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Investigation of defective reinforced concrete beams with obtained damage of compressed area of concrete

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Abstract

In the building industry, it is a frequent cause of damage to elements at different stages: during transportation, operation, installation, etc. Since replacing an element is not always possible due to various circumstances, it entails significant financial losses, logistics, and others. For this reason, the expediency of studying the effect of damage on the bearing capacity of reinforced concrete elements is growing. This effect is dependent on its type and has significant variability. In the case of the combination of the defect and damage in reinforced concrete elements, the complexity of the research of this element increases significantly. In this article is discussed: a review of damaged reinforced concrete elements; researching the influence of the damage and additional factors on the element; developed testing methodology for bending reinforced concrete elements with damage to concrete in a compressed zone with insufficient reinforcement, when performing damage to the action of the load and during the action of the load, is presented; the influence on the deformability and bearing capacity of the variability of damage on the sample with insufficient reinforcement is reflected, taking into account the factor of change in the load at which the damage is performed; a comparison is made of the dependence of the change in the actual height of the compressed zone on the change in the load on the elements; implementation of conclusions on the result of the study.

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1. Introduction

Every year, there is a growing tendency to use the building and structures for new purposes, which leads to check design solutions. In such cases, there is a need to analyze the bearing capacity of damaged structures during inspections. Damage can occur at various stages of using an element in structures: transported, installed, operated, and others. For this period, according to the current standards, the residual bearing capacity is determined by the equivalent element method. Thus, the strength of the reduced cross-section is defined (the damaged part is folded back). This calculation excludes the zones that perceive the loads but are located in plane damage.

Nowadays, studies of the effect of damage on the residual strength of elements are constantly increasing, taking into account their expediency. However, the issue of the residual bearing capacity of the damaged reinforced concrete element is broadly not disclosed, which is due to a large amount of variability in the influence of various damages and defects, as well as their combinations.

2. Aims

Carry thought of experimental studies of the effect of damage in the compressed zone on the bearing capacity of reinforced concrete beams with a defect in the form of an insufficient area of tension reinforcement.

Research methods consist of experimental tests of reinforced concrete beams with a defect (insufficient cross-section of the tension reinforcement) and damage (concrete cuttings in the compressed zone) to the action of the load. Damage is performed in the middle of the span of a reinforced concrete beam.

3. Literature review

The results of studying and researching the issue of the influence of damage on a reinforced concrete element is highlighted in several scientific works. The effect of the damages in the shear span of the one-span RC beams was considered (Klymenko and Polianskyi, 2019); the variable factor was the depth of damage, the angle of damage, and the parameters of the shear span. The critical value, which affects the deformability of concrete and reinforcement, is the parameters of the shear span. With identical combinations of factors (depth of damage and angle of damage), the percentage increase in the ultimate deformations of the reinforcement reached 174%, with a change in the shear span (Blikharskyy and Selejdak, 2021). RC structure sometimes suffers from internal defect caused by inferior construction or from internal damage caused by deterioration. In this study, post-peak behaviors of those beams were investigated both experimentally and analytically. This case is hazardous and difficult to make the diagnostic and further repair (Blikharskyy et al., 2018).

The deterioration of concrete strength and Young's modulus, the rock pocket and breaking of lateral confinement caused by alkali-silica reaction (ASR), were simulated as examples of internal damages (Kobayashi et al., 2007). Precast concrete frame structures with grouted sleeve connections are widely used.

An experimental study was conducted investigating the seismic performance of precast concrete frame structures having backflow defects in their grout sleeves (Li et al., 2021). The aim of study (Özmen et al., 2021) is to analyze the structural behavior of buildings planed for demolition by using explosive materials and demonstrating the effect of structural faults on the demolition process. In this context, the effect of structural defects on structural behavior is investigated under explosive based demolition for a typical RC framed building model.

Very important to determine the behavior and stress-strain state of different types of rebar with a defect (Blikharskyi and Maksymenko, 2021). Especially need to investigate the possibility of occurrence these defects during all time of exploitation (Blikharskyy et al., 2021a; Macek et al., 2020). The study of the damage influence in joist slabs (Semko et al., 2018) also demonstrates a significant effect of defects on the deformability of concrete and reinforcement and their joint work. The effect of the loss of the concrete body and corrosion of reinforcement up to 50% shows a significant increase in tensile stresses of the reinforcement, more than two times. As a result, it was proposed to carry out the habitation with a steel profile.

