

*Experimental data of strength, deformability, and crack resistance of 2,000×200×100 mm reinforced concrete and basalt-concrete beams are given. Longitudinal reinforcement consisted of 2 Ø14 A500C for reinforced concrete beams and 2 Ø14 BFRP (AKB800) for basalt-concrete beams. Transverse reinforcement consisted of 2 Ø3, 4, 5 BpI for reinforced concrete beams and 2 Ø4, 6, 8 BFRP (AKB800) for basalt-concrete beams. Beams were made of heavy concrete of C16/20, C30/35, and C40/50 classes. The experimental beam specimens were tested according to a four-point scheme as loosely supported beams loaded with two concentrated forces. Loading in the series of tests was stepwise increasing, static and low-cycle repeated at high levels of 0.50, 0.65, and 0.80F<sub>ult</sub>. Distance from supports to concentrated forces (shear span), a/h<sub>0</sub>, varied within 1, 2, 3. Experimental beam specimens were made and tested according to the theory of experimental design according to the Box B4, optimal plan D. Comparative analysis of main performance parameters of reinforced concrete and basalt-concrete beams under the action of abovementioned loads was performed.*

*The necessity of these studies was determined by the unsatisfactory convergence of experimental and calculated values of bearing capacity of oblique sections of basalt-concrete beams determined according to existing standard methods.*

*The studies have established the influence of design factors and loading nature on basic parameters of the working capacity of basalt-concrete beam elements in a form of experimental-statistical dependences.*

*These results will form a basis for a physical model of resistance of oblique sections in such structures to external loads. The presented results will significantly supplement the existing database of the operation of beam basalt-concrete structures and will be used in the development of an analytical method for calculating strength, deformability, and crack resistance*

*Keywords: basalt-plastic and steel reinforcement, bearing capacity, static and low-cycle loading*

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# STUDY OF STRENGTH, DEFORMABILITY PROPERTY AND CRACK RESISTANCE OF BEAMS WITH BFRP

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## 1. Introduction

In recent decades, structures with non-metallic composite reinforcement (NCR) are increasingly used in construction practice, especially in special-purpose buildings and structures.

Due to high strength, resistance to chemical and physical corrosion, dielectric and diamagnetic properties, low weight, and low thermal conductivity, NCR is increasingly replacing steel reinforcement. However, the wider use of NCR for reinforcement of concrete structures is constrained by insufficient knowledge of features of their functioning, limited normative support, and small experience in the operation of relevant facilities.

Practice has shown prospects and economic feasibility of using NCR in the road, hydraulic, transport construction, in construction of balk structures, sewage treatment plants, chemical, and food industry facilities. NCR is indispensable in special-purpose buildings and the arrangement of foundations in aggressive soils.

At the same time, prospects for the use of BFRP (Basalt Factory Reset Protection) are determined by the low cost

of main raw materials, basalt fibers due to the worldwide presence of significant reserves of basalt. BFRP has unique physical and chemical properties, in particular, improved chemical resistance to corrosive media compared to glass fiber reinforced plastic (GFRP).

Significant deposits of easily accessible basalt have been explored in the world. A series of plants are already producing high-quality basalt-plastic reinforcement. Production of such reinforcement is less harmful to the environment compared to the steel one.

Study of the load-bearing capacity of structures with basalt-plastic reinforcement in order to accumulate a data bank, improve existing and develop new normative documents that would ensure wider use of such reinforcement in these areas of construction and at special-purpose facilities is an important and urgent problem.

In 1978, the Research and Technological Institute of Concrete and Reinforced Concrete (RTICRC) was one of the first organizations that issued recommendations for calculation of structures with glass fiber reinforcement. In this document, the main application of NCR is reduced to pre-stressed structures. The specified coefficients of operating

conditions make it possible to take into account a decrease in NCR strength properties because of the long-term action of loads and uneven distribution of stresses.

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## 2. Literature review and problem statement

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Paper [1] presents the results of studies of the stress-strain state of concrete structures with glass fiber reinforcement conducted in the Soviet Union until the 1980s. The harmful influence of the aggressive environment, temperature, and long-term operation that decreases their bearing capacity was analyzed in the study. The expediency of NCR application was substantiated by the failure of a protective layer of concrete during 3–10 years of operation in sea structures and during 4–7 years in structures of the chemical industry as a result of intensive corrosion of steel reinforcement. Intensive corrosion of steel reinforcement multiply reduces the standard service life of reinforced concrete structures in such conditions.

