Investigation of Residual Bearing Capacity of Inclined Sections of Damaged Reinforced Concrete Beams

Klymenko Yevhenii

Odesa State Academy of Civil Engineering and Architecture

Kos Zeljko

University North

Grynyova Iryna

Odesa State Academy of Civil Engineering and Architecture

Polianskyi Kostiantyn

Odesa State Academy of Civil Engineering and Architecture

Abstract

The article reports on the results of the numerical and the laboratory tests to determine the effect of concrete damages near support areas in compressed zone of the reinforced concrete beams on their residual bearing capacity of inclined sections. According to the experimental plan, 15 single-span freely supported experimental samples with dimensions of 100×200×1200 mm made with different artificial damages within the shear span a_v (1d, 2d, and 3d) were tested. The numerical test of prototypes was performed in software complex LIRA-SAPR 2017. The results of laboratory and numerical experiments showed good convergence regarding the bearing capacity, however, the nature of the fracture in samples B11-B14 did not match. Empirical - conducting laboratory experiments on samples using modern methods of measurement; numerical modelling – using software complex LIRA-SAPR 2017; analysis and statistical processing of the obtained research results; comparison of the obtained results; abstraction; generalization; deduction; formulation of the main conclusions and recommendations. The analysis found that the bearing capacity decreases with increased area of damage and shear span. Conducting the calculations in software complex LIRA-SAPR allows to predict the work elements and determine the bearing capacity with good accuracy, but in comparison with the real data there still are some differences in the character of destruction.

Keywords: experimental, beams, damage, residual capacity

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Introduction

During the analysis of literature, it was established that the research strength of the inclined sections was shown in the works of famous local and foreign scientists. However, the study of the strength of the inclined sections in the damaged beams has not been conducted and is currently relevant. In particular, in the future it will be very interesting to study the impact of damages in the compressed zone of concrete in the form of chips with different values of the shear span.

Today, there are a number of methods for calculating reinforced concrete elements under the action of transverse forces. Calculation methods began to develop during the first studies of the operation of reinforced concrete elements, it turned out that the destruction of the samples under study occurs not only along normal cracks, but also along the inclined ones. During experiments with a series of Talbot A.N. (Talbot, 1909) beams, the idea of the operation of a reinforced concrete element after the formation of cracks as a spacer system was proposed.

Reinforced concrete is a relatively durable material and may serve for a long time, the vast amount of concrete structures operated with considerable exploitation terms (Klymenko, 2010). Unfortunately, during its operation, concrete structures definitely undergo deterioration and/or damages, cracking, corrosion of reinforcement, concrete corrosion, mechanical damages (such as chipped concrete), damages from construction errors, damages from exposure to elevated temperatures, damages from accidental effects of freeze-thaw cycles, etc. (Zoran et al., 2015; Lu et al., 2015; Ou and Sun, 2107; Blikharskyi, 2011). Subsequently, the first reasonably appropriate method was proposed, which was based on the so-called "truss" analogy - an analogy between a reinforced concrete element that perceives lateral forces and a diagonal truss (Johnson et al.,1981; Klymenko et al., 2019; Pavlikov et al., 2011; Dorofeev et al., 2010; Zalesov et al., 2002; Voskobiynyk et al., (2011,2016), Garkava et al., 2018; Karpyuk et al., 2016; Vegera, 2016; Bondarenko et al., 2003). According to this method, in a reinforced concrete element, the upper zone is the concrete of the compressed zone, the squeezed brackets are the concrete of the wall, the lower zone is the stretched reinforcement, the truss struts are vertical transverse reinforcement, the extended braces are transverse inclined reinforcement (bends). In the existing national building codes (BS EN 1992-1-1:2004) there are no instructions or guidance on determining residual bearing capacity of damaged concrete structures. That is why theoretical and experimental research and development of methods for its determination were done.