It should also be noted the work in the direction of the influence of damage on reinforced concrete elements: (Voskobiynyk et al., 2017; Blikharskyy et al., 2021c) where the emphasis is on the joint effect of defect and damage with the formation of be-axial bending; (Klymenko et al., 2020), the paper considers the result of modeling corner damage in a column (Labocha and Paluszyński, 2021), where a significant effect is produced by damage with a loss of 2.5% of the concrete cross section, an increase stresses in the concrete on the 10% and in the reinforcement on the 43%, damage at level of loss 10 % of the cross-section of the column leads to an increase in stresses in the concrete on 27% and in the reinforcement on 58%; Authors study the influence of damage on the T-beam when taking into account three factors with their prioritization.

The article (Vegera et al., 2021) reports the improved and verified procedure for calculating reinforced concrete beams affected by damage to stretched reinforcement when loaded. The proposed calculation provides a new approach that makes it possible to determine the residual bearing capacity of structures more accurately and increases the safety of their operation. Author (Lobodanov et al., 2021) presents the results of reinforced concrete beams damaged at the compressed fiber. That provides an overview of the influence of different types of damages in the compressed zone on the bearing capacity of reinforced concrete beams. The paper develops a nonlinear strength-deformation model of a rebar structure (Karpyuk et al., 2018; Kopiika et al., 2022, Radek et al., 2020). An investigated assessment algorithm was applied for cross-sections of reinforced concrete elements under difficult stress conditions. The article (Karpiuk et al., 2021) is about the cracking process and the destruction of test beams. Also, the mathematical models of the crack opening width and the projection length of a dangerous inclined crack were obtained. The prestress level in the working reinforcement has the most significant effect on the bending moment of cracking.

Studies of the technical condition of the structural elements, establishing the causes of damage, and evaluating the possibility of eliminating the root cause of the defects are essential for historical buildings (Chernieva et al., 2021). Also, this paper evaluates the problem of the development of cracks that appear due to the shearing of walls. An experimental program has been conducted to study the crack width variation along the cover depth in concrete prisms reinforced with a central ribbed bar and smooth bar, by varying the concrete cover depths. A surface crack width calculation model has been developed, considering both the strain difference and the effect of the nonuniform crack face along the concrete cover depth (Naotunna et al., 2021).

The evaluation results of load-bearing capacity exhaustion of steel-concrete slabs under different loading and stress-strain states are essential for safety exploitation (Vatulia et al., 2020). The obtained results proved the theoretical equations that define the load-bearing capacity of steel-concrete slabs during their destruction over the cross-section and the contact of sheet reinforcement with concrete.

Moreover, authors (Lobodanov et al., 2019) are aware that deformability and bearing capacity depend on the damage of an element. The thinning of the concrete cover of the reinforcement may lead to its corrosion, which must be considered in actual practice. That is why investigation in both fields of study as well as studies in the field of protection of reinforcement against corrosion must be continued simultaneously as they are strongly connected and are same importance for effective implementation in practice. Theoretical research of the corrosion distribution along the cross-section of the steel bars is widely researched (Raczkiewicz et al., 2021; Blikharskyy et al., 2020; Blikharskyy et al., 2021b, Lipiński, 2021) and proposed the mathematical approach to their corrosive process modeling.

The use of nondestructive testing (NDT) methods for the condition assessment of reinforced concrete structures is increasing due to the various advantages of NDT compared to traditional approaches, such as qualitative visual inspections and destructive testing protocols (Lacroix et al., 2021). Nevertheless, there remains some uncertainty over how to develop appropriate and cost-effective assessment procedures that account for the inherent advantages and disadvantages of various available NDT tools and technologies. Paper (Chow et al., 2021) presents a framework for automated defect inspection of the concrete structures, consisting of data collection, defect detection, scene reconstruction, defect assessment, and data integration stages. A mobile data collection system, comprising a 360° camera and a digital Light Detection and Ranging (LiDAR), is developed to simplify data acquisition of image and three-dimensional spatial data while users traverse complex indoor environments. The nondestructive inspection of concrete structures is indispensable for ensuring the safety and reliability of aging infrastructures. Ultrasonic waves having a frequency of tens of kHz are frequently used to reduce the scattering attenuation due to coarse aggregates (Ohara et al., 2021).

