UDC 624.012
DOI: 10.15587/1729-4061.2021.237954

DEVELOPMENT METHODOLOGY OF DETERMINATING RESIDUAL CARRYING CAPACITY OF REINFORCED CONCRETE BEAMS WITH DAMAGES TENSILE REINFORCEMENT WHICH OCCURRED DURING LOADING

Pavlo Vegera
Corresponding author
PhD, Assistant*
E-mail: Pavlo.i.vehera@lpnu.ua
Rostyslav Vashkevych
PhD, Associate Professor*
Yaroslav Blikharskyy
PhD, Associate Professor
Department of Highways and Bridges*
Roman Khmil
PhD, Associate Professor*
*Department of Building Constructions and Bridges**
**Lviv Polytechnic National University
S. Bandery str., 12, Lviv, Ukraine, 79013

This paper reports the improved and verified procedure for calculating reinforced concrete beams affected by damage to stretched reinforcement when loaded. The main results from testing the reinforced concrete beams with damage in the stretched zone in the form of one hole in the reinforcement in the middle of the beam are given. The variable parameter of the study was the level of load resulting in the damage. It acquired values of 0, 30 %, 50 %, 70 % of the bearing capacity of control undamaged samples. Overall, the results of testing 12 samples are given. A new procedure has been proposed for taking into consideration changes in the mechanical characteristics of stretched reinforcement arising from its damage. This makes it possible to more accurately establish the bearing capacity of reinforced concrete bended elements affected by damage to their reinforcement during operation. The analysis of the calculation, compared with experimental quantities, led to a conclusion that the strain model could determine when the bearing capacity of reinforced concrete beams without damage and with damage to working reinforcement is exhausted. Based on the improved algorithm, the principle of using a strain model was proposed to establish when the bearing capacity of damaged samples, taking into consideration the effect of the load level, is exhausted. The theoretical estimation, considering when the bearing capacity is exhausted, showed results that are 3...21 % less than the experimental values, which ensures reliability of calculation of such structures. The proposed calculation provides a new approach to determining the bearing capacity of reinforced concrete beams damaged during operation. That, in turn, makes it possible to more accurately determine the residual bearing capacity of structures and increases the safety of their operation

Keywords: reinforced concrete beam, damaged reinforcement, strain model, calculation of bended elements, when loaded

Received date 14.06.2021
Accepted date 20.08.2021
Published date 30.08.2021

How to Cite: *Vegera, P., Vashkevych, R., Blikharskyy, Y., Khmil, R. (2021). Devising a procedure for determining the residual bearing capacity of reinforced concrete beams with damaged stretched reinforcement as a result of loading. Eastern-European Journal of Enterprise Technologies, 4 (7 (112)), 6–17. doi: https://doi.org/10.15587/1729-4061.2021.237954*

1. Introduction

Reinforced concrete is the most common material for building structures. Its wide use is due to the cheapness of materials, the ability to create a wide range of designs of various shapes and appearances, the ease of use and application in various fields of construction. However, during operation, reinforced concrete elements are exposed to atmospheric, technological, and other influences. As a result, their stressed-strained state differs from the designed one. That, in turn, leads to a change in the bearing capacity and/or operational suitability of such elements. This is especially pronounced in the elements used in the transport sector: the structures of bridges, tunnels, roadbeds. In this case, the above influences are superimposed, which leads to a decrease in the bearing capacity and durability of such elements. At the same time, the most dangerous for a structure is corrosion of stretched reinforcement since stretching strains in the bended reinforced concrete elements are perceived only by the reinforcement (according to calculation theory). These factors are also superimposed with the internal stressed-strained state – all reinforced concrete elements operate under a certain level of load. It arises from the natural weight of the structure and increases up to the operational load level (which is approximately 50–70 % of the bearing capacity of an element). There are almost no structures in construction that would work without any load while most research tackles the emergence of defects and damage without any loads.

Studying building structures always begins with the study of their design features [1]. This is the first step in the development of a new structure, or the detection of features in the known one. Having determined these data, it is necessary to determine their bearing capacity [2] and establish the criteria when it is exhausted. At the next stage, the deformability of this design is investigated, since even providing strength, it can be short-lived [3]. These data are acquired from mathematical modeling using software packages or/and based on experimental tests [4]. Based on the test results, it is necessary to provide a procedure of theoretical estimation – to test the existing one, to provide recommendations for its changes, or to devise a new methodology [5]. In some cases, a new procedure for determining bearing capacity [6] is suggested, while in others – changes or clarifications to acting norms are proposed [7]. Improvement of existing procedures for calculating building structures is the most common practice since this verifies a given technique and introduces the necessary changes [8]. An important element of the possibility of applying building structures is determining their reliability and operational suitability [9].

All further studies are related to the change of initial parameters, first of all, the reinforcement of structures by classical methods [10] and modern materials [11]. After passing these stages, it is usually the stage of research into structures in which damage occurs [12] as one of the parameters for changing the initial (project) stressed-strained state. Such studies are extremely complex and require long-term research [13]. Another complexity of such studies is the complex stressed-strained state caused by the presence of materials with different characteristics: concrete and steel (or composite) reinforcement [14].

Based on the above, one can note that conducting studies that address changes in the stressed-strained state under the influence of load is of significant practical importance; however, given the complexity of such studies, they are not common. Accounting for the greater number of parameters that determine the stressed-strained state of structures achieves greater safety of operation, which affects the safety of people or equipment involved.

2. Literature review and problem statement

A study reported in [15] attempted to analyze the effect of 20 % NaCl aqueous solution on steel hardness as a result of corrosion. The steel hardness and corrosion damage were determined according to the time of corrosion. It is especially important to investigate the effect of reinforcement corrosion on the adhesion strength of steel and concrete. Paper [16] investigated the adhesion behavior of reinforced concrete elements, including the maximum strength of adhesion, free slip, and modes of destruction at the stages of initial cracking, crack formation, and subsequent crack evolution. Methods for quantitative estimation of the relationship between the magnitude of corrosion and the spread of cracks were devised in work [17]. The variables studied were the protective layer/diameter ($c/\varnothing$), cement proportions, w/c, reinforcement arrangement, transverse reinforcement, and corrosion rate. Those works are common in that the mechanism of reinforcement corrosion was studied: the rate, influence of other substances, and not a change in bearing capacity.

Steel corrosion products create a volumetric expansion around the reinforcement, damaging concrete. Such an effect on reinforced concrete elements is described in work [18]. The authors of [19] considered the impact of both load-caused cracks and defects caused by yield strength on the corrosion characteristics of stretched rods in reinforced concrete beams at prolonged load and exposure to a chloride medium. It remains critically important to investigate the process and mechanism of corrosion that occurs in the reinforcement and to build a theoretical model for predicting the strength of concrete expansion in corrosion cracking of reinforcement [20]. This issue is widely researched in the world: the research method is applied to different structures [21]. This approach is used in work [22], which considers the effect of temperature on the corrosion rate based on theoretical prerequisites for chloride-induced microelement corrosion of steel in concrete. The results showed that with concrete coating there could be two ways of cracking due to uneven corrosion of steel reinforcement, including corrosion-induced crack along the radius direction of the concrete cover and two branches in the secant direction of the corrosion zone [23]. The composition of concrete can also significantly affect the propagation of the cracking path. Hence, one can conclude that the damage caused by corrosion of the reinforcement essentially affects the parameters of operational suitability, but the effect on the bearing capacity is not described.

The purpose of study [24] was to provide a forecasting approach based on a large number of published studies related to corrosion reinforcement in concrete elements by using artificial neural networks (ANNs). The criterion of minimizing the root mean square error and increasing the value of the regression of the predicted results are considered to assess the training performance of ANN models. The validity of the proposed model is checked using the collected experimental database. The results show that the estimation model has acceptable agreement with experimental data. However, the cited work does not describe the impact of various kinds of damage and defects on a strained state.