Study [2] was taken as a basis in the development of USA and Canada standards for calculation and design of concrete structures with composite reinforcement (CR).

Results of the study on the use of prestressed CR in concrete structures were summarized. However, bearing capacity of oblique sections in structures with CR has remained insufficiently studied.

Diagrams and results of studies [3] show the dependence of CR creep on loading duration and bond with heavy concrete. An overview of normative documents related to the calculation and design of NCR structures is given only for normal sections.

Studies of bearing capacity of concrete structures with conventional basalt-plastic reinforcement performed in 1998–2003 are presented in [4]. Eleven beams of various cross-sections with a span of 750–900 mm were tested. The obtained results were compared with experimental test data for twin beams with steel reinforcement. Specimens with smooth basaltoplastic reinforcement were destroyed because of the insufficient bond of reinforcement with concrete and slippage.

Study [5] was performed in the framework of the development of Italian standards for calculation and design of structures with NCR. The author has made a comparative analysis of basic requirements in many national standards to structures with NCR. As a part of the study, the stress-strain state in a large number of concrete specimens reinforced with CR was mathematically modeled. When conducting the numerical experiment, the author took into account the influence of a large number of variable design factors on bearing capacity. An unsatisfactory convergence of calculated and experimental data was pointed out.

The draft Ukrainian standard (State Standards of Ukraine, SSU) is a re-edition of previously issued Ukrainian standards [6], as well as current standards for the calculation of reinforced concrete structures. The first Ukrainian standards [6] were prepared by taking into account the data of [7]. Analysis of the Guidelines [6] shows that the structures reinforced with CR are calculated in accordance with the current standards of calculation of reinforced concrete structures and a linear diagram of CR deformation during tension is used. This document provides for the use of additional coefficients of working conditions for NCR. However, the magnitude of these coefficients is not standardized for all

boundary states of structures with NCR including calculation of bearing capacity of their near-support sections.

Results of experimental studies of the stress-strain state of continuous beams with various contents of basalt-plastic reinforcement in support zones of multi-span beams are described in [8]. The span zone of experimental specimens had steel reinforcement. The author proposed an improved procedure for the calculation of continuous multi-span concrete beams with mixed reinforcement in a boundary state and with the use of real diagrams of material state. This procedure makes it possible to take into account the redistribution of internal forces between normal support and span sections. However, the study does not reflect the most probable scheme of fracture of experimental elements from punching over the middle support in the form of an inverted trapezoid at a prescribed quantity of transverse steel reinforcement.

Recommendations for designing concrete structures reinforced with NCR are modifications of existing national standards for calculation and design of structures with steel reinforcement. Recommendations for clarifying design factors for the structures reinforced with BFRP are found only in the Guidelines [6], standards [9] supplemented by Annex L, and in recommendations [10].

Studies [11] have shown that basalt-plastic reinforcement (Basalt Factory Reset Protection) can be used as an alternative to steel reinforcement in structures operated in seawater, acid, alkaline, and other environments. However, the design of such structures is constrained by insufficient experimental study and imperfection of existing building codes.

Durability and corrosion resistance of BFRP were studied in [12]. It was established that guaranteed strength of this reinforcement is about 1,300 MPa, modulus of elasticity of 40 GPa and that 72–80 % of the initial strength will be retained after its interaction with concrete or cement mortar for 100 years. A comprehensive long-term model for predicting the strength of BFRP rods was proposed. However, this model must be further experimentally tested for practical purposes.

The behavior of BFRP and concrete beams reinforced with it were studied in a corrosive medium in [13]. The study results have shown that BFRP meets the requirements of CSA 5807-10 in terms of their physical and mechanical properties. In addition, they recommended the use of factor  $k_b=0.8$  in the calculation of structures with BFRP. However, these recommendations do not have experimental confirmation in terms of the load-bearing capacity of oblique sections in structures with BFRP.