All these articles show the importance and necessity of investigating the stress-strain state of damaged construction methods of their diagnostic and repair.

4. Experimental part

Experimental reinforced concrete samples of rectangular cross-sections manufactured with 2100 × 200 × 100 mm dimensions. Two concentrated forces simulated the load in 1/3 of the span.

Reinforcement is made in tensile zone Ø12 mm, compressed reinforcement in the zone of maximum shear force - Ø10 mm. Transverse reinforcement is made with smooth reinforcement Ø8 mm, placed in the support zones. The transverse reinforcement was carried out with a significant margin due to an increase in the design cross-section of the reinforcement and a decrease in the pitch between the rods. The reinforcement class is A500C, and the concrete class is C35/45 (Fig. 1).

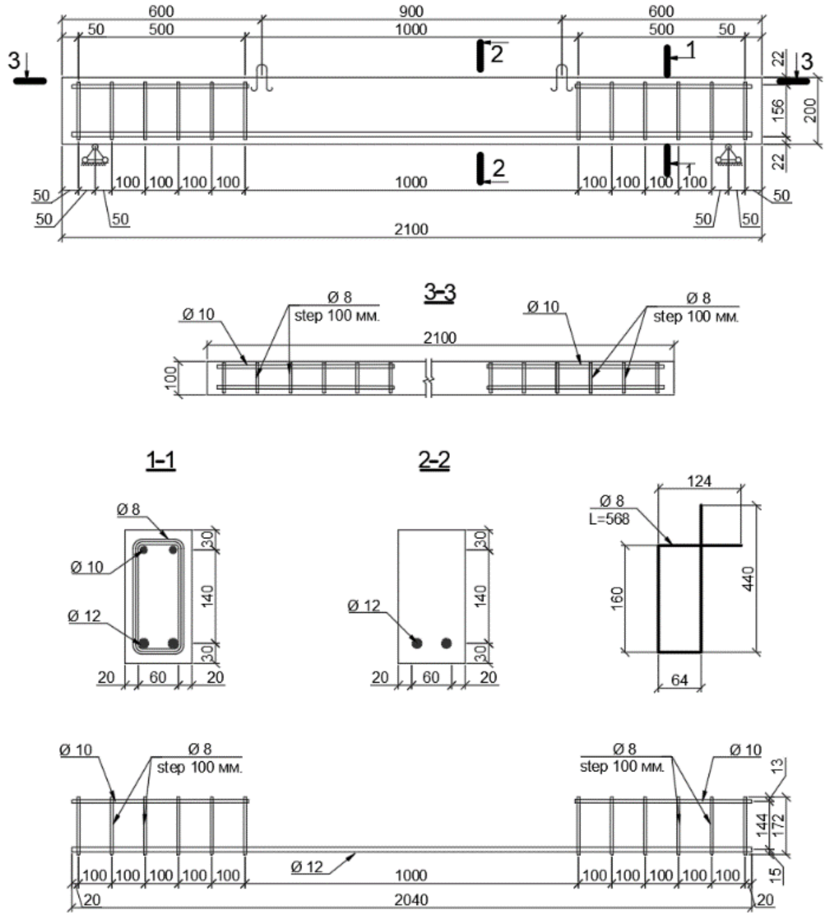

Fig. 1. Structures and reinforcement of samples

The damage was performed in two types (before applying the load):

- first type - damage with a size of 20 × 30 mm (Fig. 2), as an imitation of a concentrated (pointed) damage (1 test with two samples). It simulates point damage from leaking enclosing structures;
- second type - with dimensions of 80 × 30 mm (Fig. 2), as distributed (linear) (2 tests with two samples each). This simulates distributed damage in the case of environmental influences (soaking) along the length.

Experimental samples are divided by the following principles: BC-control beams; BD.20-0-beams with the first type of damage without initial loading BD.80-0-beams with the second type of damage without initial load too, and BD.80-0.3 beams with the second type of damage again but at the level 0.3 M_{dest} from bearing capacity of the control sample.