Work [25] presents various corrosion effects of reinforcement on reinforced concrete buildings. For this purpose, a hypothetical five-story reinforced concrete frame was designed. Three different scenarios were chosen – corrosion only on the ground floor, corrosion on one façade, and corrosion on two adjacent facades of the building. It would be good to enhance the considerable relevance of that work with experimental data or calculation results according to acting norms. An experimental study to assess the initial behavior of reinforcement of different types under controlled conditions and in the conditions of simulated marine environment is reported in paper [26]. It was established that the resistance to polarization of machined reinforcement is 1.8 times greater than that of corrosion-resistant reinforcement. However, it is not specified what effect the structures may experience as a result of such an influence. In [27], the experimental and numerical research was carried out to study the worsened characteristics of the sloping cross-sections of reinforced concrete beams. Corrosion of reinforcement, crack structures, and structural behavior of corrosion samples with different levels of corrosion accelerated by the affected current method were analyzed. The cited work is of considerable practical importance but does not cover the impact of the level of workload at which the damage occurred. Work [28] is aimed at researching the consequences of reinforcement corrosion to impair the bearing capacity of damaged reinforced concrete structures. A new analytical method has been proposed to predict the evolution of cracks in the cover concrete and assess the residual strength of reinforced concrete structures with corrosion reinforcement that has no adhesion to concrete. Structural characteristics such as the growth of concrete cracks and the rate of deterioration of bending strength are considered a stochastic process for modeling distribution throughout the lifetime of operation. On the other hand, it is necessary to take into consideration the occurrence and development of defects in the concrete of the structure [29], which also reduces the bearing capacity of structures and can be critical.

Full-time research of transport, bridge structures is given in article [30]. The subject of that analysis is associated with the verification of the bearing capacity of span structures, taking into consideration the degree of corrosion of the components of the railroad viaduct. As prototypes, the authors analyzed structures located at 41.446 km, on the railroad line number 301 «Kotlarnia» SA, and railroad tracks PKP-PLK near T. Kosciuszko Street in Zabzhe (Poland). The cited work emphasizes the importance of such research. All reinforced concrete structures, when checking calculations, should include the history of loads, as well as the existing stressed-strained state. The latter parameter is typically not taken into consideration.

The approach of probabilistic analysis for the formation of cracks caused by corrosion, formed on the basis of improved models of wear, is given in work [31]. The results show that increasing the strength of concrete, the depth of the protective layer, and the diameter of the steel bars, or reducing the density of CO_2 are effective countermeasures in order to increase the durability of the reinforced concrete bridge [31]. However, the cited work does not sufficiently reveal how those parameters change during the lifetime of the structure and how it affects its strength.

Corrosion of prestressed reinforced concrete structures leads to a decrease in the size of reinforcement, deterioration of mechanical properties of steel, cracking of surrounding concrete, and decay of bonds at the interface «steel-concrete». Paper [32] proposes a numerical approach that can take into consideration all the effects associated with the corrosion process using a nonlinear analysis of the finite elements (NLFEA) and modeling of membrane or shell elements. The cited work is based on a huge theoretical base and computer simulation; however, it would be good to support it with experimental research. Still, such studies are very complex and require high accuracy of the experiment.

Paper [33] constructed conceptual, mathematical, and system-dynamic models of the impact of the load on the damaged reinforced concrete column in accordance with the real values of the destructive load. The forecasting model is adapted and can also be used for thin elements of other lengths, other angles of damage, or depth of damage. However, the model does not take into consideration the level of loads at which damage arose and spread. Accordingly, this factor would affect further models of load impact.

The equations proposed in paper [34], called concentration functions, are used to calculate corrosion velocity for standard materials such as carbon steel, zinc, etc. The input parameters for calculating the functions are sulfur dioxide, temperature, relative humidity, and chloride ions. This variability of input parameters can represent different conditions under which structures may appear. However, those functions should take into consideration that when the load is in effect, corrosion processes would differ from those that occur without a load level.

Based on the above review, we can conclude that there are a significant number of studies into the bearing capacity and parameters of the stressed-strained state of damaged structures. However, there is a small body of research that would take into consideration the level of load, the real stressed-strained state of the structure in which the damage occurs. And since all structures operate under a certain level of load, ranging from the natural weight of the structure to the operational load level, acquiring data on changing their bearing capacity and devising a methodology for its calculation is a promising area of research.

3. The aim and objectives of the study

The purpose of this study is to devise the principle of calculating reinforced concrete beams with damaged tensile reinforcement (based on the strain procedure), when damage occurs at a certain level of load. This will make it possible to determine the bearing capacity of damaged reinforced concrete beams when damage to reinforcement appeared during operation. That, in turn, determines its service life and safety.

To accomplish the aim, the following tasks have been set:

– to give the results of experimental studies into the bearing capacity of reinforced concrete beams, in which the diameter of working reinforcement decreases at the load level of 0, 0.3, 0.5, 0.7 from the bearing capacity of control samples;

– to propose and apply a strain procedure for calculating reinforced concrete beams with damage to working reinforcement caused by the load, based on the strain model.

4. The study materials and methods

In total, 12 reinforced concrete beams, 9 concrete prisms, 20 concrete cubes, and 7 concrete cylinders were designed and manufactured in the factory. Reinforcement bars were selected to determine the physical-mechanical characteristics from the same batch of reinforcement used for prototypes.

The following designations have been adopted: C – control; B – beam; D – damaged (Table 1). In the case of corrosion or mechanical damage to reinforcement in actual reinforced concrete structures, the area of the cross-section of reinforcement decreases and, accordingly, the bearing capacity of reinforced concrete structures.

Table 1

Experimental research program

12 beams	→	Series 1 (working reinforcement with a diameter of 20 mm)	→	Control undamaged samples (2 beams)	→	CB-1.1 CB-1.2
				Damaged, without initial load level (2 beams)	→	BD-1.3 BD-1.4
				Damaged, at initial load level $0.3 \cdot M_{ult}^{exp}$, $0.5 \cdot M_{ult}^{exp}$, $0.7 \cdot M_{ult}^{exp}$ (6 beams)	→	BD-1.5-0.3 BD-1.6-0.3 BD-1.7-0.5 BD-1.8-0.5 BD-1.11-0.7 BD-1.12-0.7
		Series 1 (working reinforcement with a diameter of 16 mm)	→	Control undamaged samples (2 beams)	→	CB-2.13 CB-2.14

When performing experimental studies, it is customary to simulate a decrease in the area of the working reinforcement of the beams by drilling holes in the bars. At the same time, the diameter of the drilled hole modeled the degree of damage to the reinforcement and, accordingly, the reduction of the area of the cross-section of the bars. During the tests, the diameter of the drilled holes gradually increased, making, for example, the area of the cross-section of the bars ∅20 to the area of the bars ∅16. All beams were damaged by a single hole.

The program of experimental research is given in Table 1.

Experimental samples: 2,100 mm long, 100 mm wide, and 200 mm high (Fig. 1). Concrete composition: C:S:G=1:1.16:2.5 at W/C=0.375. Cement grade: M-500; quartz sand without impurities with a module of size M_k=2.00; granite gravel, fractions 5...10 mm – 66 %, 10...20 mm – 33 %.

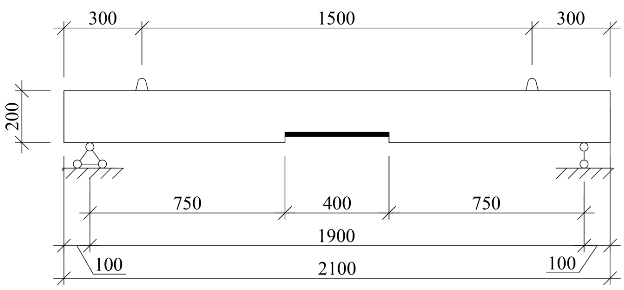

Fig. 1. Formwork drawing of experimental samples

More details on the test bench and the procedure of testing are given in work [35].