At the Odessa State Academy of Civil Engineering and Architecture a lot of studies of the residual bearing capacity of concrete elements were conducted by Klymenko, Ye.

V. (from 2006 till present) and his PhD students. According to the results of these studies a number of methods to determine residual bearing capacity of damaged concrete columns, beams for normal sections, etc. were suggested (Klymenko and Arez, 2011; Orešković et al., 2018; Klymenko et al., 2013). But studies of residual bearing capacity of damaged beams inclined sections in the compressed area are not carried out and there is no available scientific information in sources.

Nowadays, reinforced concrete has become one of the main materials for the construction of objects of any complexity for a number of its positive features, such as: high strength, fire resistance, density, ability to resist both static and dynamic loads, earthquake resistance, durability. The durability of reinforced concrete structures can reach, under certain favorable conditions, more than 100 years, thereby exceeding even the designated service life during design. But under unfavorable conditions (improper operation, design errors, exposure to an aggressive environment, increased loads on the structure after reconstruction or modernization of equipment, mechanical and various types of damage), on the contrary, lead building structures into emergency conditions and force repairs to be carried out even earlier than this provided by the Ukraine and Croatian building norms. In the conditions of the difficult economic situation of the country in our time, it is very important to extend the life of buildings and structures, since it is much cheaper in comparison with new construction. The topic of the article is directly related to and corresponds to the topic financed by the Ukrainian state for the development of the entire Ukrainian region "Restoration of the performance of reinforced concrete building structures damaged during operation and military activity."

Methodology

The method of evaluation of residual bearing capacity in the software complex LIRA-SAPR 2017, non-destructive method is proposed in this article. At the first stage, the points on coordinates are created, which are later connected and the boundary conditions to nodes in five degrees of freedom are set. At the second stage, the stiffness of the elements is set. Using the "Hardness →Hardness Elements" menu, the "Elemental Hardness" dialog is called. In this window, click on the "Add" button to display the list. Choose the third dialog "Plastic, Volume, Numerical", the type of section - "Volume Limit Elements", and then put a tick on the account of nonlinearity and press "parameters of the material", choose the "law of nonlinear deformation", in our case, it is 14 (piecewise -linear law of deformation), and then data on the characteristics of the material from the received graph of the dependence of "stress-deformation" are introduced. The beams were divided into finite elements in the form of rectangular parallelepipeds with a face dimension of 1 to 2 cm, as well as octal and six-node endpoints in the form of triangular and quadrangular prisms in places where this required the geometry of the sample for modeling the slope of the shelves and the front of the damage.

The laying was given by physically nonlinear spatial eight-node and six-node isoparametric FEs of type 236 - "physically nonlinear universal spatial 8-node isoperimetric Limit Elements " and a metal plate for the transfer of load FEs of type 234, taking into account geometric and physical nonlinearity.