Recommendations for designing beams of sea sand and concrete reinforced with BFRP were worked out in [14]. However, such structures have not yet passed full experimental verification for the first group of limiting states and durability, so additional studies are needed.

The positive experience of using prestressed BFRP for reinforcement of large beams in order to reduce their deflections and opening of normal cracks under load was pointed out in [15]. It is unknown how the bearing capacity of oblique beam sections will change in this case.

Results of experimental studies and computer modeling of the stress-strain state of beams with prestressed BFRP were presented in [16]. The authors have pointed out that controlled prestressing of BFRP increased both stiffnesses of the test elements without transverse reinforcement and bearing capacity of their oblique sections. It remains unclear

how to take into account the increase in bearing capacity of normal and oblique sections of such beams in their design.

Fire resistance of both basalt reinforcement (BFRP) and concrete beams reinforced with BFRP was investigated in [17]. It was found that the use of a polymer matrix with a high value of  $T_g$  and good compatibility (joint work) with basalt fibers improves fire resistance of BFRP after the process of pultrusion hardening. Fire resistance of girder structures is improved by protecting the ends of BFRP rods with concrete or wrapping them with fire shields. However, the load-bearing capacity of oblique and normal sections of these structures remains unclear in such conditions.

It was shown in [18] that bearing capacity of normal sections of beams reinforced with BFRP is still insufficiently studied. Shear strength of near-support sections still remains virtually unexplored, so the authors manufactured and tested in a three-point bending installation concrete beams with a low coefficient of longitudinal reinforcement with BFRP and without transverse reinforcement elements. During the tests, they controlled deflections in the middle of the span, width of cracks, and deformation of upper fibers of the compressed concrete. These data can be used in the development of a model of BFRP shear in near-support sections of the beams. However, this is only the first step towards building a general physical model of BFRP reinforced beams without transverse reinforcement.

Market and the current state of production and use of basalt reinforcement (Factory Reset Protection, FRP) were analyzed. An overview of the current state and practical experience of American and international manufacturers and suppliers of BFRP reinforcement was made with an emphasis on logistics. To centralize information needed by civil engineers and designers, 23 BFRP manufacturers from 10 countries have conducted a corresponding survey. The survey results have shown that most BFRP manufacturers produce solid round rods covered with sand or spiral winding. It turned out that BFRP differs little in form and type which simplifies standardization. BFRP has greater tensile strength and higher modulus of elasticity compared to Glass Factory Reset Protection (GFRP). Only two in ten manufacturers started the production of BFRP by 2000. Moreover, more than 50 % of manufacturers started production of BFRP reinforcement after 2007. It was emphasized that the production of this reinforcement in Asia and Europe was higher than in the US. The authors of [19] recommend continuing studies of structures with BFRP in order to develop general recommendations for its production and the design code. Thus, the widespread introduction of basalt-plastic reinforcement in construction lack of reliable methods of calculation of the structures with BFRP both in Eurocode-2 and national design standards.

Experimental beam specimens of the main normative documents and recommendations for calculation of structures with NCR have been developed in the USA, Canada, Japan, Great Britain, Italy for the last 23 years based on norms for calculation and design of reinforced concrete structures with steel reinforcement. Guidelines [6] and Annex L to SP [9] have been prepared respectively in Ukraine and Russia. They can be considered as drafts of future standards. However, experiments have shown that concrete elements reinforced with steel and NCR differently bear loads, deform, and fracture.

The basic principles of calculation are preserved as for reinforced concrete structures taking into account linear

work of the NCR. Specifics of the work of structures with NCR was taken into account by the introduction of special reducing factors of working conditions and standardization of material characteristics. In general, formulas for determining design parameters of structures with NCR repeat formulas for structures with steel reinforcement. However, design requirements in most cases are accepted more cautiously in comparison with reinforced concrete structures.

