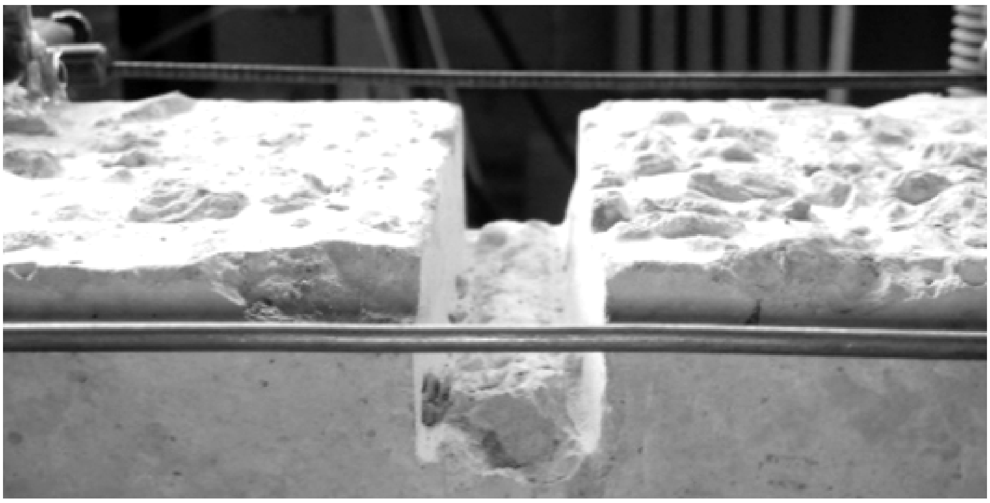


Fig. 3. General view of the damages in the compressed zone

The experiment was conducted according to the developed program, given in Table 3. Each beam had its individual marking.

Table 3

Program of the experiment

No.	Marking of the experiment	Marking of the testing sample	Type of the experiment
1	B 1.1	B 1.1.1-0	Without damages (control sample)
	BD 1.2	BD 1.1.2-0-20	With damages of 20–30 mm in the center of pure bending zone at load level of 0 % from bearing capacity of control sample
2	BD 2.1	BD 1.2.1-0.3-20	With damages of 20–30 mm in the center of pure bending zone at load level of 30 % from bearing capacity of control sample
3	BD 3.1	BD 1.3.1-0.5-80	With damages of 80–30 mm in the center of pure bending zone at load level of 50 % from bearing capacity of control sample

Results and discussion

Three sections of measures were considered for comparison and analysis of deformation distribution in concrete. The first section- measures, obtained using indicators I1-4, second – from indicators I11-14, and third – from indicators I5-8 (Fig. 2).

Obtained results demonstrate typical changes of compressed concrete zone height for undamaged reinforced damaged concrete beams (Fig. 4).