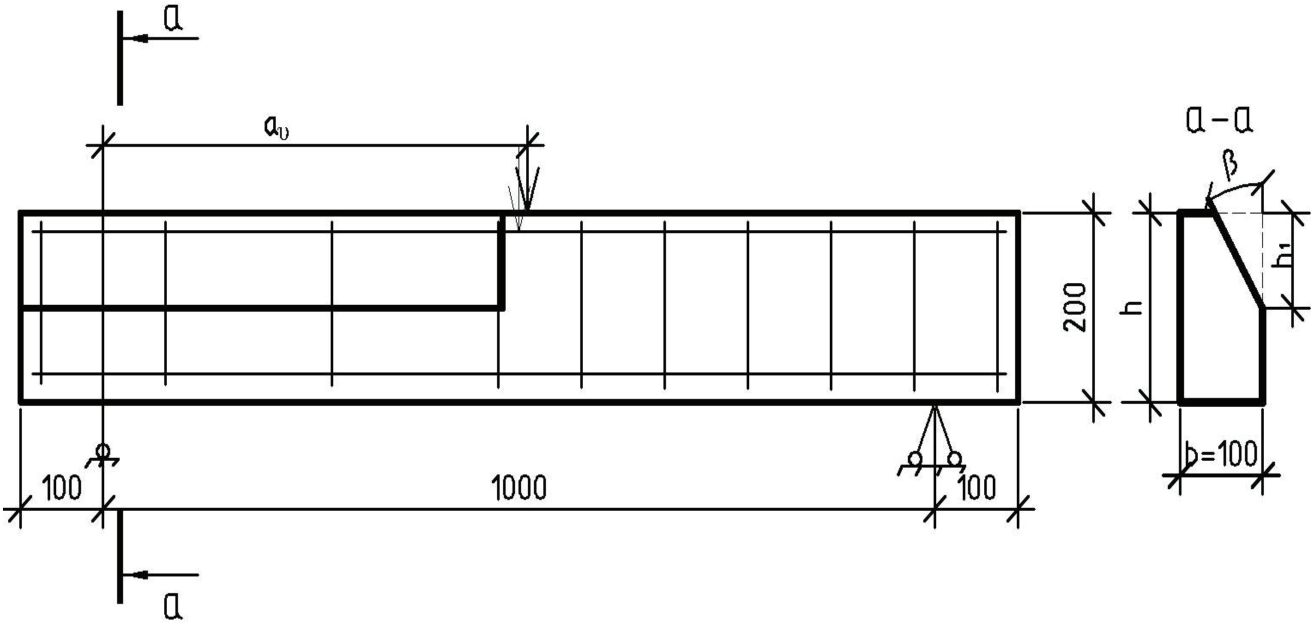
According to the plan of the experiment, 15 one-span reinforced concrete beams of the size 100×200×1200 mm and working span 1000 mm were made and tested. For control samples concrete cubes and prisms were identified, concrete grade used for samples - C25/30; for control samples for reinforcing bars longitudinal working rebars were determined - Ø18 mm of grade A500C, mounting longitudinal and transverse reinforcement in the form of vertical links - Ø6 mm of grade A240C. At the ends of longitudinal working bars reinforcing short-bars are welded to ensure reliable anchoring.

The influence of three factors on the bearing capacity is studied – the shear span a_v (1d, 2d, and 3d), the depth of damage h_1 (0, 50 and 100 mm) and the angle of inclination of the damage β_1 (0˚, 30˚, 60˚). For measuring the strain of bars within the shear span, on the surface of transverse reinforcing bars strain gauges with a base of 10 mm were glued. To measure the deformation of concrete beams on the surface of concrete strain gauges with a base of 50 mm were glued. Sectional beams with dimensions of damages and values of shear span on codes samples are shown in Figures 1, 2 and Table 1.

The laboratory tests of beams were conducted on the universal power plant using hydraulic jacks, which produced the loading. The samples were loaded stepwise in the form of a concentrated force Fu within the relative shear range av with uniformly increasing steps.