5. The results of studying the bearing capacity of experimental beams

5. 1. The strength of experimental beams without damage and with damage to reinforcement without load and under load

According to the research program, 6 samples were tested without an initial load level before damaging. Among them are 2 control (undamaged) samples with single working reinforcement ∅20 mm – CB-1.1 and CB-1.2. The next 2 samples are designed with ∅20 mm working reinforcement with a 36 % damage (corresponds to the area of diameter of 16 mm) – BD-1.3 and BD-1.4. The last 2 samples are made with single working reinforcement ∅16 mm (CB-2.13 and CB-2.14), which corresponds to the damage to the working reinforcement of control samples by 36 %.

Summarized test results of the samples without initial load level are given in Table 2.

In samples BD-1.3 and BD-1.4, CB-2.13 and CB-2.14, the area of the working reinforcement, like all other parameters (the strength of concrete, frame arrangement, etc.), are the same. However, according to Table 2, the strength of the samples with damaged reinforcement with a diameter of 20 mm (BD-1.3 and BD-1.4) is greater than the strength of the samples with the working reinforcement with a diameter of 16 mm (CB-2.13 and CB-2.14). This is because in the damaged samples the main working cross-section of the reinforcement is the thermally-strengthened outer layer. Therefore, the deviation of bearing capacity in damaged samples, compared to control in series 1, is, on average, 25 %, and in the non-damaged ones with the same area of the working reinforcement – 30 %.

Series 1 included, according to the experimental program of research, reinforced concrete beams with the working reinforcement with a diameter of 20 mm. Experimental samples were exposed to the appropriate load level (0.3, 0.5, or $0.7 \cdot M_{u\,exp}$), after which the working reinforcement of the samples was damaged. The working reinforcement was damaged by 36 %, which corresponds to the area of reinforcement with a diameter of 16 mm.

In total, 8 reinforced concrete beams from series 1 were tested damaged under the load.

Samples BD-1.5-0.3 and BD-1.5-0.3 before damage were exposed to the load level of 30 % of the bending moment value, which corresponds to the bearing capacity of non-damaged control samples CB-1.1 and CB-1.2. After that, damage was done in the form of holes with a gradual increase in diameter of 0.0, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, and 5.6 mm. After making each hole, the samples aged during 10 minutes and 5 minutes to acquire the readings from all devices. Holes were made at the bending moment M=9.9 kNm (30 % of the bearing capacity of control undamaged samples).

Summarized results of testing the samples damaged under the initial load level are given in Table 3.

The test results (Table 3) show a significantly smaller bearing capacity of samples CB-2.13 and CB-2.14 with the working reinforcement with a diameter of 16 mm compared to reinforced beams with a diameter of 20 mm; the deviation is 30.2 %. In samples damaged at load levels, the bearing capacity is approximately the same within 3.7...13.2 %. The greater bearing capacity of samples with damaged reinforcement with a diameter of 20 mm, at load levels, compared to samples with the working reinforcement with a diameter of 16 mm, is explained by the presence of a thermally-strengthened layer. That is, during the damage using a hole, the area of the cross-section of the core (non-strengthened cross-section of the reinforcement) is significantly reduced, and the external thermally-strengthened layer is slightly reduced, which explains the higher results of bearing capacity.

Table 2

Bearing capacity of experimental samples

Sample code	Bearing capacity is exhausted, kNm		Physical destruction, kNm		Bearing capacity deviation, %		Physical destruction deviation, %	
	sample	mean	sample	mean	sample	mean	sample	mean
CB-1.1	24.9	24.2	32.9	31.1	–	–	–	–
CB-1.2	23.5		29.3		–		–	
BD-1.3	19	18.1	22.9	23.5	21.5	25.2	26.4	24.4
BD-1.4	17.2		24.1		28.9		22.5	
BD-2.13	16.3	16.9	20	21.1	32.6	30.2	35.7	32.2
BD-2.14	17.5		22.2		27.7		28.6	

Note: the deviations were determined relative to control samples CB-1.1 and CB-1.2

Table 3

Strength of experimental samples damaged at load level

Sample code	Bearing capacity is exhausted, kNm		Physical destruction, kNm		Bearing capacity deviation relative to CB-1, %		Physical destruction deviation relative to CB-1, %	
	sample	mean	sample	mean	sample	mean	sample	mean
CB-1.1	24,9	24.2	32.9	31.1	–	–	–	–
CB-1.2	23,5		29.3		–		–	
CB-2.13	16,3	16.9	20	21.1	32.6	30.2	35.7	32.2
CB-2.14	17,5		22.2		27.7		28.6	
BD-1.5-0.3	19,9	21	24.3	25.7	17.8	13.2	21.9	17.4
BD-1.6-0.3	22,1		27.1		8.7		12.9	
BD-1.7-0.5	23,3	21.5	26.9	25.5	3.7	11.2	13.5	18.0
BD-1.8-0.5	19,7		24.1		18.6		22.5	
BD-1.11-0.7	23,9	23.3	26.6	25.9	1.2	3.7	14.5	16.7
BD-1.12-0.7	22,7		25.2		6.2		19.0	

Note: the deviations were determined relative to control samples CB-1.1 and CB-1.2

5. 2. Procedure for calculating the bearing capacity of reinforced concrete beams with damage to reinforcement according to the strain model

In 2010, SNiP 2.03.01-84* «Concrete and reinforced concrete structures» [36] in Ukraine was replaced with a new national standard of calculation DSTU B V.2.6-156:2010 «Concrete and reinforced concrete structures of heavy concrete. Design rules» and DBN V.2.6-98:2009 «Concrete and reinforced concrete structures. Basic provisions» [37], which is based on the norms of Eurocode [38].

One of the main differences of this calculation is the use of a nonlinear strain procedure. The essence of the calculation is to take into consideration real nonlinear strain diagrams for concrete «σ–ε_c» and two-linear for reinforcement «σ–ε_s». This procedure makes it possible to model the work of a structure at any stage of loading for the height of the cross-section of samples. At the same time, it is possible to calculate reinforced concrete structures of various shapes of cross-section with any arrangement of reinforcement. The model of calculation according to the strain procedure is adopted in most foreign norms.

However, the strain procedure does not imply the calculation of structures under load, especially if the structures have suffered damage during operation, being exposed to a certain level of load. This load can be induced by equipment, natural weight, overlapping structures, etc.

Thus, according to [37], the calculation of the bearing capacity of the normal cross-section of reinforced concrete bending elements takes as a basis a nonlinear strain model and is performed under the condition of equilibrium of internal and external forces assuming the following hypotheses:

– the strains of concrete and reinforcement are distributed across the cross-sectional height according to a linear law;

– the hypothesis of straight cross-section is adopted;

– the largest increase in strains is taken in the average cross-section since it experiences the greatest strains;

– the strains of reinforcement are taken in the form of a two-line diagram. Strains of concrete – according to nonlinear diagrams, which are mathematically notated as a polynomial of the 5th power with appropriate coefficients (taken from real concrete tests with a complete diagram of destruction);

– only reinforcement resistance is taken into consideration in the stretched zone, the concrete of the stretched zone is not taken into consideration.

To determine the stressed-strained state of reinforced concrete rectangular beams during a static bending test, the second form of equilibrium employs the following formulas [39]:

$$\frac{b\cdot f_{cd}\cdot\varepsilon_{c1}}{\aleph^{0}}\cdot\sum_{k=1}^{5}\frac{a_k}{k+1}\left(\frac{\varepsilon^{0}_{c(1)}}{\varepsilon_{c1}}\right)^{k+1}+\sum_{i=1}^{n}\sigma_{si}\cdot A_{si}=0, \quad (1)$$

$$\frac{b\cdot f_{cd}\cdot\left(\varepsilon_{c(1)}\right)^{2}}{\aleph^{0^{2}}}\cdot\sum_{k=1}^{5}\frac{a_k}{k+2}\left(\frac{\varepsilon^{0}_{c(1)}}{\varepsilon_{c1}}\right)^{k+2}+$$

$$+\sum_{i=1}^{n}\sigma_{si}\cdot A_{si}\cdot\left(\chi_1^{0}-Z_{si}\right)=M_0, \quad (2)$$

where $\varepsilon^{0}_{c(1)}$ is the strain of concrete in the compressed fiber of the main cross-section at $M=M_0$; f_{cd} is the prism strength of concrete for compression; $\aleph^0$ is the curvature of the curved axis in the main cross-section at $M=M_0$; χ_1^0 is the height of compressed zone of main cross-section at $M=M_0$; M_0 is the value of the bending moment if damaged; b is the width of the cross-section of the design element; χ is the curvature of the curved axis in the cross-section; $\bar{\chi}$ is the relative curvature; a_k is the polynomial coefficients; σ_{si} is the strain in the i-th reinforcement; A_{si} is the cross-sectional area of the i-th reinforcement; z_{si} is the distance of the i-th bar of the reinforcement to the most compressed face of the cross-section.