Definition of previous unsolved parts of the general problem:

1. The use of basaltoplastic reinforcement BFRP in concrete structures is still insufficiently standardized.
2. Based on analysis of the results of studies of chemical resistance, physical and mechanical properties and practice of CR application, the feasibility of using BFRP in civil and road construction, construction of hydraulic structures as well as the facilities to which special requirements are imposed is obvious. There are not enough publications on this topic in scientific periodicals.
3. Comparison of published research data with the results of calculations of bearing capacity of basalt-concrete structures according to national design standards and the author's methods shows their generally unsatisfactory convergence. As shown by the above analysis, the lion's share of publications concerns the determination of the load-bearing capacity of normal sections in structures with NCR for the first and second groups of boundary conditions while the strength study of their oblique sections is still in its infancy, practically not covered.

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### 3. The aim and objectives of the study

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This study objective is to identify experimentally patterns of changes in load-bearing capacity, cracking resistance, and deformability of concrete beams reinforced with BFRP taking into account the action of static and cyclic loading of high levels.

To achieve this goal, the following tasks were set:

- using the theory of experimental planning, study the stress-strain state, nature of fracturing, bearing capacity, the width of the opening of normal cracks and deflections in beam-type basalt-concrete elements in the process of their static and low-cycle loading;
- study the influence of main design factors on bearing capacity of sections of the experimental near-support elements, their crack resistance and deformability with the help of experimental and statistical dependences obtained in the process of processing the obtained data;
- conduct a comparative analysis of the influence of the main structural factors on the specified parameters of test beams with similar steel and BFRP reinforcement taking into account the action of static and low-cycle loading.

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### 4. Materials, methods, and main results of the study of basalt-concrete beams

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Odesa State Academy of Civil Engineering and Architecture conducts systematic experimental studies [20–22] of bearing capacity of near-support sections of reinforced concrete beam structures under complex stresses.

To achieve this goal, two series of field experiments were additionally implemented using the planning theory. The

experiments were performed with single-span beams reinforced with BFRP under the action of static and low-cycle loading of high levels.

It is known that the main performance parameters of reinforced concrete, fiber concrete and basalt-concrete structures are subject to the Gaussian law of normal distribution and the method of least squares can be used in processing. Since the study factors can nonlinearly influence the “yield” function, it is expedient to approximate it by a polynomial of the second degree. Therefore, the experimental specimens were made according to a B3 three-factor three-level D-optimal plan of Box [23] which provides the same accuracy of the forecast of the initial parameter in the region described by a radius equal to conditional “1” relative to the “zero” point.

The following factors (design factors) were selected as experimental factors which varied at three levels:  $X_1$ : relative shear span (distance from the support to the concentrated force),  $a/h_0 = 1, 2, 3$  at  $h_0 = d = 175$  mm;  $X_2$  is concrete class C, MPa, C16/20, C30/35, C40/50;  $X_3$  is the coefficient of transverse reinforcement  $\rho_{fw}$  (AKB-800) = 0.0029; 0.0065; 0.0115 for basalt-concrete beams and  $\rho_{sw}$  (BpI) = 0.0016; 0.0028; 0.0044 for reinforced concrete specimens. Coefficients of upper and lower longitudinal reinforcement  $\rho_{lf} = \rho_{ls} = 0.0176$  for both types of beams with calculated spans  $L_0 = 9h_0 = 1575$  mm and width  $b = 100$  mm.

Each test of a field experiment was provided with two twin beams with four near-support sections. In total, 30+30=60 basalt-concrete beams were tested under the action of gradually increasing static and low-cycle loading, respectively. For comparison, results of testing similar reinforced concrete beams were used [22].

Experimental specimens: basalt-concrete beams reinforced with BFRP in the form of two tied flat frames (Fig. 1). Heavy concrete of the above classes using 5–10 mm fractions of crushed granite stone and quartz sand with a fineness modulus of 1.5 were used for the manufacture of the above elements. Portland cement of grade 500 without additives was used as a binder. To reduce the water-cement ratio, improve ease of laying the concrete mixture and reduce the time of accumulation of concrete strength, a Relaxol-Super M (ISO 9001 No. 04.156.26) complex additive in an amount of 1 % by weight of cement in conversion to dry matter was used in all experiments.

