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PRODUCTION ENGINEERING ARCHIVES 2023, 29(3), 298-303

PRODUCTION ENGINEERING ARCHIVES

ISSN 2353-5156 (print)
ISSN 2353-7779 (online)

Exist since 4th quarter 2013
Available online at https://pea-journal.eu

Bearing capacity of reinforced concrete beams with and without damages of rebar

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Article history
Received 02.03.2023
Accepted 12.06.2023
Available online 11.09.2023

Keywords
design of RC beams
damage of reinforcement
RC production
experimental studies

Abstract
The article presents the results of the bearing capacity of reinforced concrete beams with and without damages of internal reinforcement. One of the main elements of the production of the reinforced concrete industry is beams. The analysis of the experimental tests showed that the bearing capacity of reinforced concrete beams with damaged tensile main reinforcement decreases according to control undamaged samples due to the reduction of the reinforcement cross-section. However, the bearing capacity of reinforced concrete beams with tensile main reinforcement Ø20A500C, damaged to the cross-section area equal the rebar Ø16mm is more on 3.7… 24.0% than the bearing capacity of reinforced concrete beams with undamaged Ø16mm rebar. This is due to the non-uniform material properties of used thermally strengthened reinforcement A500C. When during testing the tensile main reinforcement is damaged by drilling a hole, the most damages occur in the core with lower physical and mechanical characteristics. In contrast, the outer thermally strengthened layer with bigger physical and mechanical characteristics is damaged to a lesser extent. The analysis of the obtained results shows that during design of reinforced concrete beams with damaged, it is necessary to consider using thermally strengthened non-uniform steel A500C as tensile main reinforcement.

DOI: 10.30657/pea.2023.29.34

1. Introduction

The development of construction methods and principles should be accompanied by experimental research. At the current stage of science and technology, modern materials are widely introduced for design and strengthening constructions (Blikharskyy et al., 2017). Researching the main parameters of reinforced structures, such as strength and deformability, must be carried out constantly using new types and methods of using materials. For example, a study of the strength of reinforced concrete columns, strengthened with a fiber concrete layer installed around the column (shirt)((Koteš et al., 2022). Also, the main parameters for the second limit state are the width of the crack opening and deflection (Blikharskyy et al., 2018; Malíková et al., 2020; Jończyk, 2020).). The study of knowledge about the patterns of crack propagation, the nature of their development, and the possibility of determining the residual bearing capacity based on the crack opening width for reinforced structures are described in the study (Selejdak et al., 2021; Blikharskyy and Selejdak , 2021). However, it should be noted that when pre-stressed elements strengthen structures, the nature of crack propagation changes since, in this case, pre-stressing leads to the closing of cracks (Kovalchuk et al., 2020). One of the most effective ways to restore bearing capacity is the installation of steel jacketing (Nimnim, Al-Bahadli, 2018). However, in this case, it is necessary to consider that the steel jacketing does not provide an opportunity to restore the cross-section, strength of materials, or cover. The most compelling case for using steel jacketing is the strengthening of structures for the action of seismic influences (Sancin et al., 2021). This is one of the most effective strengthening methods for increase seismic resistance of the RC structures (Formisano, et al., 2020). It should be noted that when conducting research, it is essential to perform a full-scale experiment with many variables that would consider possible changes in the structures` operation (Karpiuk et al., 2021). This is especially important when studying the joint operation of different structures (for example, the joint operation of a damaged main beam and a new reinforcement plate) (Krizma, et al., 2017).

It is essential to assess the reliability based on theoretical and experimental studies (Khmil et al., 2021b). The article (Khmil et al., 2021a) is devoted to studying the influence of the load level on the probability of trouble-free operation of undamaged reinforced concrete beams with a rectangular cross-section in case of strengthening with tensile steel reinforcement. The load level's presence simulates the structure's actual operating conditions during strengthening.

Researching reinforced concrete structures is a broad and constantly relevant field of research.

2. Literature review

One of the parameters that precede the formation of defects or damage in reinforced concrete structures is the development of cracks.

An essential parameter in the analysis of crack resistance is the study of their specific origin, growth, and rate of spread (Ostash et al., 2011). Based on this data, the actual stress-strain state of the structure could be studied. One of the best solutions to improve the crack resistance of concrete is adding steel anchor fiber and a hardening accelerator to increase it (Kos et al., 2019b). The appearance of defects (such as cracks) is often related to a concrete structure change (Dorofeyev et al., 2021). It was established that a crack that should be safe, from the point of view of the strength of the large aggregates, can be critical for the cement matrix.