The damage execution in BD.20-0 and BD.80-0 was done in two stages, the first stage is damage, and the second is surface smoothing. Damage in BD.80-3.0 was performed in four stages, with gradual heaving by 10, 20, 30 mm, and surface cleaning (Fig. 3). Damage to each stage was carried out gradually by taking readings from devices when performing a groove.

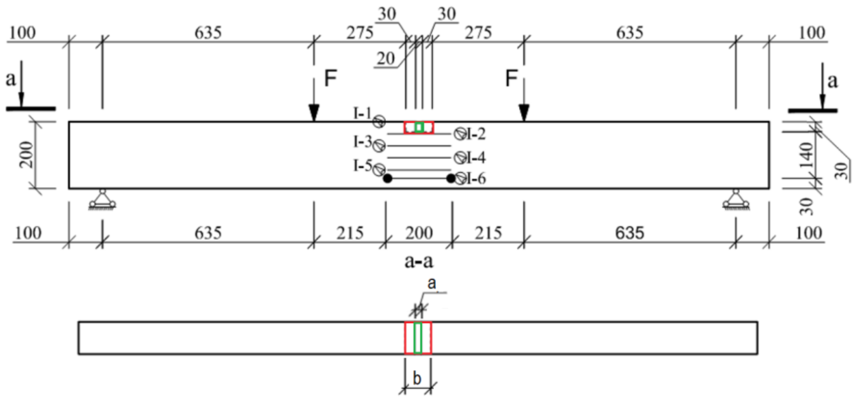

Fig. 2. Layout of dial indicators in the zone of maximum deformation. The damage was performed in two types (before applying the load): a - first type and b - second type

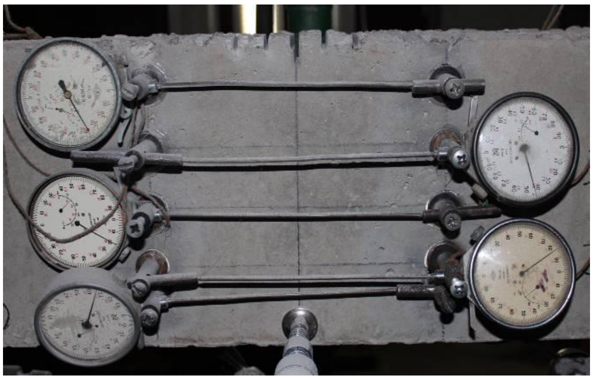

Fig. 3. Diagram showing the end of the 1st stage and the beginning of the 2nd stage of damage BD.80-3.0 under load

The above-indicated variability is due to the experimental establishment of the dependence changing in internal stresses and the bearing capacity of an element on the geometric dimensions of the damage, on a reinforced concrete bending, a rectangular element with a defect.

Placement of measuring devices of deformation is in the central section for getting maximum values. Indicators I1...I5 shows the changing deformations in concrete along with the height of the element. The data obtained from them provide information on the immediate change in the distribution of compression and tension zones in concrete with a fundamental change in the height of the compressed zone (Fig. 2). Indicator I6 displayed changes in deformations from the load in the tensile rebar.

5. Results and discussion

To compare the change in the strain from the load for concrete, we consider the indicator I2 through the formation of cracks and chips from the lower plane of damage to the load application points. Also, indicator I1 cannot serve as an indicator of the stress-strain state of compressed concrete due to the absence of a part of concrete in the plane of the indicator base. This factor makes it impossible to redistribute what was happening in the control beam. Thus, I1 demonstrates changing work of the element in the damaged zone.

The readings for the experimental sample BD.80-3.0 took place after each cutting with a 20 mm pitch, so five impressions were taken for each 10.20.30 mm stage. It was done for measurements change from strain when performing damage, taking into account the influence of changes in the geometric parameters of damage (Fig. 4, 5).