Figure 1

Samples characteristics



Source: Author's illustration

Table 1

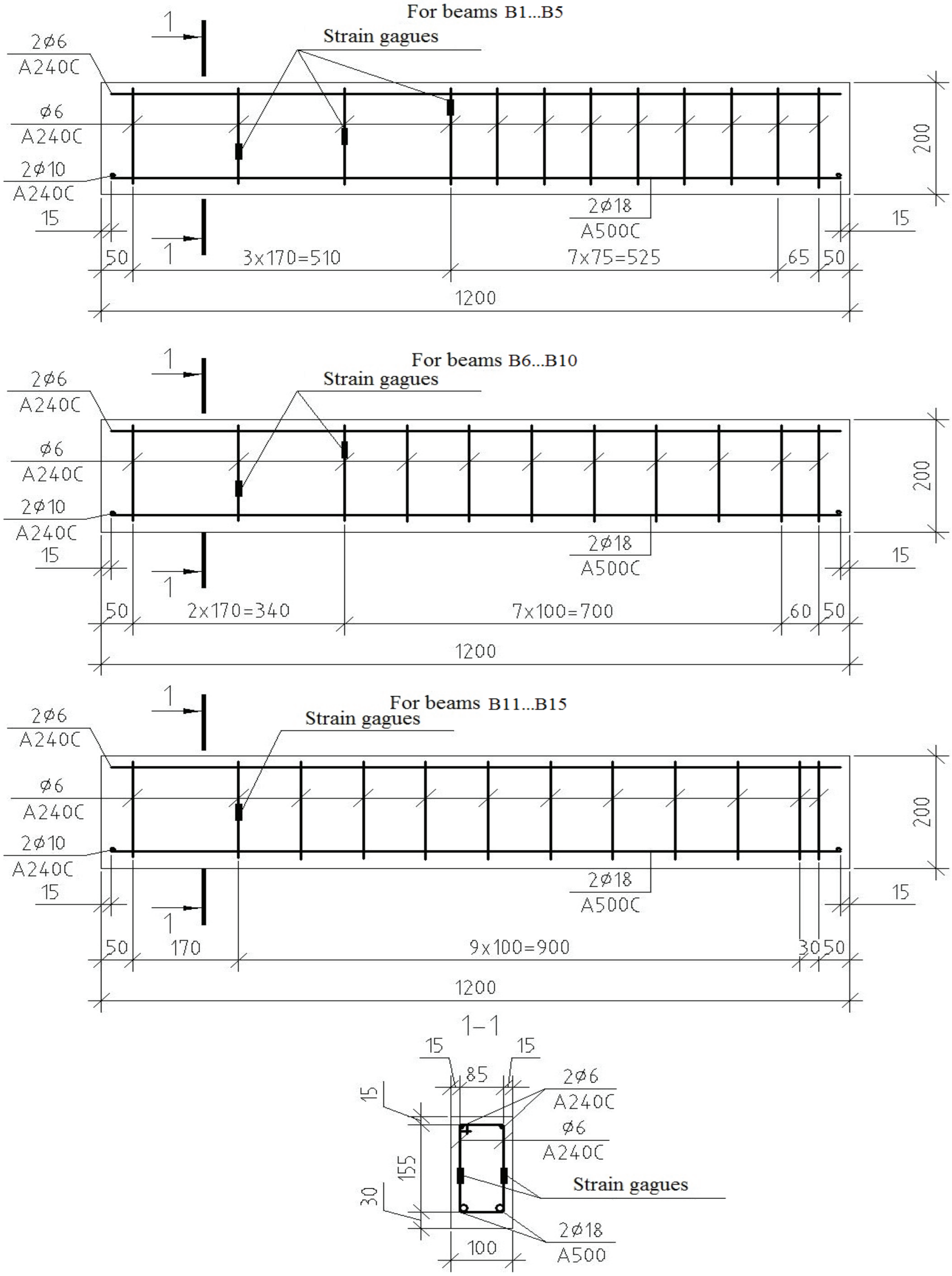
Samples characteristics

Call number	Depths of damage h1, mm	Angle of damage β_1, °	Shear span a_y, °
B1	0	0	3d
B2	50	30	3d
B3	50	60	3d
B4	100	30	3d
B5	100	60	3d
B6	0	0	2d
B7	50	30	2d
B8	50	60	2d
B9	100	30	2d
B10	100	60	2d
B11	0	0	1d
B12	50	30	1d
B13	50	60	1d
B14	100	30	1d
B15	100	60	1d

Source: Author's calculation

Figure 2

Samples reinforcement characteristics



Source: Author's illustration

Results

Results of laboratory tests

For the destruction criterion of beams one of the criteria was accepted: the excessive values of deformation of concrete or reinforcement rebar, the excessive values width of opening cracks, the excessive values beam deflections. The results of the test showed that all prototypes were destroyed on the inclined sections – prevailing action of the transverse force leads to significantly revealed inclined cracks in the samples and concrete was destroyed above the crack top. The bars of the transverse reinforcement began to yield in samples B1...B4, B6...B8, B11. Typical destruction nature of experimental samples is shown in Figure 3.