Developing equipment and technologies leads to higher building structure requirements and higher quality production (Ulewicz, et al., 2023). Experimental research requires further theoretical adaptation and development of calculation methodology. The work (Krainskyi et al., 2019) developed and approved the theoretical method for calculating crack opening in the reinforced concrete column, strengthened with a reinforced concrete clamp. A new factor in these studies was the loading level at which the strengthening was applied. The procedure of considering changes in the mechanical characteristics of tensile reinforcement due to damage is proposed in the study (Vegera et al., 2021). This enables a more accurate determination of the bearing capacity of RC bent elements with existing damage to tensile reinforcement, which occurred during operation.

The method of calculating the foundation RC beams on the shear, uniting the piles in a solid foundation structure, is based on the scheme in which the destruction occurs due to the punching of the grillage over the middle support. (Kos et al., 2019a). Confirmation of the proposed method included: the data of the experimental tests, comparison of external applied shear force with the calculating results according to current codes, and modeling of the stress-strain state of the grille in extreme conditions.

In work (Karpyuk et al., 2018) studied the non-linear model of the work of reinforced concrete structures. In the mechanics of reinforced concrete, this allows considering the specifics of the joint work of concrete and internal reinforcement during loading, including failure, under conditions of a general stress state. The model is helpful for practical application due to its possible use for designing or strengthening beams, columns, and girder frames` structures with rectangular cross sections.

The article (Azizov et al., 2020) describes the calculation method of stone beams strengthened with two-side-reinforced concrete slabs. This method includes conditional dividing the beam into stone and reinforced concrete parts and further verifying the deformation compatibility conditions at the junction of both parts of the combined structure. It was established that the degree of joint actions of the stone beam and reinforced concrete slabs depends on the number and diameter of joints, their placement, and most from the characteristics of strength and deformation of the stone beam and reinforced concrete slabs.

When conducting research, the finite element method is increasingly used to model the operation of structures. This method is especially relevant when the structure is subject to a complex combination of loads, and the structure itself is complex (Panchenko et al., 2021). In such cases, when experimental data on the influence of individual factors on the structure is available, their combined effect can be determined using a mathematical model.

Current economic circumstances could be the reason for the change in the functional purpose of structures. In this case, an important aspect is determining the residual bearing capacity of reinforced concrete constructions, considering existing defects and damage. The article (Lobodanov et al., 2019) describes the basic types of damage and defects, research methods of damaged reinforced concrete elements, and the feasibility of using these elements. Investigating damaged reinforced concrete structures is related to high complexity and responsibility in theoretical and practical issues (Vavruš et al., 2021). In such cases, several factors affect the performance of the elements due to the component features of reinforced concrete elements. Authors (Lobodanov et al., 2021) have analyzed data on the influence of damages in the concrete compressed area on reinforced concrete structures' bearing capacity. Experimental studies of reinforced concrete beams with damage to stretched reinforcement, which occur under the action of the initial load and without it, showed significant changes in the stress-strain state of the element (Kopiika et al., 2021). One or five holes are used for modeling local or distributed along the length damages of the reinforcement. In samples with different types of damage, different stress-strain states and residual bearing capacities were determined.

Based on the above sources of information, it could be concluded that experimental tests are an essential step in research, especially in the case of the variable or complex stress-strain state.

Therefore, the study aims to determine the impact of damage cross section of the tensile rebar on the caring capacity of reinforced concrete beams, and reason and the reasons that led to this.

3. Materials and Methods

Six full-size reinforced concrete beams were designed and manufactured in the factory to carry out these studies (Fig. 1). Experimental samples were taken with a length of 2100 mm, width of 100 mm and height of 200 mm. The composition of concrete – C:S:G = 1:1.16:2.5 at W/C=0.375, cement of grade M-500, quartz sand without impurities with size modulus of Mk = 2.00, granite crushed stone of 5 ... 10 mm fractions - 66%, 10 ... 20 mm fractions - 33%.

Beams samples B-1 and B-2 were designed with A500C class reinforcement of 20 mm. In beams BD-3 and BD-4, A500C class reinforcement of 20 mm diameter was damaged with the hole to cross-section equivalent to the diameter of 16 mm (Fig. 2). Beams BC-5 and BC-6 were designed with A500C steel bars of 16 mm diameter. The general appearance of the reinforcement of the beams is described in article (Vegera et al., 2021).