The graph in Fig. 4 reflects the close deformations (of concrete in compression and reinforcement in tension) of damaged elements compared with a control sample. The percentage difference in strain between BD.20-0 and BD.80-0 does not exceed 10%. When comparing the strain of damaged elements BD.20-0 and BD.80-0 with the control BC at a bending moment M=13.97 kNm, in compressed concrete more by 45.9%, in reinforcement by 20%. The graph in Fig. 6 demonstrates the dynamics of changes in the strain of concrete in the zone of pure bending (I5). At the stage of elastic-plastic operation of the element, the strain of concrete working in tension in experimental samples have a slight deviation. With the appearance and opening of cracks, the dependence is lost. The percentage difference between the strain of tensile concrete BD.20-0 and BD.80-0 does not exceed 5.2%.

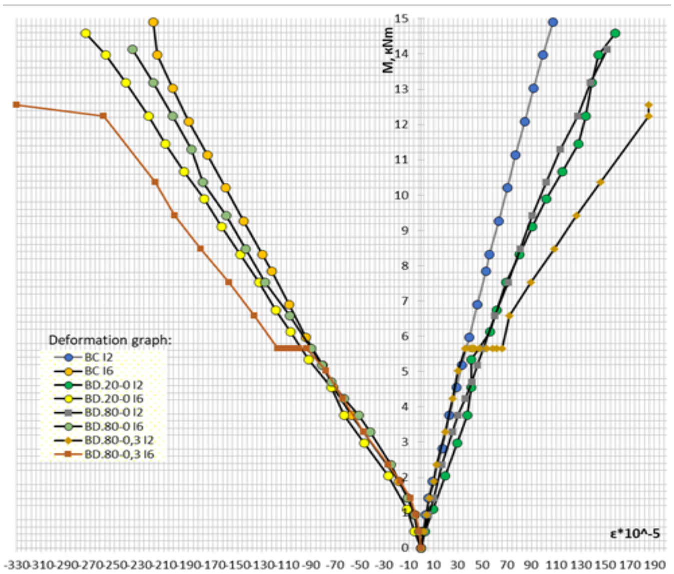

Fig. 4. Graph of averaged strain of reinforcement (left) and compressed concrete (right), experimental samples: BC, BD.20-0, BD.80-0, and BD.80-0.3

At the moments of the opening new cracks, the difference in the readings of the BD.20-0 and BD.80-0 elements increases, but with the stabilization of the elements, the difference in deformations decreases. When comparing the strain of the damaged elements BD.20-0 and BD.80-0 with the control ones at a bending moment M = 13.97 kNm, in concrete, the tensile force is 38.8% higher.

After performing damage of experimental sample BD.80-0.3 a dynamic increase of strain for both concrete and reinforcement took place. At damage of 10 mm on height, a difference in the strain in comparison with an identical loading without damage for compressed concrete (I1) changed on $\varepsilon c.c.0\text{-}1 = 7{,}6\times10\text{-}5$, for tensed concrete (I5) $\varepsilon c.s.0\text{-}1 = 6{,}93\times10\text{-}5$, reinforcement - $\varepsilon r.0\text{-}1 = 7{,}7\times10\text{-}5$.

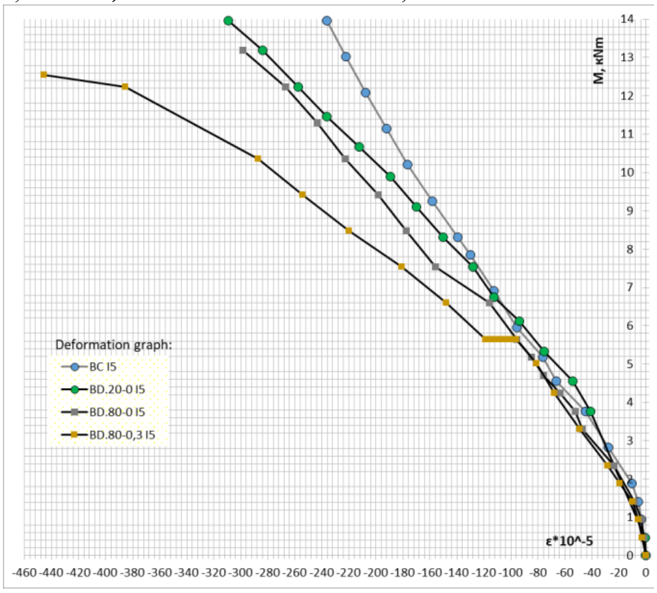

Fig. 5. Graph of average strain of tensile concrete, experimental samples: BC, BD.20-0, BD.80-0 and BD.80-0.3

When comparing the strain of the damaged elements BD.80-0.3 to the control samples BC, at the bending moment M = 12.24 kNm, in compressed concrete values are greater by 116.7%, in tensed concrete - 434.8%, and reinforcement by 35%.