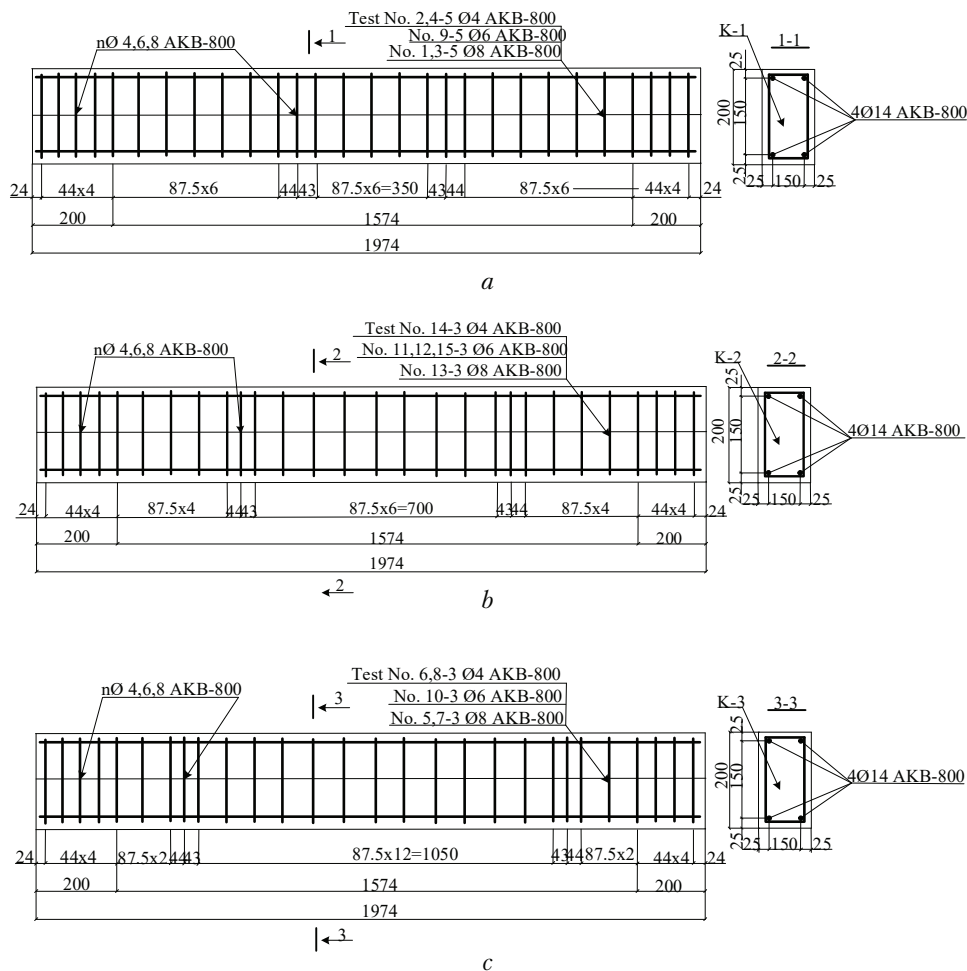


Fig. 1. Design and reinforcement of experimental beam specimens with spans: a – small; b – middle; c – large

Special power plants were designed, manufactured, and certified to test experimental beam specimens. The load was applied according to a four-point scheme using a hydraulic jack DG-50 and a distribution cross-bar beam by two concentrated forces in steps: (0.04...0.06)  $F_{ult}$  until first normal and oblique cracks appeared, and then (0.08...0.12) up to a failure. The load in each step was applied for 15 min with conducting all measurements at the beginning and end of the step.

Before making the test beams, strain gages KF5P1-5-200 (with a base of 5 mm) were glued on the stretched reinforcement of one of the flat frames in compliance with the technology recommended by the manufacturer (Veda LLC, Kyiv).

Deformation of concrete of experimental specimens was measured using wire and foil strain gages with a base of 40 and 50 mm glued on one lateral and top polished faces according to the generally accepted procedure. The transition from deformations measured in reinforcement during the experiment was carried out using Hooke's law and according to the modulus of section elasticity in concrete.

Deformation of concrete in the compressed zone and the stretched reinforcement was controlled with the help of dial indicators and vertical displacements were measured with flexometers (Fig. 2).