The estimated cross-section of bended reinforced concrete beams is shown in Fig. 2.

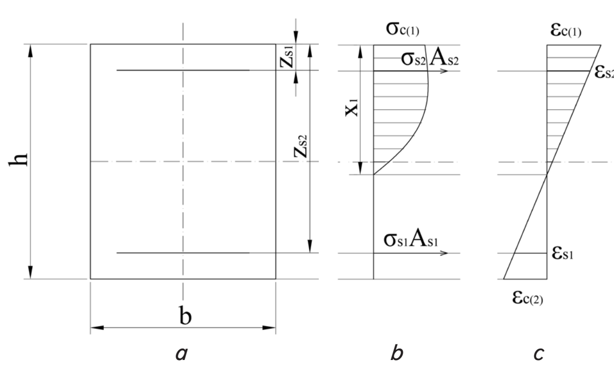

Fig. 2. The estimated cross-section of the bending element of a rectangular cross-section: *a* – cross-section of the element; *b* – stress diagram; *c* – strain diagram

The algorithm for determining the parameters of the stressed-strained state of the normal cross-section of the reinforced concrete element, according to [39], is an iterative process. At each stage, a gradual method of calculating the averaged strains of lower fiber concrete according to the predetermined values of strains on the upper fiber of the cross-section using equation (1) is implemented.

At the end of the calculation, at the predefined value of strains of concrete on the upper fiber, we increased them, and the calculation was repeated. Upon reaching the required bending moment value using equation (2), the iterative process was terminated.

A schematic flowchart for determining the stressed-strained state of a normal cross-section of a reinforced concrete bending element is shown in Fig. 3.

According to the flowchart shown in Fig. 3, we determined the parameters of the stressed-strained state of the bended structures according to the strain procedure: we derived the strains of concrete, the layers of reinforcement, the curvature of the curved axis in a normal cross-section at the predefined load value.

However, according to [39], and considering the above flowchart (Fig. 3), a given procedure does not imply taking into consideration the level of load at which damage to samples may occur.

The calculation of the bending strength of reinforced concrete elements damaged under the load of reinforced concrete structures is proposed to be carried out in two stages. At the first stage, the stressed-strained state of the normal cross-section of the main structural element is investigated before damage occurs, using the current procedure.

According to a given procedure (Fig. 3), the method of iterative selection determines curvature at each level of load. Having reached the level of load at which damage is done (or the level of operational load), one proceeds to stage 2. At this stage, a condition is set: if the curvature is less than the level of load at which the damage occurred (Fig. 4), then the calculation is performed similar to an ordinary intact element. In the case when the value of curvature exceeds a certain value at the load at which the damage was done, the calculation for the structure with damage parameters (reduction of the percentage of reinforcement, a change in the physical-mechanical characteristics) is performed.

According to DSTU B V.2.6-156:2010 [39], the curvature of a curved axis in the cross-section:

$$\chi = \frac{1}{r} = \frac{\left(\varepsilon_{c(1)} - \varepsilon_{c(2)}\right)}{h}. \qquad (3)$$

The ratio of strains of concrete of the compressed zone to the ultimate strains of the concrete of the compressed zone:

$$\gamma = \frac{\varepsilon_{c(1)}}{\varepsilon_{c1}}. \qquad (4)$$

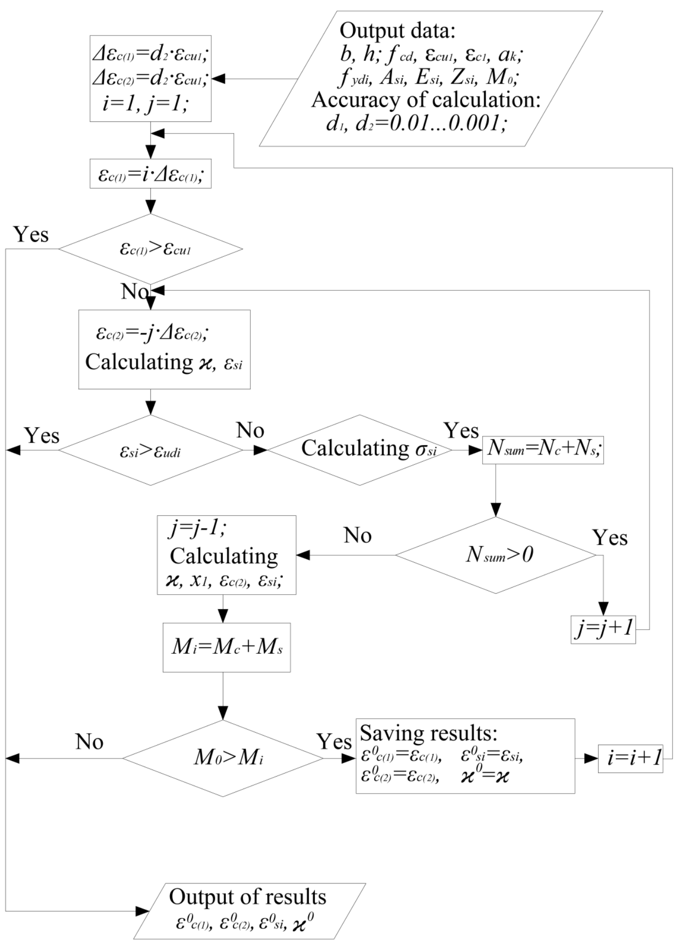

Fig. 3. Flowchart for determining the stressed-strained state of the normal cross-section of the reinforced concrete bending element.

Note: the definition of conditional notation is given after equation (3). Other parameters are standard characteristics of concrete and reinforcement and are taken from appropriate legal documents (e.g. [36, 38, 39])

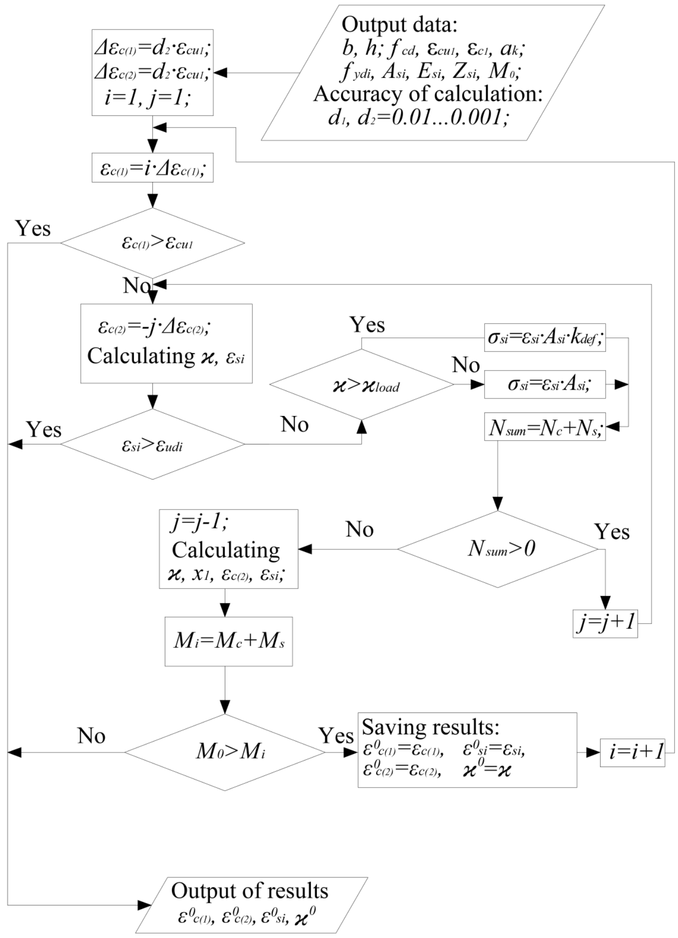

Fig. 4. Schematic flowchart for determining the stressed-strained state of the normal cross-section of the reinforced concrete bending element damaged by the load