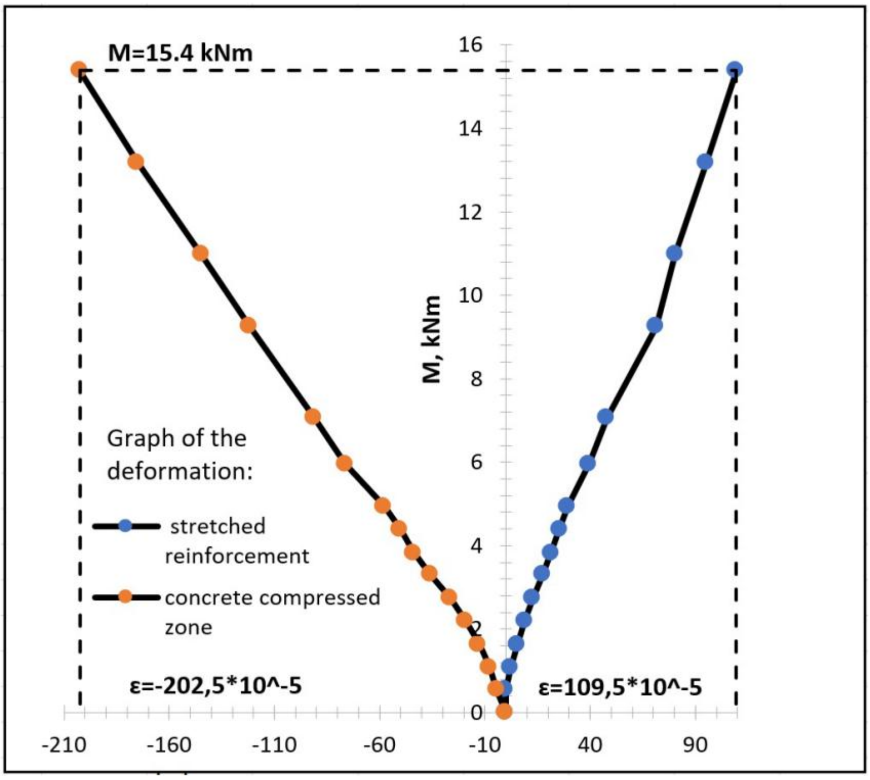


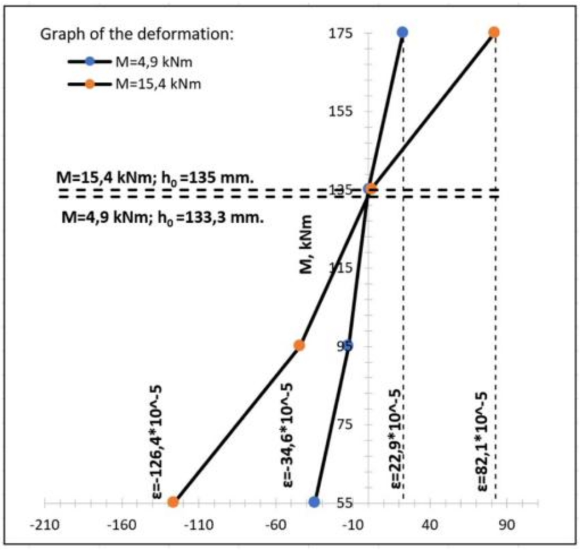
Fig. 4. The sample of strain graph for reinforcement (left) and compressed concrete (right) of undamaged beams BD 1.1.1-0 of the first series

Additionally, these results demonstrate certain symmetricity in measures in the first and third sections (Fig. 5). Such the difference in measures in the stretched zone was caused by cracks' opening at the end of the first stress-strain state of the element. Obtained results are given in Table 4.