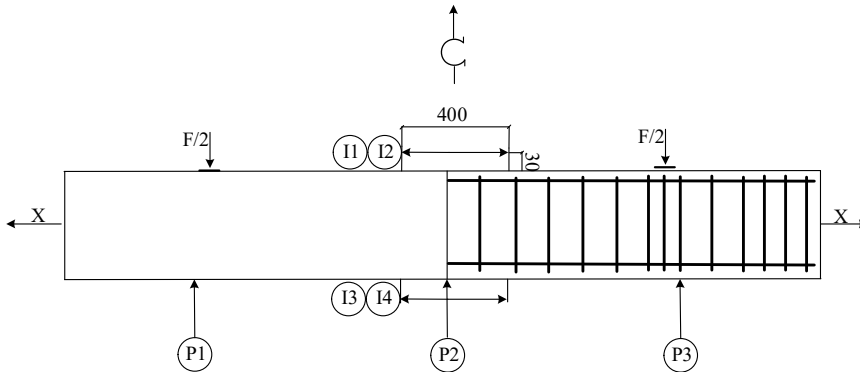


Fig. 2. The layout of measuring instruments in experimental specimens

**5. Presentation of the main material and the results obtained in the study of the load-bearing capacity of concrete beams reinforced with BFRP**

Deformation, crack formation and failure of experimental basalt-concrete and reinforced concrete beams took place according to the rules of structural mechanics and were predictable. Normal cracks in the zone of action of maximum bending moments were the first to appear. With a further increase in the transverse load, normal cracks proliferated deep into the beam, the width of their opening increased and new normal cracks appeared. Subsequently, first oblique cracks appeared. Further growth of the load led to the development of normal and oblique cracks with the predominant opening of oblique ones up to a failure caused by dangerous oblique cracks.

Experimental beam specimens were designed to be almost equal in strength both in normal and oblique cross-sections but so that their failure occurred, after all, in oblique sections. As a result of the processing of experimental data, removal of insignificant coefficients and recalculation of remaining ones, adequate experimental-statistical dependences of main parameters of bearing capacity of experimental specimens were obtained. The presented dependences have good information utility and show good agreement with the experimental data.

**5.1. Strength (bearing capacity) of the experimental elements**

Bearing capacity of the experimental elements can be described by the following dependences:

$$\hat{Y}(V_{us}) = 98 - 41x_1 + 12x_2 + 6x_3 + 16x_1^2 - 7x_2^2 - 5x_3^2 - 7x_1x_2, \text{ kN},$$

$$\bar{\sigma} = 5.1\%, \tag{1}$$

$$\hat{Y}(V_{us}^{cyc}) = 90 - 36x_1 + 10x_2 + 7x_3 + 18x_1^2 - 6x_2^2 - 6x_3^2 - 8x_1x_2, \text{ kN},$$

$$\bar{\sigma} = 5.1\%, \tag{2}$$

$$\hat{Y}(V_{uf1}) = 51,8 - 30,1x_1 + 11,8x_2 + 5,5x_3 + 15,9x_1^2 - 5,5x_2^2 - 2,3x_3^2 - 10,6x_1x_2 - 4,8x_1x_3, \text{ kN},$$

$$\bar{\sigma} = 5,0\%, \tag{3}$$

$$\hat{Y}(V_{uf2}^{cyc}) = 44,3 - 27,0x_1 + 10,4x_2 + 4,5x_3 + 17,3x_1^2 - 4,0x_2^2 - 2,4x_3^2 - 10,2x_1x_2 - 2,9x_1x_3, \text{ kN},$$

$$\bar{\sigma} = 5,5\%, \tag{4}$$

where  $V_{us}, V_{us}^{cyc}$  are destructive transverse forces, respectively at static and low-cycle reloading of reinforced concrete beams according to [22];  $V_{uf1}, V_{uf2}^{cyc}$  are destructive transverse forces, respectively at static and low-cycle reloading of concrete beams reinforced with BFRP at the same values of structural factors.

The presented adequate experimental and statistical dependences (1) to (4) have a significant advantage over correlation and other dependences because they make it possible to comprehensively assess the effect of each of the above factors on the determining initial parameters both individually and in interaction with each other. Also, they make it possible to compare the magnitude of this effect on both reinforced concrete beams and concrete elements reinforced with BFRP under the action of gradually growing static and low-cycle reloading. Geometric interpretation of the bearing capacity of the near-support sections of experimental beams is partially presented in Fig. 1.