Fig. 1. General view of test samples

Fig. 2. General view of a single hole in the reinforcement of damaged samples BD-3 and BD-4

The experimental samples were tested for type "pure bending" under short-term loading. The loading level was checked with annular dynamometers, which served as hinged support on one side and fixed support on the other side of the beam. The span of the beam was equal to 1900 mm. Loads were applied in the form of two concentrated forces in one-third of the span of the beam using a hydraulic jack and a distribution traverse. The general view of the location of devices and the experimental setup is shown in Fig. 3. Strains of the reinforcement were measured using dial gauges with a sensitivity 0.001 mm. For determining the strains of compressed concrete, two gauges were installed on the upper face of the beams. The gauges were located in the area of "pure bending".

As the damaging method for samples with BD-marking, stepwise drilling of holes was used. At each stage of damage, the change in the increase of strains of the reinforcement, compressed area of the concrete, and concrete strains along the cross-section height were measured. Holes in the rebar were made with a gradual increase: 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, and 5.6 mm.

Fig. 3. General view of experimental stand and location of devices

As a result, the residual cross-sectional area corresponded to the equivalent area of steel bars with a 16 mm- diameter. After the damage was performed, the study continued with further loading the samples until their destruction.

4. Results and Discussion

According to the research program, six samples of reinforced concrete beams were tested. Two of them were control undamaged samples reinforced with single steel bars of Ø20 mm (B-1 and B-2). Next, two samples with Ø20 mm rebar were damaged by 36% from starting cross-section area, that corresponding to undamaged 16 mm diameter (BD-3 and BD-4). Furthermore, the last two samples with undamaged Ø16 mm rebar (BC-5 and BC-6) were as control samples as too.

The strains diagrams of the most compressed concrete fibre and tensile reinforcement of undamaged samples with the reinforcement Ø20 mm (B-1 and B-2) is shown in Fig. 4. It should be noted that all the graphs, including the diagram in Fig. 4, show the average values for both "twin" beams.

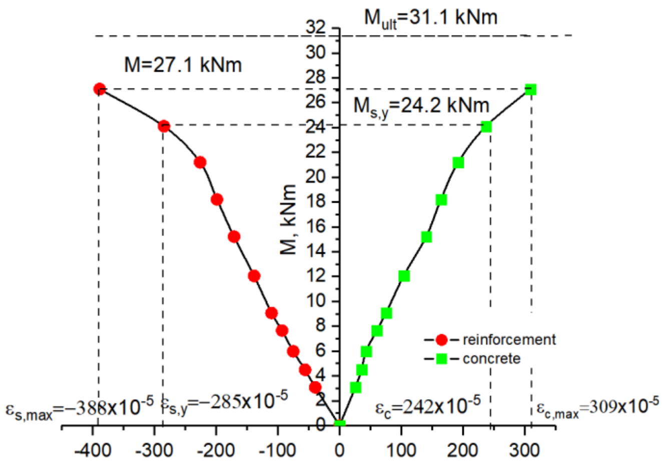

Fig. 4. The average graphs of the strain of tensile rebar (reinforcement) and compressed concrete (concrete) of undamaged beams B-1 and B-2

As seen in Fig. 4, the strains of the tensile reinforcement and the most compressed fiber of the concrete increased smoothly with the same step of increased load.

When the strain in the tensile reinforcement reaches the yielding $\sigma_y = f_y$, which happened at a force of $M_{s,y}$=24.2kNm, the bearing capacity of the beams B-1 and B-2 is exhausted. The strain of the compressed concrete area and tensile reinforcement was observed at this load. The maximum strain was measured at the bending moment *M*=27.1 kNm: in the stretched reinforcement, $\varepsilon_{s,max}=388\cdot10^{-5}$ and in the compressed concrete fiber $\varepsilon_{c,max}=309\cdot10^{-5}$. After it, ultimate concrete strains were reached, and furthermore, the brittle fracture of the most compressed concrete fiber occurred. (Fig. 5) under the force of *Mult*=31.1 kNm.