The height of the compressed concrete zone:

$$x_1 = \frac{\varepsilon_{c(1)}}{\chi}. \quad (5)$$

The relative curvature:

$$\bar{\chi} = \frac{\chi}{\varepsilon_{c1}}, \quad (6)$$

where $\varepsilon_{c(1)}$ is the strain of concrete compressed fiber; $\varepsilon_{c(2)}$ is the averaged strains of stretched concrete fiber. The strains in the *i*-th layer of reinforcement during elastic work was determined from the following formula:

$$\sigma_{si} = \varepsilon_{si} \cdot E_{si}, \quad (7)$$

and when the yield strength is reached:

$$\sigma_{si} = f_{yd}. \quad (8)$$

The strains, according to the flat cross-section hypothesis, were determined from the following formula:

$$\varepsilon_{si} = \chi \cdot \left(x_1 - z_{si}\right). \quad (9)$$

It should be noted that when calculating the structures damaged due to the execution of holes with a diameter of 5.6 mm of thermally strengthened reinforcement, the acting norms [39] do not provide for changes in the physical-mechanical characteristics of the reinforcement.

5. 3. The results of calculating control and damaged reinforced concrete beams

Based on the proposed calculation shown by the flowchart in Fig. 4, we built strain plots of stretched reinforcement and the most compressed concrete fiber. This calculation takes into consideration the reduction of the physical-mechanical characteristics of the reinforcement due to damage, as well as a possibility to perform calculations for structures damaged when loaded, which is not implied by a strain procedure. Calculating the bearing capacity after the use of reduced characteristics of materials makes it possible to obtain a reliable result, which is consistent with experimental data.

We calculated control undamaged reinforced concrete beams CB-1.1 and CB-1.2 without the use of additional lowering coefficients, according to formulas (1) and (2) (block diagram in Fig. 3); the results are shown in Fig. 5.

The physical destruction of samples during the experiment occurred as a result of the fragile destruction of the compressed zone of concrete at a value $M_{ult}^{exp} = 31.1$ kNm, greater than the theoretical values of calculation by 24.4 % $\left(M_{ult}^{th} = 23.5 \text{ kNm}\right)$. The calculation of samples BD-1.3 and BD-1.4 was carried out according to formulas (1) and (2) (block diagram in Fig. 3) since the damage was done without a load level. The calculation results are shown in Fig. 6.

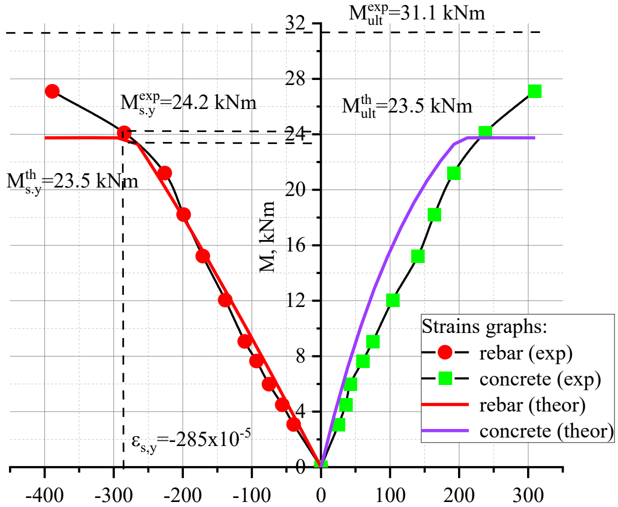

Fig. 5. Strain plots of the theoretical calculations of stretched reinforcement (rebar (theory)) and concrete of the most compressed fiber (concrete (theory)) compared to experimental average data on control beams CB-1.1 and CB-1.2

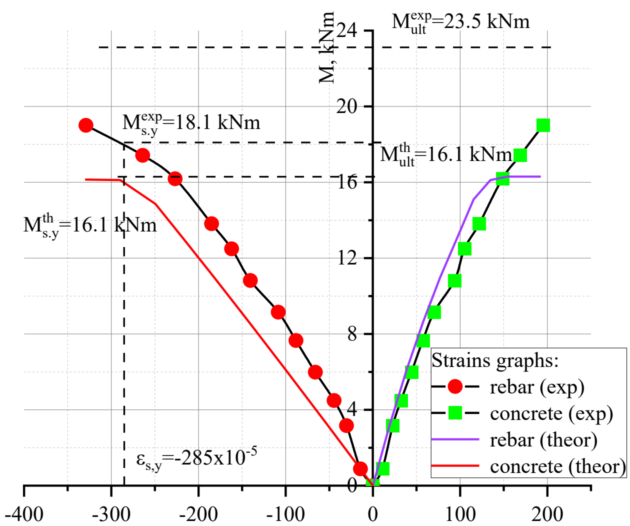

Fig. 6. Strain plots of the theoretical calculations of stretched rebar (rebar (theory)) and concrete of the most compressed fiber (concrete (theory)) compared to the experimental average data on beams BD-1.3 and BD-1.4

In beams BD-1.3 and BD-1.4, the working rebar with a diameter of 20 mm is damaged to an area corresponding to the diameter of 16 mm by drilling the hole without the effect of the load. According to the results of the theoretical calculation of when the bearing capacity is exhausted, it happened when the strains of the working reinforcement reached the yield strength $\varepsilon_{s,y}$=285·10^{-5}, at the bending moment $M_{s,y}$ = 31.1 kNm. This value is less than the experimental value by 11.0 % and makes it possible to use the calculation in the practice of designing. As a result of the damage, a thermally-strengthened layer of reinforcement is included in operation. Therefore, the physical destruction of the samples, according to the theoretical calculation, occurred at M_{ult}^{th} = 16.1 kNm, less than 31.5 % of the experimental value M_{ult}^{exp} = 23.5 kNm.

In control beams CB-2.13 and CB-2.14, the working rebar with a diameter of 16 mm was without damage. The results are shown in Fig. 7.

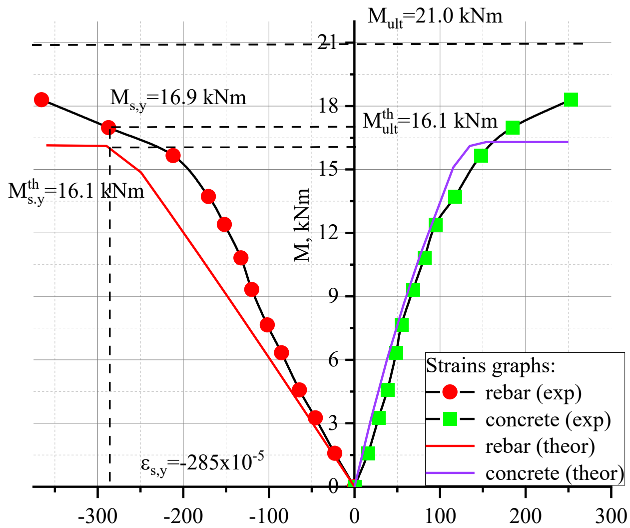

Fig. 7. Strain plots of the theoretical calculations of stretched rebar (rebar (theory)) and concrete of the most compressed fiber (concrete (theory)) compared to the experimental average data on control beams CB-2.13 and CB-2.14

In samples CB-2.13 and CB-2.14, according to theoretical calculations, the bearing capacity was exhausted at a bending moment $M_{s,y}^{th}$ = 16.1 kNm at an experimental value $M_{s,y}^{exp}$ = 16.9 kNm. This is 5 % less, and allows the design of such structures according to the strain model.

Physical destruction, according to the theoretical calculation, occurred at the bending moment M_{ult}^{th} = 16.1 kNm, that is less than the experimental value M_{ult}^{exp} = 21.0 kNm by 23.3 %.