The percentage difference in the strain of BD.80-0.3 to BD.80-0 at M = 12.24 kNm is 45.1% more in compressed concrete, 44.5% in tension concrete, and 27.8% in reinforcement.

With increasing height of the damage the following values were obtained: the difference with increase of 10 mm→20 mm $\varepsilon_{c.c.1\text{-}2} = 10{,}1\times10^{-5}$, $\varepsilon_{c.s.1\text{-}2} = 4{,}95\times10^{-5}$ and $\varepsilon_{r.1\text{-}2} = 4{,}81\times10^{-5}$; at 20 mm→ 30 mm $\varepsilon_{c.c.2\text{-}3} = 12{,}1\times10^{-5}$, $\varepsilon_{c.s.2\text{-}3} = 9{,}9\times10^{-5}$ and $\varepsilon_{r.2\text{-}3} = 10{,}6\times10^{-5}$; at 0 mm→30 mm $\varepsilon_{c.c.0\text{-}3} = 29{,}8{,}1\times10^{-5}$, $\varepsilon_{c.s.0\text{-}3} = 21{,}8\times10^{-5}$ and $\varepsilon_{r.0\text{-}3} = 23{,}1\times10^{-5}$.

The dynamics of changes in strain at the moment of damaging sample BD.80-0.3 shows a gradual increase of the difference in strain of compressed concrete between steps 7.7×10-5 → 10.1×10-5 → 12.1×10-5 with increase of a damage height 10 → 20 → 30 mm (Fig. 4,5).

The damage resulted in a sharp decrease in bearing capacity relative to BC samples. The choice of the bending moment M = 12.24 kNm is caused by the use of the data before reinforcement deforming at the beginning of yielding (Fig. 4,5).

Fig. 6. General view of tested beam BC with common cracks marked

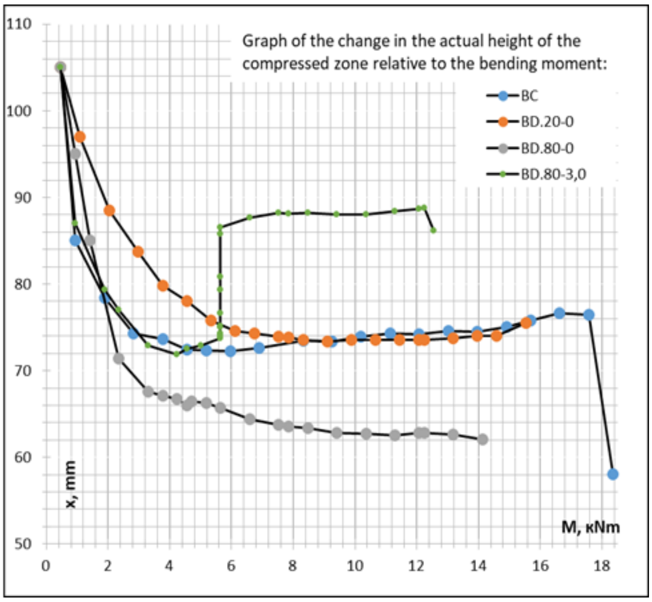

Fig. 7. Graph of the average change in the accurate height of the compressed zone relative to the bending moment

Taking readings of dial indicators I2...I4 made it possible to determine neutral axis in the zone of pure bending with a dependence on the bending moment (Fig. 7). The graph of the actual height of the compressed zone «x» is shown in Fig. 7 demonstrates the internal redistribution of the efforts in the experimental samples BC, BD.20-0, BD.80-0, and BD.80-0.3. RC beam BD.20-0 has a significant similarity in the change in «x» with control samples BC in the second stage of the stress-strain state. This dependence is reflected in Fig. 4, 5. In contrast to samples BD.80-0, the results of BD.20-0 show less deformability of concrete in the zone between damage and reinforcement along with the section height. This is mainly due to the exclusion of a larger zone of concrete at the place of concentration of stresses, respectively. With an increase in the width of the damage, the stress is redistributed into adjacent zones, reducing the bearing capacity of the section along the width of the damage.