Among the design factors, the value of the relative shear span (Fig. 3, a) had the greatest influence on bearing capacity of the near-support sections of experimental elements.

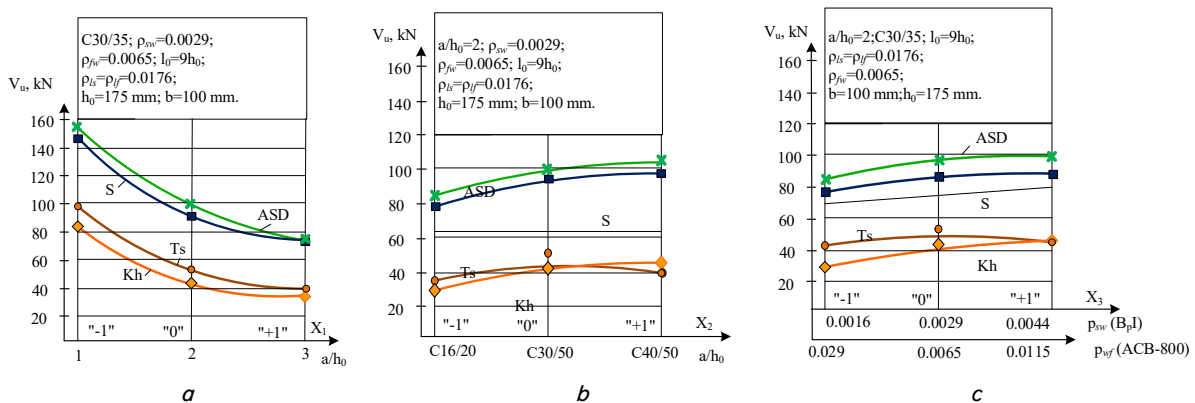


Fig. 3. Influence of design factors on bearing capacity of near-support sections of experimental elements: a – relative shear span; b – concrete class; c – the amount of transverse reinforcement; ASD – according to [22]; S – according to [22]; Ts – at static loading; Kh – at low-cycle reloading

Dependence of decrease in strength of oblique sections of basalt-concrete beams according to the nonlinear law with an increase in shear span previously revealed in [21, 22, 24] for reinforced concrete beams was confirmed.

The concrete class has the next largest impact: with an increase in concrete class from C16/20 to C30/35, bearing capacity of oblique sections increased more intensively.

A similar pattern was observed with an increase in the coefficients of transverse reinforcement  $\rho_{sw}$ ,  $\rho_{fw}$ .

The two upper graphs in Fig. 3 and other figures with designations ASD and S, characterize bearing capacity and other parameters of reinforced concrete beams at the reference static and low-cycle reloads, respectively.

### 5.2. Deflections in experimental specimens at operational ( $N=0.65F_u$ ) loading level

Deflections in experimental specimens at operational ( $F=0.65F_u$ ) loading level can be represented by the following experimental-statistical dependences:

$$\hat{Y}(f_{s,\eta F_u}) = 4.5 + 0.8x_1 + 0.35x_2 + 0.25x_3 - 0.35x_1^2 - 0.15x_2^2 + 0.30x_1x_3, \text{ mm},$$

$$\bar{U} = 6.0\%.$$

$$\hat{Y}(f_{(s,\eta F_u)}^c) = 5.00 + 0.85x_1 + 0.40x_2 + 0.25x_3 - 0.40x_1^2 - 0.15x_2^2 + 0.30x_1x_2, \text{ mm},$$

$$\bar{U} = 6.4\%.$$

$$\hat{Y}(f_{f1,2,\eta F_u}^{cyc}) = 10.20 + 0.91x_1 + 1.04x_2 + 0.73x_3 - 0.74x_1^2, \text{ mm},$$

$$\bar{U} = 5.3\%.$$

It is seen from expressions (5) to (7) that deflections in concrete beams reinforced with BFRP were more than 2 times greater than those in similarly reinforced concrete elements with the same design factors and reach, on average, 1/154 of the calculated span length.