Fig. 5. General view of a fracture of damaged samples BD-3 and BD-4

We were made the 5.6 mm-diameter hole in the reinforcement of samples BD-3 and BD-4, which were with initial ∅ 20 mm steel bar, that equalled the cross-sectional area of ∅16-mm reinforcement. However, the hole reduces the cross-section of the rebar core while leaving a larger area of the outer layer. It was identified based on experimental data from tested damaged steel bars (Blikharskyy et al., 2021). Accordingly test results, there was drove the strains diagrams (B-3 and B-4) in Fig. 6. There is no clear yield point could be identified.

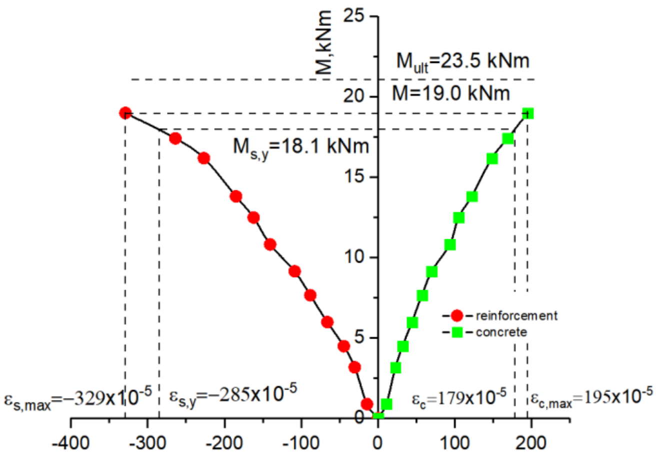

Fig. 6. The average graphs of the strain of tensile rebar (reinforcement) and compressed concrete fibre (concrete) of damaged beams BD-3 and BD-4

The strain of the tensile reinforcement and the most compressed concrete fiber is gradually increased. The bearing capacity of the beam was exhausted at $M_{s,y}$=24.2 kNm when the strain of the tensile reinforcement reached the yield point $\varepsilon_{s,y}=285\cdot10^{-5}$. In addition, the maximum values of the most compressed concrete fiber $\varepsilon_{c,max}=195\cdot10^{-5,}$ and tensile reinforcement $\varepsilon_{s,max}=329\cdot10^{-5,}$ were reached at the loading level *M*=19 kNm.

After the value of M_{ult}=23.5 kNm, the destruction of the beams occurred due to the rupture of the tensile rebar was reached (Fig. 7).

The change in the destruction process for samples could be noted, which is due to the more significant part of the unstrengthen layer and the insignificant part of the hardened part in the residual cross-section of the rebar. In addition, there was no destruction of the concrete compressed fibre, and strains of the most compressed concrete fiber did not reach limit values. This fact could be explained by the localized damage of tensile reinforcement corresponding to the drilled hole. This could also be confirmed by the absence of a clear yield point on the graphs in Fig. 8.

Fig. 7. Destruction of sample BD-3 due to rupture of the rebar

When testing control samples of the 3rd part with tensile reinforcement with a ∅16 mm diameter, the gradual increase in strains of tensile rebar and the most compressed concrete fiber is observed (Fig. 8).

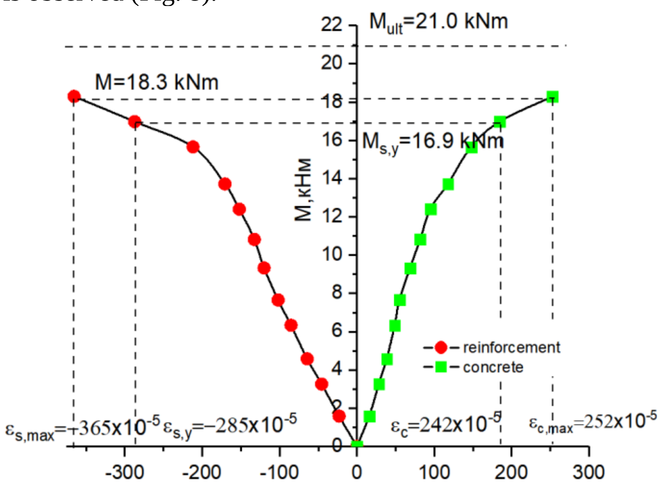

Fig. 8. The average graphs of the strain of tensile rebar (reinforcement) and compressed concrete (concrete) of undamaged beams BC-5 and BC-6

At $M_{s,y}$=16.9 kNm, the strain of stretched rebar, which corresponds to the yield point $\varepsilon_{s,y}=285\cdot10^{-5}$, was reached, and, correspondingly, the bearing capacity was exhausted. After achieving these strains, a sharp increase in the compressed and tensile area could be observed.