Experimental samples BD.80-0 have a difference in the dynamics of changes in «x» due to an increase in geometric dimensions by four times of damage from BD.20-0. Increasing the width of the damage leads to displacement and an increase in the stress concentration zone. Accordingly, there is a rapid loss of the actual height of the compressed zone in the first stage of the stress-strain state with the absence of a zone of relative stability «x» inherent in the second stage, which can be seen in BC, BD.20-0, BD.80-0.3 see Fig. 7.

Reinforced concrete beams BD.80-3.0 show identical dynamics of «x» change concerning the bending moment to failure. When damage is performed, «x» increases. After damage, «x» is relatively stable in the third stage of the stress-strain state. Since the effect of the defect excluded significant areas of concrete from the joint work of normal cracks, there was no possibility of redistribution of internal stresses during damage. The result is a significant loss of the bearing capacity of the element.

The presence of a defect in the insufficient cross-section of the tensile reinforcement leads to a greater deformability of the reinforcement relative to the compression concrete.

This type of defect leads to the early opening of cracks and their significant propagation in the zone of pure bending, leading to the exclusion of a significant height from the cross-section of concrete from joint work (Fig. 6). Cracks propagate into the upper zone of concrete, which leads to compression. Respectively, the cracks restrain the lower zones of concrete, which are compressed by neighboring zones and have minimum compression values. The opposite physical process takes place before prestressing but with a similar effect.

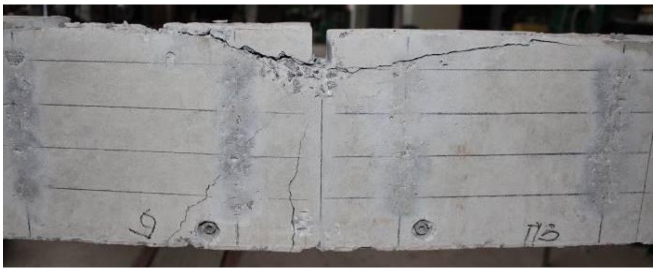

Fig. 8. Display of generated cracks and chips in beams BD.20-0

In the presence of damage 20×30 mm, a similar opening of normal cracks occurred, as in samples BC, see Fig. 6. However, due to the presence of damage, there was a redistribution of internal stresses in the compressed zone, around the damage with the formation of cracks, and then trapezoidal chips, see Fig. 8. Accordingly, a concentration zone of concrete working in compression has formed around the damage and stopped the spreading of cracks.

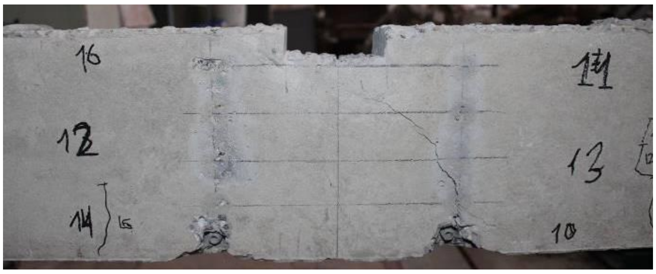

Fig. 9. Display of formed cracks in beams BD.80-0

In the presence of damage 80 × 30mm, a similar opening of normal cracks took place, as in samples BC (see Fig. 7) after the first stage of the stress-strain state. In the future, a similar effect did not occur with forming a compressed zone, which would be relatively non-variable with increasing load, due to a significant loss of zones that perceived the concentration of compressive stresses. A vivid demonstration of this is the absence of cracks and chips directed from the lower plane of the damage, as shown only in Fig. 8,9.

When performing damage for the action of the load, we see the compatible effect as in BD.20-0 and BD.80-0. Significant opening of normal cracks is typical for samples with a defect. Fragmentary zones of concrete from joint work in the zone of concrete working in compression are excluded.