Samples BD-1.3-0.3 and BD-1.4-0.3 before damage were brought to the level of 30 % of the bearing capacity of non-damaged control samples CB-1.1 and CB-1.2. After that, we damaged the working rebar with a diameter of 20 mm. After the damage, the diameter of the working rebar in terms of area corresponded to the diameter of 16 mm, which corresponds to the reinforcement of control samples with the working rebar with a diameter of 16 mm, CB-2.13 and CB-2.14.

We calculated samples BD-1.5-0.3 and BD-1.6-0.3 according to the same formulas (1) and (2) but according to the procedure given in the block scheme in Fig. 4. The results of this calculation are shown in Fig. 8.

In beams BD-1.5-0.3 and BD-1.6-0.3, the bearing capacity was exhausted, according to the results of the theoretical calculation, at the bending moment $M_{s,y}^{th}$ = 17.1 kNm, that is less than the experimental value $M_{s,y}^{exp}$ = 21.0 kNm by 18.6 %. According to the theoretical calculation, the physical destruction of the samples occurred at M_{ult}^{th} = 17.1 kNm as a result of reaching the maximum strains by the most compressed concrete fiber. At the same time, experimental physical destruction was achieved at M_{ult}^{exp} = 25.7 kNm due to the rupture of the rod of the working rebar with a diameter of 20 mm.

Based on the calculation of beams BD-1.5-0.3 and BD-1.6-0.3, according to the devised procedure, which is shown in Fig. 4, the strain plots of concrete of the most compressed fiber and the stretched working rebar (Fig. 9) were built, and their bearing capacity and physical destruction were determined.

The bearing capacity of beams BD-1.7-0.5 and BD-1.8-0.5 was exhausted at the bending moment $M_{s,y}^{th}=17$ kNm, which is less than the experimental value $M_{s,y}^{exp}=21.5$ kNm by 20.9 %.

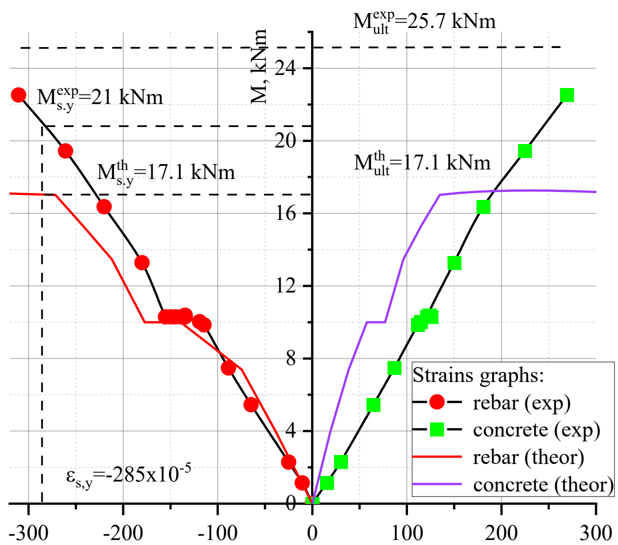

Fig. 8. Strain plots of the theoretical calculations of stretched rebar (rebar (theory)) and concrete of the most compressed fiber (concrete (theory)) compared to the experimental average data on beams BD-1.5-0.3 and BD-1.6-0.3

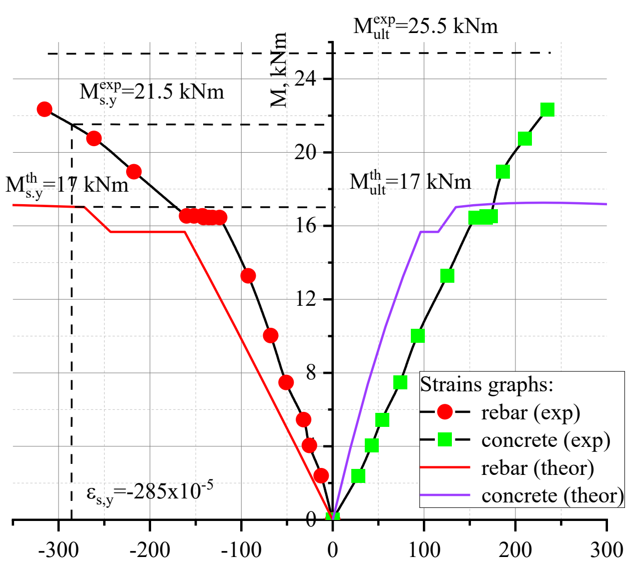

Fig. 9. Strain plots of the theoretical calculations of stretched rebar (rebar (theory)) and concrete of the most compressed fiber (concrete (theory)) compared to the experimental average data on beams BD-1.7-0.5 and BD-1.8-0.5

The physical destruction, according to the theoretical calculation, occurred at the bending moment $M_{ult}^{th}=17$ kNm due to the destruction of the compressed zone of concrete. The experimental physical destruction was achieved at moment $M_{ult}^{th}=25.5$ kNm, due to rupture of the working rebar.

The results of determining when the bearing capacity of prototypes was exhausted are summarized in Table 4.

Table 4

Strength of beams according to the criterion of reaching the maximum yield strains of the working stretched rebars (the bearing capacity is exhausted)

Sample code	Moment corresponding to the boundary strains of the main rebar (the bearing capacity is exhausted), kNm		Deviation of experimental value from theoretical, %
	Experiment, M_s^{exp}	Theory, M_s^{th}	
CB-1.1 and CB-1.2	24.2	23.5	2.9
BD-1.3 and BD-1.4	18.1	16.1	11.0
BD-1.5-0.3 and BD-1.6-0.3	21	17.1	18.6
BD-1.7-0.5 and BD-1.8-0.5	21.5	17	20.9
CB-2.13 and CB-2.14	16.9	16.1	5.0

Deviation of the results of theoretical calculation from experimental data is 2.9...20.9 % in the direction of understatement of the theoretical values.

6. Discussion of results of studying the procedure for calculating reinforced concrete beams with damages caused by the load

The calculation of strains of stretched rebar and compressed concrete control samples CB-1.1 and CB-1.2 with a working rebar with a diameter of 20 mm without damage shows a satisfactory convergence with the experimental data. The beginning of the yield limit in the theoretical calculation was achieved at the bending moment $M_{s,y}^{th}=23.5$ kNm, that is less by 2.89 % than the experimental moment $M_{s,y}^{exp}=24.2$ kNm. That confirms the reliability of the calculation since the experimental values are higher than the theoretical ones with a slight difference. The fragile physical destruction of samples CB-1.1 and CB-1.2 (Fig. 5) is explained by the fact that according to the calculation according to the strain procedure, a two-line diagram of the strain-stress of the reinforcement is used, which does not take into consideration the curve of plastic strains that occur after reaching the yield limit. Since the calculation for such elements is carried out in terms of when the bearing capacity is exhausted, the result satisfies its use in the design of such structures.

Deviation of experimental values from theoretical ones for the tested control samples (without damage), upon reaching the yield strain of the main reinforcement (the bearing capacity is exhausted) was 2.9...5.0 % (Table 4) in the direction of understatement of theoretical values. This ensures the reliability of calculation according to the strain model, and makes it possible to apply it in practice.

A significant discrepancy in the calculation of beams BD-1.3 and BD-1.4 (Fig. 6) is explained by the fact that the calculation model does not provide for a thermally-strengthened layer with higher physical-mechanical characteristics. It should also be noted that according to the experiment, the destruction occurred as a result of rupture of the working rods of the rebars, and, according to the calculation, the destruction is due to the fragile destruction of the compressed zone of concrete when reaching the limits of concrete strains. This is due to the fact that working rebars were damaged in one local place, and not along the entire length.

In beams BD-1.5-0.3 and BD-1.6-0.3, the experimental value of the physical destruction of samples is greater than theoretical by 18.6 % (Table 4). This is due to the fact that the working rebar was damaged in one local place, and not along the entire length; and a change in the physical-mechanical characteristics of thermally-strengthened reinforcement with damage was not taken into consideration.