At a force of M=18.3 kNm, before removing the testing gauges, maximum strains were recorded in tensile reinforcement - $\varepsilon_{s,max}=365\cdot10^{-5}$ and in the most compressed concrete fiber,- $\varepsilon_{c,max}=252\cdot10^{-5}$. After that, the bearing capacity of the sample is exhausted at M_{ult}=21.0 kNm, due to the brittle destruction of the compressed concrete fibre (Fig. 9).

The summary results of testing samples without initial loading are shown in Table 1.

Table 1. Strength of experimental samples without an initial loading

Marking of samples	Yield point of the rebar		Exhaustion of load-bearing capacity		Deviation of bearing capacity		Deviation of physical destruction values	
	sample	average	sample	average	sample	average	sample	average
B-1	24.9	24.2	32.9	31.1	-	-	-	-
B-2	23.5		29.3		-		-	
BD-3	19.0	18.1	22.9	23.5	21.5	25.2	26.4	24.4
BD-4	17.2		24.1		28.9		22.5	
BC-5	16.3	16.9	20.0	21.1	32.6	30.2	35.7	32.2
BC-6	17.5		22.2		27.7		28.6	

Fig. 9. Brittle concrete destruction of the most compressed fiber of the sample BC-5

In samples BD-3 and BD-4, BC-5, and BC-6, the cross-section area of the tensile rebar, as well as all other parameters (concrete strength, location of frames, etc.), are the same. However, the strength of the samples with damaged reinforcement from ∅20 to ∅16 mm diameter (BD-3 and BD-4) is bigger than for samples with ∅16 mm rebar (BC-5 and BC-6), according to the data from Table 1. This is due to the fact that in damaged samples, the rebar cross section mainly remains a thermally strengthened outer layer. Therefore, the deviation of bearing capacity in damaged samples was 24% on average, and in undamaged samples with the same area of the tensile main reinforcement - 31% on average.

5. Conclusion

Over time, any products of the building industry receive various damages and/or defects. This leads to a change in the stress-deformed state and the character of the exhaustion of the bearing capacity. The bearing capacity of reinforced concrete beams with undamaged tensile main rebar was exhausted due to reaching the yield point by reinforcement. After a gradual increase in the load, ultimate concrete strains were reached, and the compressed area was destroyed. In reinforced concrete beams with damaged rebar, the bearing capacity was exhausted by reaching the yield point of reinforcement. After a further increasing load, the rupture of tensile main reinforcement occurred, whereas no crushing of compressed concrete was observed. This is due to the fact that the damage to the reinforcement was performed in one local place by drilling a hole, which in turn served as a stress concentrator. Reinforced concrete beams with rebar of ø20 mm were reduced to the equivalent cross section area of ø16 mm bars due to damage and had a final bearing capacity 7% bigger than samples with ø16 mm bars without damage. This could be explained that during damaging ∅20 mm reinforcement by making holes, the core of the rebar, which has lower physical and mechanical properties, was damaged to a greater extent. In contrast, the external layer, which is thermally strengthened, with bigger physical and mechanical properties was less damaged.

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钢筋有损伤和无损伤的钢筋混凝土梁的承载力

關鍵詞
RC 梁的设计
钢筋损坏 钢筋混凝土生产
实验研究

摘要
本文介绍了内部钢筋损坏和未损坏的钢筋混凝土梁的承载力结果。 钢筋混凝土工业生产的主要要素之一是梁。 试验分析表明，受拉主筋受损的钢筋混凝土梁的承载力较未受损的对照样有所下降，原因是钢筋截面减小。 然而，受拉主筋 Ø20 A500C、受损横截面积等于 Ø16mm 钢筋的钢筋混凝土梁的承载力比未受损 Ø16mm 钢筋的钢筋混凝土梁的承载力高出 3.7…24.0%。 这是由于所用热强化钢筋 A500C 的材料特性不均匀造成的。 在测试过程中，当受拉主钢筋因钻孔而损坏时，大多数损坏发生在物理机械特性较低的核心部分。 相比之下，具有较大物理机械特性的外热强化层受损程度较小。 对所得结果的分析表明，在有损伤的钢筋混凝土梁设计时，需要考虑采用热强化非均匀钢 A500C 作为受拉主筋。