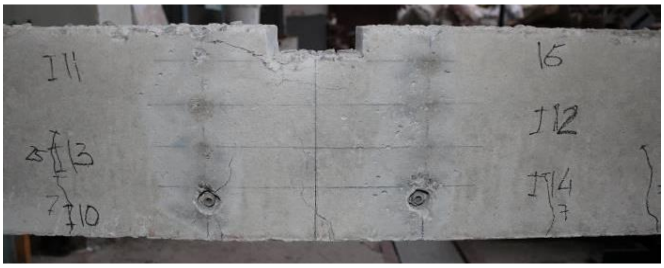

Fig. 10. Display of generated cracks and chips in beams BD.80-0.3

When the damage was performed, the cracks were partially closed with an increase in «x» (see. Fig. 7). Since the element already had deformations during the execution of damage, a partial redistribution of internal forces to neighboring zones took place. However, due to the greater deformability of the reinforcement relative to compressed concrete, the closing effect and an increase in «x» continued until the zones that received stress by fiber concrete by deformations of the limiting values ε_{cu1}, ε_{cu2} were reached. As a result, the formation of cracks and chipping occurred at the damaged Fig. 10.

6. Summary and conclusion

Investigation of the operation of damaged elements with the presence of a defect in an insufficient cross-section of the working rebar, when damage is performed, the load is deported:

- the percentage difference in maximum strain between BD.20-0 and BD.80-0 does not exceed 10%. When comparing the strain of damaged elements BD.20-0 and BD.80-0 with the control BC at a bending moment M=13.97 kNm, in concrete more by 45.9%, in reinforcement by 20%;
- damage with dimensions 80×30mm, as opposed to 20×30mm, significantly reduces the effect of redistribution of stress concentration to adjacent zones from damage, thereby significantly weakening the section along the entire width of the damage;
- damage with dimensions 80×30mm has a dynamic loss of the actual height of the compressed zone at the beginning of the second stage of the stress-strain state and a further gradual decrease in the actual purity of the compressed zone;
- due to the redistribution of internal stresses in the damage zone, trapezoidal cracks are formed beginning in the lower damage zone, followed by the formation of chips;
- investigation of the operation of damaged elements with the presence of a defect in an insufficient cross-section of

the working rebar, when damage is performed for the action of the load, the following are deported;

- when comparing the strain of damaged elements BD.80-0.3 with control samples BC at a bending moment of M=12.24 kNm, in compressive concrete more by 116.7%, in tension concrete by 434.8% in reinforcement by 35%;
- the dynamics of changes in strain during exhalation damage in BD.80-0.3 demonstrates a gradual increase in the difference in the strain of compressed concrete between stages $7.7x10^{-5} \rightarrow 10.1x10^{-5} \rightarrow 12.1x10^{-5}$ with increasing height damage 10 → 20 → 30 mm (Fig. 5.6);
- the percentage difference in strain BD.80-0.3 to BD.80-0 at M=12.24 kNm is 45.1% more in compressed concrete, 44.5% in tension concrete and 27.8% in reinforcement;
- a common effect occurred when executing damage for load actions as in BD.20-0 and BD.80-0. Significant opening of normal cracks is characteristic of samples with a defect. Fragmentary zones of concrete are excluded from joint work in the zone of concrete working in compression.

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钢筋混凝土受压区损伤后缺陷钢筋混凝土梁的研究

關鍵詞
弯曲元件
钢筋混凝土梁
损坏
缺陷
承载力。

摘要
在建筑行业中，在运输、运行、安装等不同阶段，经常会导致元件损坏。由于各种情况，更换元件并不总是可行的，因此会带来重大的经济损失、物流等. 出于这个原因，研究损伤对钢筋混凝土构件承载能力的影响的权宜之计正在增长。这种影响取决于其类型并且具有显着的可变性。在钢筋混凝土构件的缺陷与损伤相结合的情况下，该构件的研究复杂性显着增加。在这篇文章中讨论的是：受损钢筋混凝土构件的回顾；研究损伤和附加因素对元件的影响；介绍了在对载荷作用和载荷作用期间进行破坏时，在钢筋不足的压缩区域弯曲钢筋混凝土构件并损坏混凝土的开发测试方法；考虑到发生损伤时的载荷变化因素，反映损伤变化对钢筋不足样品的变形能力和承载能力的影响；比较压缩区实际高度的变化与元件载荷变化的关系；对研究结果的结论的实施。