Figures should be submitted as separate documents in jpg, jpeg or tiff format. Figures should have minimum resolution of 300 dpi. Every figure should have an individual title. Use italic font and capitalize each word (except and, in, of, with, etc.). For example: Macroeconomic indicators.

Breaking load and transverse forces in the experimental samples are shown in Table 2.

Table 2

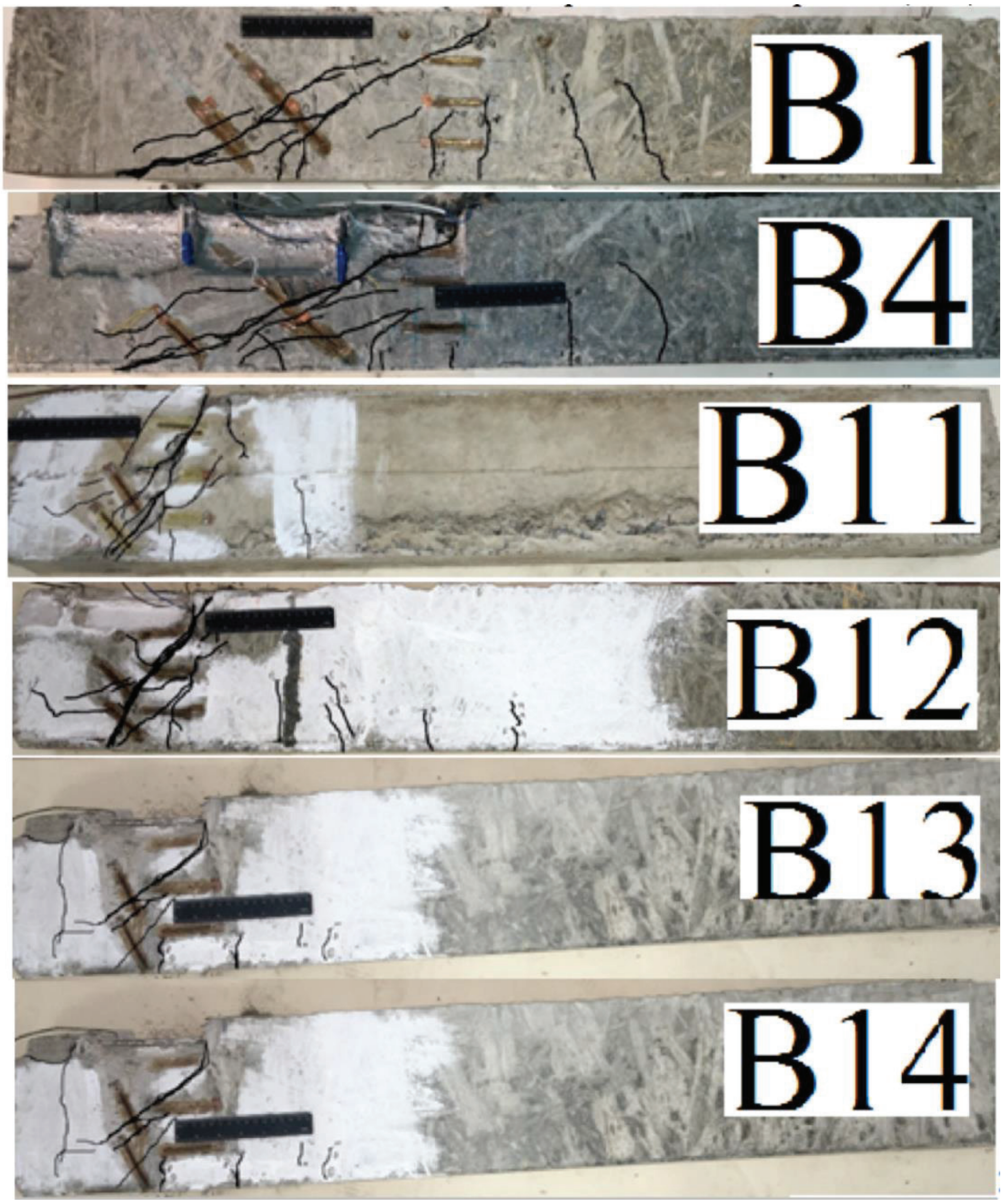
Samples characteristics

Call number	Ultimate force F_u, кN	Ultimate transverse force V_u, кN, °
B1	121,62	59,59
B2	116,62	57,14
B3	98,29	48,16
B4	96,63	47,35
B5	49,98	24,49
B6	133,28	87,96
B7	99,96	65,97
B8	93,296	61,58
B9	73,304	48,38
B10	56,644	37,39
B11	158,27	131,36
B12	149,94	124,45
B13	139,944	116,15
B14	124,95	103,71
B15	106,624	88,5

Source: Author's calculation

Figure 3

Experimental samples destruction nature B1, B4, B11...B14 (laboratory tests)