Samples BD-1.11-0.7 and BD-1.12-0.7 could not be calculated according to the strain procedure. At a load level of 70 % of the bearing capacity of control samples, if the working rebars are damaged, strains reach the onset of the yield limit, so it is impossible to calculate these samples according to the strain model.

The analysis of the theoretical calculation allows us to conclude that the strain model with sufficient accuracy shows when the bearing capacity of reinforced concrete beams without damage and with damage to the working rebars without the effect of the load is exhausted. According to the improved calculation algorithm, taking into consideration the effect of the load level, with satisfactory convergence, it calculates when the bearing capacity of samples damaged during the action of different load levels is exhausted. The calculation of damaged elements at high loads levels (70 % of the bearing capacity of control undamaged samples, and larger) cannot be performed due to the achievement of the onset of the yield limit of the damaged rebar. The theoretical calculation when the bearing capacity is exhausted gives smaller than the experimental values of bending moments, which ensures the reliability of the calculation of such structures.

For damaged samples without the effect of the load, a deviation was 11 % (Table 4) in the direction of understatement of theoretical values; it also makes it possible to use it in the practice of calculation according to the strain model. For samples that were damaged when loaded, the divergence between the theoretical calculation and experimental values was 18.6...20.9 %. This ratio provides the possibility of using in practice the proposed calculation methodology according to the strain model for samples damaged when loaded, with a sufficient degree of reserve.

The greatest danger of local damage to the reinforcement is in the sudden destruction of samples; however, the theoretical calculation according to the strain model makes it possible to predict this with a sufficiently large margin (approximately 20 %) relative to the experimental result (Table 4). Therefore, the result of calculation according to the strain model can be used for such structures.

Our results can be explained by the influence of the following factors: changes in the ratio of the area of different layers of rebars and the current load on reinforced concrete beams. The existing external thermally-strengthened layer differs in its characteristics from the inner, more plastic layer. Changing these ratios has led to a change in the bearing capacity of samples (Table 2) with the same area of rebars. In subsequent studies, the effect of the load level (Table 3) is superimposed, which also affects the residual bearing capacity of prototypes.

The proposed calculation procedure makes it possible to take into consideration the damage to working rebars and the level of operating load. Such adaptation of the strain procedure (Fig. 3) makes it possible to calculate the stressed-strained state closer to the real operating conditions, compared to other studies [6, 12, 18, 25]. However, it should be noted that the calculation of bending elements in which damage occurs at high loads levels (70 % or more of their bearing capacity) (Table 4) cannot be carried out. The reason for this is the achievement of working reinforcement yield during damage.

It should also be noted that the disadvantage of this study is the type of damage. Damage in the form of a through hole makes it possible to perform a study with an accurate, controlled value of the amount of damage. However, in real structures, such cases are rare. The limitation of this calculation is the cases of other ratios of the external thermally-strengthened layer of reinforcement to the inner one, more plastic. However, for a given case, the proposed calculation procedure can be used to solve practical engineering tasks.

Further research should consider other types of damage: different quantity, size, and type. Such studies can be carried out with fewer variables (e.g., load levels) and associated with a general model of the strain-deformed structural state. However, such studies are dangerous because it is difficult to ensure controlled (and fixed) values of damage, since, in the case of violation of the parameters of the study, premature destruction of structures is possible. In combination with the current load, this poses a danger to the integrity of devices and to the health of researchers. The method in this article is more secure for studies but less consistent with real cases. Extrapolating our results, with point, experimental confirmation of the findings, for other types of damage in reinforced concrete beams could make it possible to increase the safety of operation of these structures.

7. Conclusions

1. Based on the results of experimental data, samples in which the rebar was damaged to the area of the cross-section of control samples showed a lower bearing capacity, by 3.7...30.2 %. This is due to the different characteristics of the outer and inner layers of the reinforcement, and the change in their ratios in the process of damage, as well as the level of load at which the damage was performed.

2. The analysis of plots results showed that the proposed procedure simulates a stressed-strained state close to experimental data and makes it possible to determine the strains of concrete and reinforcement, taking into consideration damage to them. This algorithm with satisfactory accuracy, from 11.0...20.9 % (in the direction of understatement of theoretical data), determines when the bearing capacity of reinforced concrete beams with damage to working rebars when loaded is exhausted.

3. The results of our theoretical studies and their satisfactory convergence with the experimental data (up to about 20 %, in the direction of understatement of theoretical data) makes it possible to apply the proposed procedure for calculating reinforced concrete beams with damage to working rebars as a result of loading.

References

1. Bobalo, T., Blikharskyy, Y., Kopiika, N., Volynets, M. (2020). Influence of the Percentage of Reinforcement on the Compressive Forces Loss in Pre-stressed RC Beams Strengthened with a Package of Steel Bars. Proceedings of EcoComfort 2020, 53–62. doi: https://doi.org/10.1007/978-3-030-57340-9_7
2. Vatulia, G., Berestianskaya, S., Opanasenko, E., Berestianskaya, A. (2017). Substantiation of concrete core rational parameters for bending composite structures. MATEC Web of Conferences, 107, 00044. doi: https://doi.org/10.1051/matecconf/201710700044
3. Blikharskyy, Z., Vegera, P., Vashkevych, R., Shnal, T. (2018). Fracture toughness of RC beams on the shear, strengthening by FRCM system. MATEC Web of Conferences, 183, 02009. doi: https://doi.org/10.1051/matecconf/201818302009
4. Vatulia, G. L., Lobiak, O. V., Deryzemlia, S. V., Verevicheva, M. A., Orel, Y. F. (2019). Rationalization of cross-sections of the composite reinforced concrete span structure of bridges with a monolithic reinforced concrete roadway slab. IOP Conference Series: Materials Science and Engineering, 664, 012014. doi: https://doi.org/10.1088/1757-899x/664/1/012014
5. Bambura, A. M., Dorogova, O. V., Sazonova, I. R., Bogdan, V. M. (2018). Calculations of the eccentriccompressed slender reinforced concrete members applying an «effective» curvature method. Nauka ta budivnytstvo, 3 (17), 10–20.
6. Pavlikov, A., Kochkarev, D., Harkava, O. (2019). Calculation of reinforced concrete members strength by new concept. Proceedings of the fib Symposium 2019: Concrete – Innovations in Materials, Design and Structures. Kraków, 820–827.
7. Khmil, Ye. R., Tytarenko, Yu. R., Blikharskyy, Y. Z., Vegera, P. I. (2021). Improvement of the method of probability evaluation of the failure-free operation of reinforced concrete beams strengthened under load. IOP Conference Series: Materials Science and Engineering, 1021, 012014. doi: https://doi.org/10.1088/1757-899x/1021/1/012014
8. Blikharskyy, Z., Vegera, P., Vashkevych, R., Khmil, R. (2020). Improvement Method of Calculation Reinforced Concrete Beams on the Shear Strengthened FRCM System. System Safety: Human – Technical Facility – Environment, 2 (1), 215–222. doi: https://doi.org/10.2478/czoto-2020-0026
9. Khmil, R., Tytarenko, R., Blikharskyy, Y., Vegera, P. (2020). The Probabilistic Calculation Model of RC Beams, Strengthened by RC Jacket. Proceedings of EcoComfort 2020, 182–191. doi: https://doi.org/10.1007/978-3-030-57340-9_23
10. Kovalchuk, B., Blikharskyy, Y., Selejdak, J., Blikharskyy, Z. (2020). Strength of Reinforced Concrete Beams Strengthened Under Loading with Additional Reinforcement with Different Levels of its Pre-tension. Proceedings of EcoComfort 2020, 227–236. doi: https://doi.org/10.1007/978-3-030-57340-9_28
11. Koteš, P., Vavruš, M., Jošt, J., Prokop, J. (2020). Strengthening of Concrete Column by Using the Wrapper Layer of Fibre Reinforced Concrete. Materials, 13 (23), 5432. doi: https://doi.org/10.3390/ma13235432
12. Klymenko, Y., Kos, Z., Grynyova, I., Maksiuta, O. (2020). Operation of Damaged H-Shaped Columns. Proceedings of EcoComfort 2020, 192–201. doi: https://doi.org/10.1007/978-3-030-57340-9_24
13. Koteš, P., Strieška, M., Brodňan, M. (2018). Long-time measurements of reinforcement due to air pollution corrosion on reinforced girder bridge. 18th International Multidisciplinary Scientific GeoConference SGEM2018, Energy and Clean Technologies, 18 (4.2), 515–522. doi: https://doi.org/10.5593/sgem2018/4.2/s19.067
14. Blikharskyy, Y., Kopiika, N., Selejdak, J. (2020). Non-uniform corrosion of steel rebar and its influence on reinforced concrete elements' reliability. Production Engineering Archives, 26 (2), 67–72. doi: https://doi.org/10.30657/pea.2020.26.14
15. Lipiński, T. (2017). Roughness of 1.0721 steel after corrosion tests in 20% NaCl. Production Engineering Archives, 15 (15), 27–30. doi: https://doi.org/10.30657/pea.2017.15.07
16. Almusallam, A. A., Al-Gahtani, A. S., Aziz, A. R., Rasheeduzzafar (1996). Effect of reinforcement corrosion on bond strength. Construction and Building Materials, 10 (2), 123–129. doi: https://doi.org/10.1016/0950-0618(95)00077-1
17. Alonso, C., Andrade, C., Rodriguez, J., Diez, J. M. (1998). Factors controlling cracking of concrete affected by reinforcement corrosion. Materials and Structures, 31 (7), 435–441. doi: https://doi.org/10.1007/bf02480466
18. Capozucca, R. (1995). Damage to reinforced concrete due to reinforcement corrosion. Construction and Building Materials, 9 (5), 295–303. doi: https://doi.org/10.1016/0950-0618(95)00033-c
19. Zhang, W., François, R., Yu, L. (2020). Influence of load-induced cracks coupled or not with top-casting-induced defects on the corrosion of the longitudinal tensile reinforcement of naturally corroded beams exposed to chloride environment under sustained loading. Cement and Concrete Research, 129, 105972. doi: https://doi.org/10.1016/j.cemconres.2020.105972
20. Chen, F., Jin, Z., Wang, E., Wang, L., Jiang, Y., Guo, P. et. al. (2021). Relationship model between surface strain of concrete and expansion force of reinforcement rust. Scientific Reports, 11 (1). doi: https://doi.org/10.1038/s41598-021-83376-w
21. Cao, J., Liu, L., Zhao, S. (2020). Relationship between Corrosion of Reinforcement and Surface Cracking Width in Concrete. Advances in Civil Engineering, 2020, 1–14. doi: https://doi.org/10.1155/2020/7936861
22. Raupach, M. (2020). Results From Laboratory Tests and Evaluation of Literature on the Influence of Temperature on Reinforcement Corrosion. Corrosion of Reinforcement in Concrete – Monitoring, Prevention and Rehabilitation, 9–20. doi: https://doi.org/10.1201/9781003076957-2
23. Luo, G., Zhang, K., Zhu, W., Chen, T., Yang, X., Yang, S., Xu, Y. (2021). Effect of non-uniform corrosion on the cracking propagation of the RC specimens. Construction and Building Materials, 270, 121460. doi: https://doi.org/10.1016/j.conbuildmat.2020.121460
24. Ahmadi, M., Kheyroddin, A., Kioumarsi, M. (2021). Prediction models for bond strength of steel reinforcement with consideration of corrosion. Materials Today: Proceedings, 45, 5829–5834. doi: https://doi.org/10.1016/j.matpr.2021.03.263