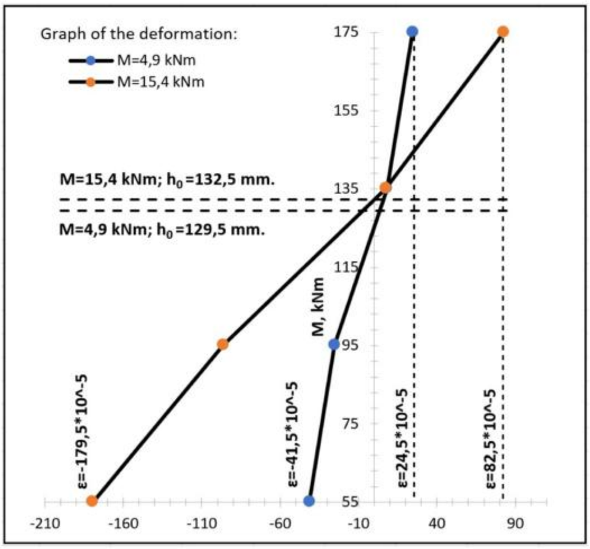
Table 4

Program of the experiment

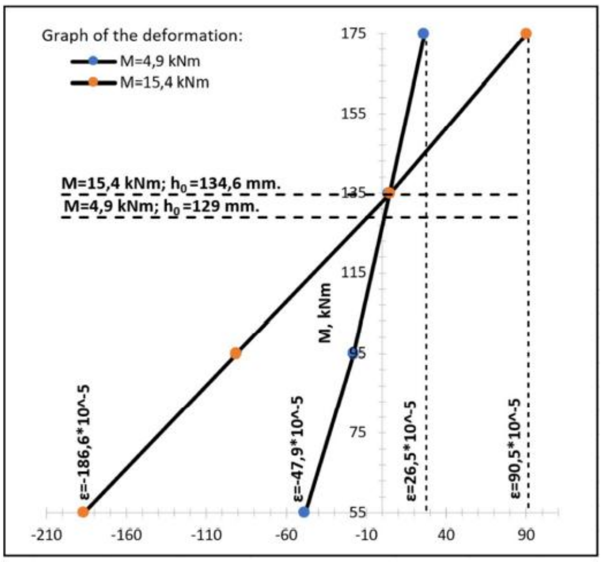
Testing samples' marking	Sample bearing capacity, kNm	Deviation in bearing capacity according to B 1.1.1-0	Concrete compressed zone height at $M = 4.9$ *kNm*, mm	Concrete compressed zone height at $M = 15.4$ *kNm*, mm	Deviation in changes of concrete compressed zone height at $M = 15.4$ *kNm* according to $M = 4.9$ *kNm*, %
B 1.1.1-0	25.703	–	66.71	65	2.563
BD 1.1.2-0-20	20.869	−18.807	67.12	67.759	−0.464
BD1.2.1-0,3-20	21.655	−15.749	67.12	75.711	−12.8
BD1.3.1-0.5-80	21.02	−18.298	75.83	80.21	−5.776



a



b



c

Fig. 5. Deformation graph for concrete in unaamaged beams BD 1.1.1-of the first series: a – first section; b – second section; c – third section

During analyzing the results, it was indicated that bearing capacity could be strongly influenced by damages, which appear during the loading. Damages at 0.3 and 0.5 M from the limit strength for the sample demonstrate the distribution of stresses and increase of bearing capacity, compared with the sample, damaged before load application. Additionally, changes in neutral axis position were fixed, where the transition from the stretched zone to the compressed zone takes place.

Conclusions

Research results demonstrate an increase of 3.8 % in reinforced concrete beams bearing capacity if they are damaged under the load, compared with the unloaded damaged reinforced concrete beams. Additionally, the effect of neutral axis position change was fixed: if the sample is damaged, the stretched concrete zone is decreased (in the damaged zone), and the compressed zone is increased. If the damages occur during the loading, this tendency is fulfilled. This occurrence takes place due to the distribution of internal stresses in the spatial changes of elements in dynamics.

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ТЕОРЕТИЧНИЙ АНАЛІЗ ТА ЕКСПЕРИМЕНТАЛЬНЕ ДОСЛІДЖЕННЯ ДЕФЕКТІВ У СТИСНЕНІЙ ЗОНІ ЗАЛОЗОБЕТОННИХ ЕЛЕМЕНТІВ

У зв'язку з економічними тенденціями в будівельній галузі останніми роками все більше уваги приділяється дослідженню залишкової несучої здатності залізобетонних елементів. Вивчення впливу пошкоджень на несучу здатність залізобетонних елементів є однією із основних тем досліджень у цій галузі. У статті зосереджено увагу на впливах пошкоджень у стиснутій зоні бетонних елементів з погляду мінливості таких пошкоджень. Хоча деякі методи дослідження пошкоджених залізобетонних елементів висвітлені в цій статті, зазначимо, що більшість методів придатні лише для певних дефектів і пошкоджень через велику багатофакторність і складність дослідження. Крім того, висвітлено теоретичні та експериментальні дослідження впливу пошкоджень у стиснутій зоні під час вигину залізобетонних елементів. З погляду впливу на несучу здатність порівнювали рівень навантаження та втрату покриття у стиснутій зоні. Запропоновано результати випробувань чотирьох залізобетонних балок, одна з яких була контрольною (випробувана без пошкоджень), і три – типово пошкоджені в зоні стиснення за різних рівнів навантаження. У результаті було виявлено, що найістотніше впливають тип пошкодження, навантаження та зміна положення нейтральної осі. Крім того, результати досліджень свідчать про збільшення несучої здатності залізобетонних балок у разі їх пошкодження під навантаженням на 3,8 % порівняно із пошкодженими залізобетонними балками без навантаження. Отже, видаються актуальними та доцільними для подальшого вивчення експерименти з метою визначення залишкової несучої здатності в пошкоджених залізобетонних елементах.

Ключові слова: згинальні елементи; залізобетонна балка; пошкодження; дефекти; несуча здатність; корозія.