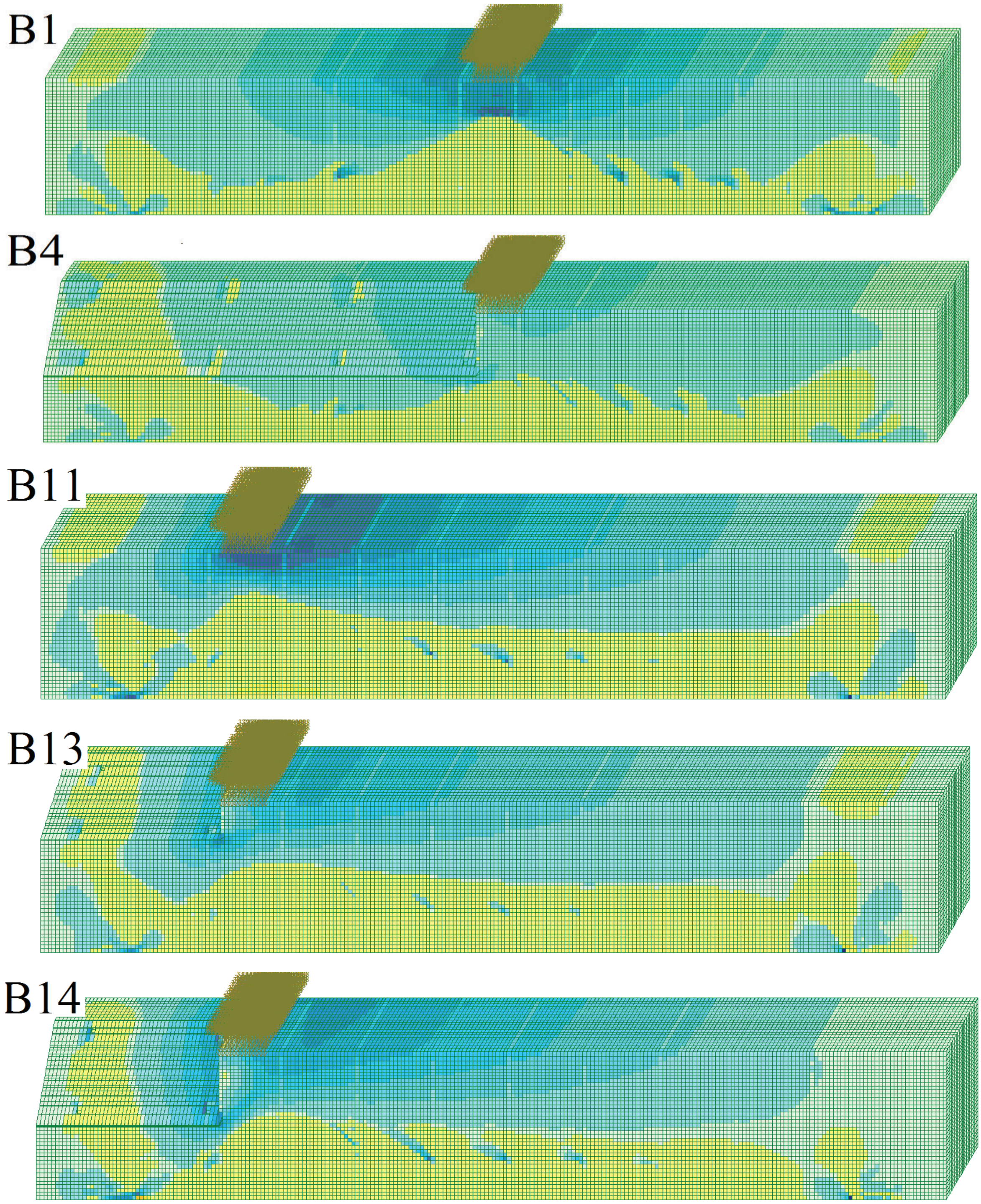
Source: Author's illustration

Results of numerical tests

Numerical tests of the samples were performed on the software complex LIRA-SAPR. This software complex makes calculations based on the finite element method. Its advantage is the ability to perform non-linear steps iterative calculation using the actual stress-strain diagrams "σ-ε" for materials. Criterion of the destruction of experimental samples was taken to achieve one of the conditions: stresses in the compressed concrete reached ultimate values, stresses in the reinforcement reached ultimate values, significant fast-growing movements of the elements of the design scheme.

Figure 4

Experimental samples destruction nature B1, B4, B11...B14 (numerical tests)



Source: Author's figure

Comparative breaking loads and transverse forces in the experimental samples are shown in Table 3.

Table 3