25. Yuksel, I., Sakcalı, G. B. (2021). Effects of reinforcement corrosion on reinforced concrete buildings. Proceedings of the Institution of Civil Engineers - Structures and Buildings, 1–15. doi: https://doi.org/10.1680/jstbu.19.00111
26. Naveen Kumar, V., Daniel Ronald Joseph, J., Ashok, M., Suresh Kumar, M. (2020). An experimental study on assessing the corrosion performance of steel reinforcement for the durability of concrete. IOP Conference Series: Materials Science and Engineering, 989, 012025. doi: https://doi.org/10.1088/1757-899x/989/1/012025
27. Huang, L., Ye, H., Jin, X., Jin, N., Xu, Z. (2020). Corrosion-induced shear performance degradation of reinforced concrete beams. Construction and Building Materials, 248, 118668. doi: https://doi.org/10.1016/j.conbuildmat.2020.118668
28. Chen, H.-P., Nepal, J. (2020). Load bearing capacity reduction of concrete structures due to reinforcement corrosion. Structural Engineering and Mechanics, 75 (4), 455–464. doi: https://doi.org/10.12989/sem.2020.75.4.455
29. Lobodanov, M., Vegera, P., Khmil, R., Blikharskyy, Z. (2020). Influence of Damages in the Compressed Zone on Bearing Capacity of Reinforced Concrete Beams. Proceedings of EcoComfort 2020, 260–267. doi: https://doi.org/10.1007/978-3-030-57340-9_32
30. Selejdak, J., Urbański, M., Winiarski, M. (2018). Assessment of a steel bridge corrosion degree. E3S Web of Conferences, 49, 00098. doi: https://doi.org/10.1051/e3sconf/20184900098
31. Sun, B., Xiao, R., Ruan, W., Wang, P. (2020). Corrosion-induced cracking fragility of RC bridge with improved concrete carbonation and steel reinforcement corrosion models. Engineering Structures, 208, 110313. doi: https://doi.org/10.1016/j.engstruct.2020.110313
32. Belletti, B., Vecchi, F., Bandini, C., Andrade, C., Montero, J. S. (2020). Numerical evaluation of the corrosion effects in prestressed concrete beams without shear reinforcement. Structural Concrete, 21 (5), 1794–1809. doi: https://doi.org/10.1002/suco.201900283
33. Kos, Ž., Klimenko, Y. (2019). The development of prediction model for failure force of damaged reinforced-concrete slender columns. Tehnički vjesnik, 26 (6), 1635–1641. doi: https://doi.org/10.17559/tv-20181219093612
34. Kotes, P., Strieska, M., Brodnan, M. (2018). Sensitive analysis of calculation of corrosion rate according to standard approach. IOP Conference Series: Materials Science and Engineering, 385, 012031. doi: https://doi.org/10.1088/1757-899x/385/1/012031
35. Turchyn, B. R., Blikharskyy, Z. Z., Vegera, P. I., Shnal, T. M. (2017). Research metodology of reinforced cocrete beams with damage obtained under loading. Visnyk natsionalnoho universytetu «Lvivska politekhnika». Seriya: Teoriya i praktyka budivnytstva, 877, 212–217.
36. SNiP 2.03.01-84*. Betonnye i zhelezobetonnye konstruktsii (1989). Moscow: TSITP Gosstroy SSSR, 80. Available at: https://files.stroyinf.ru/Data2/1/4294854/4294854677.pdf
37. DBN V.2.6-98:2009. Konstruktsiyi budynkiv i sporud. Betonni ta zalizobetonni konstruktsiyi. Osnovni polozhennia (2011). Kyiv: Minrehionbud Ukrainy, 71. Available at: http://kbu.org.ua/assets/app/documents/dbn2/110.1.%20%D0%94%D0%91%D0%9D%20%D0%92.2.6-98~2009.%20%D0%9A%D0%BE%D0%BD%D1%81%D1%82%D1%80%D1%83%D0%BA%D1%86%D1%96%D1%97%20%D0%B1%D1%83%D0%B4%D0%B8%D0%BD%D0%BA%D1%96%D0%B2%20%D1%96%20%D1%81%D0%BF%D0%BE%D1%80%D1%83%D0%B4..pdf
38. EN 1990:2002. Eurocode - Basis of structural design (2002). Brussels: European Committee for Standardization (CEN), 87.
39. DSTU B V.2.6-156:2010. Structures of buildings end erections. Concrete and reinforsed concrete snructures with heavy weight structuralconcrete. Design rules (2011). Kyiv: Minrehionbud Ukrainy, 118. Available at: https://dwg.ru/dnl/9603