Comparative Breaking Loads and Transverse Forces in the Experimental Samples

Call number	Ultimate force (numerical test) F_u^{lira}, кН	Ultimate force (laboratory test) F_u^{exp}, кН	Ultimate transverse force (numerical test) V_u^{lira}, кН	Ultimate transverse force (laboratory test) V_u^{exp}, кН	Difference $\frac{V_u^{exp}-V_u^{calc}}{V_u^{exp}} \cdot 100\%$, %
B1	111,24	121,618	54.51	59.54	**8.45**
B2	105.6	116,62	51.74	57.14	**9.46**
B3	90.828	98,294	44.51	48.16	**7.59**
B4	88.56	96,628	43.39	47.35	**8.36**
B5	46.2	49,98	22.64	24.49	**7.55**
B6	124,2	133,28	81.97	87.98	**6.83**
B7	121.41	99,96	80.13	65.97	**-21.46**
B8	79,8	93,296	52.67	61.58	**14.46**
B9	78	73,304	51.48	48.38	**-6.41**
B10	49.56	56,644	32.71	37.39	**12.51**
B11	136.5	158,27	113.3	131.36	**13.75**
B12	132.6	149,94	110.06	124.45	**11.56**
B13	124.8	139,944	103.58	116.15	**10.83**
B14	120.9	124,95	100.35	103.7	**3.23**
B15	86.85	106,624	72.09	88.5	**18.54**
Z	65.68				
σ	10.02				
ν	**14.81**				

Discussion

The results of experimental and theoretical studies have made it possible to create a model for the calculation of inclined sections of damaged reinforced concrete beams of rectangular cross section, which can be applied in the practice of construction, reconstruction of buildings and structures, which will allow a rational approach to the issue of reinforcing and repairing damaged flexing elements, knowing their residual bearing capacity. The database of laboratory and theoretical data was supplemented on bearing capacity, deformation, cracks and deflections of reinforced concrete beams. According to the experimental data it can be seen that increasing the shear span a_v (from *1d* to *3d*) leads to reducing the bearing capacity in the samples. Obtained data also show that bearing capacity decreases with an increase in the area of damage. Analysis of the obtained data showed that the character of destruction nature is the same as character of destruction for laboratory tests – prevailing action of the transverse force leads to significantly revealed inclined cracks in the samples and concrete was destroyed above the crack top, the exception is character of destruction for samples B11...B14. In these samples, destruction was due to the destruction of concrete on a support. Also, there is a difference in the yielding of the transverse reinforcement bars – they did not begin to yield in any sample.

According to the obtained experimental data it can be seen that results of residual bearing capacity conducted in the software complex LIRA-SAPR are very close to the results of the laboratory tests. It is evidenced by the coefficient of variation ν = 14,81%.

Conclusion

Conclusion should be based on answering the research questions and/or should include the results of hypothesis investigation. Limitations of the study should be noted and further research directions should be proposed.

The experimental research of determining the residual bearing capacity of inclined sections for damaged reinforced concrete beams of rectangular section was conducted. The results of laboratory and numerical studies showed that with an increase in the depth or volume of damage and an increase in the relative shear span a_v, the value of the bearing capacity in the samples decreased. Conducting the calculations in software complex LIRA-SAPR allows the prediction of the work elements and determination of the bearing capacity with good accuracy, but in comparison with the real data there are still some differences in character of destruction. Operating with the received data we are planning to submit proposals regarding the calculation of residual bearing capacity of damaged reinforced concrete beams inclined sections of rectangular section. In further research, it is planned to develop proposals for calculating the residual bearing capacity of inclined sections of damaged reinforced concrete elements to select a reinforcement method.

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About the authors

Klymenko Yevhenii, Doctor of Technical Sciences, Professor, a head of the department of Reinforced Concrete Structures and Transport Facilities, Odesa State Academy of Civil Engineering & Architecture. The chairman of the specialized scientific council for the defence of graduation thesis for PhD and Doctoral degree at the Odessa State Academy of Civil Engineering and Architecture. Area of scientific interest: technical condition of reinforced concrete and stone structures, definition, forecasting and regulation during the operation of buildings and structures. Member of the editorial boards of leading Ukrainian and foreign (Belarus, Croatia) scientific publications. The author can be contacted at klimenkoew57@gmail.com

Kos Zeljko, PhD, Associate professor at the department of Civil Engineering, University North. Area of scientific interest: building materials, finite element method, load-bearing capacity, damaged reinforced concrete column, mathematical analysis, geotechnics and particularly energy efficiency. Owner of mandates on the base of state: Energy efficiency certifier, Occupational safety expert, Coordinator of occupational safety in civil engineering, Forensic expert in the field of civil engineering, Real estate assessment. He is actively engaged in number of EU funded projects and continuously participating in workshops and training related to education and research. The author can be contacted at zeljko.kos@unin.hr.

Grynyova Iryna, PhD in Technical Sciences, Assistant at the department of Reinforced Concrete Structures and Transport Facilities, Odesa State Academy of Civil Engineering & Architecture. Laureate of the scholarship of the Cabinet of Ministers of Ukraine for young scientists. Area of scientific interest: finite element method, load-bearing capacity. The author can be contacted at Irene.grinyova@gmail.com

Polianskyi Kostiantyn is a post-graduate student at the Odesa State Academy of Civil Engineering and Architecture (Ukraine), Department of Reinforced Concrete Structures and Transport Facilities. He is currently working on a dissertation on “Stress-strain state and the bearing capacity of the inclined sections of damaged reinforced concrete beams”. He also works as a senior teacher at the Donbass National Academy of Civil Engineering and Architecture (Ukraine). Area of scientific interest: connected with the work of damaged element and also high strength concrete. The author can be contacted at kostyapolyanski@gmail.com