Breaking transverse force at low-cycle loading decreases approximately by 14 % in comparison with static loading and the deformability of compressed concrete increases by the same amount. Therefore, the effect of low-cycle loading is not reflected in deflections.

Graphical representation of deflections in beams of basalt-concrete and reinforced concrete at operational loading is presented in Fig. 4.

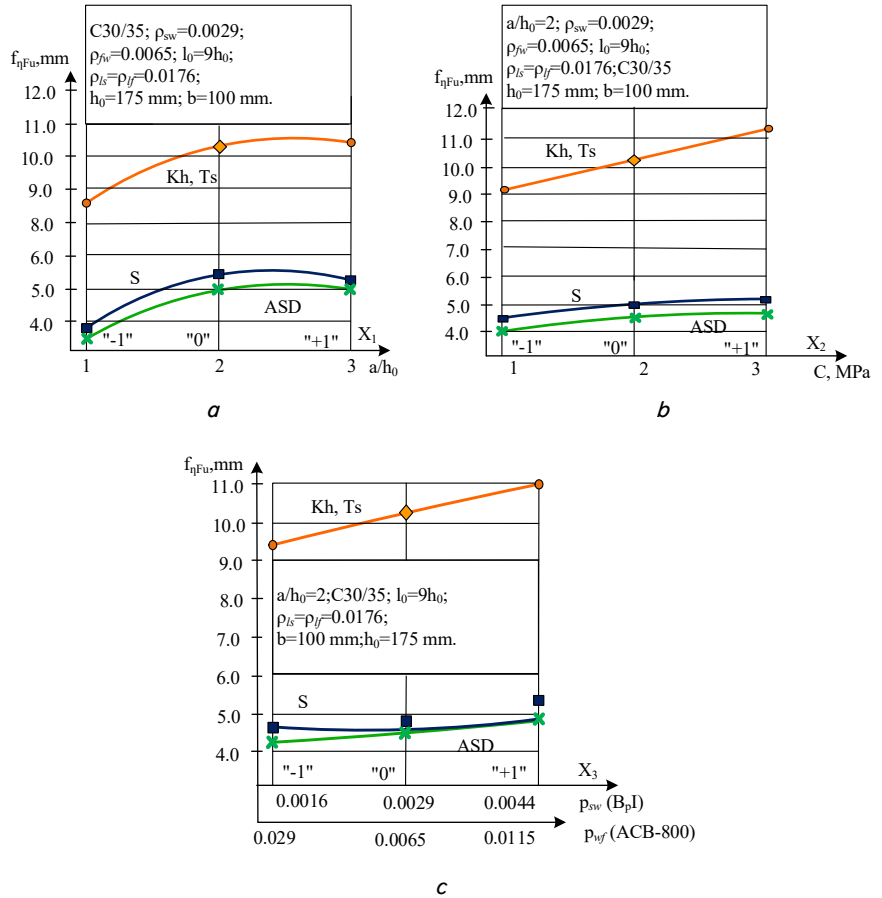


Fig. 4. Dependence of beam deflections at an operational level of transverse loading on:  $a$  – magnitude of shear span;  $b$  – concrete class;  $c$  – quantity of transverse reinforcement; ASD – according to [22]; S – according to [22]; Ts – at static loading; Kh – at low-cycle loading

(5) The above experimental data are confirmed by the results of study [26].

### 5.3. Deflections in experimental beams before their failure

Deflections in experimental beams before their failure are described by the following expressions:

$$\hat{Y}(f_{us}) = 6.00 + 1.50x_1 + 0.65x_2 + 0.70x_3 - 0.50x_1^2 + 0.20x_1x_3, \text{ mm},$$

$$\bar{U} = 5.8\%.$$

$$\hat{Y}(f_{us}^{cyc}) = 6.5 + 1.5x_1 + 0.75x_2 + 0.75x_3 - 0.55x_1^2 + 0.20x_1x_3, \text{ mm},$$

$$\bar{U} = 5.1\%.$$

$$\hat{Y}(f_{uf1,2}^{cyc}) = 14.28 + 1.34x_1 + 1.46x_2 + 1.01x_3 - 1.03x_1^2, \text{ mm},$$

$$\bar{U} = 5.6\%.$$

Their geometric interpretation is shown in Fig. 5.

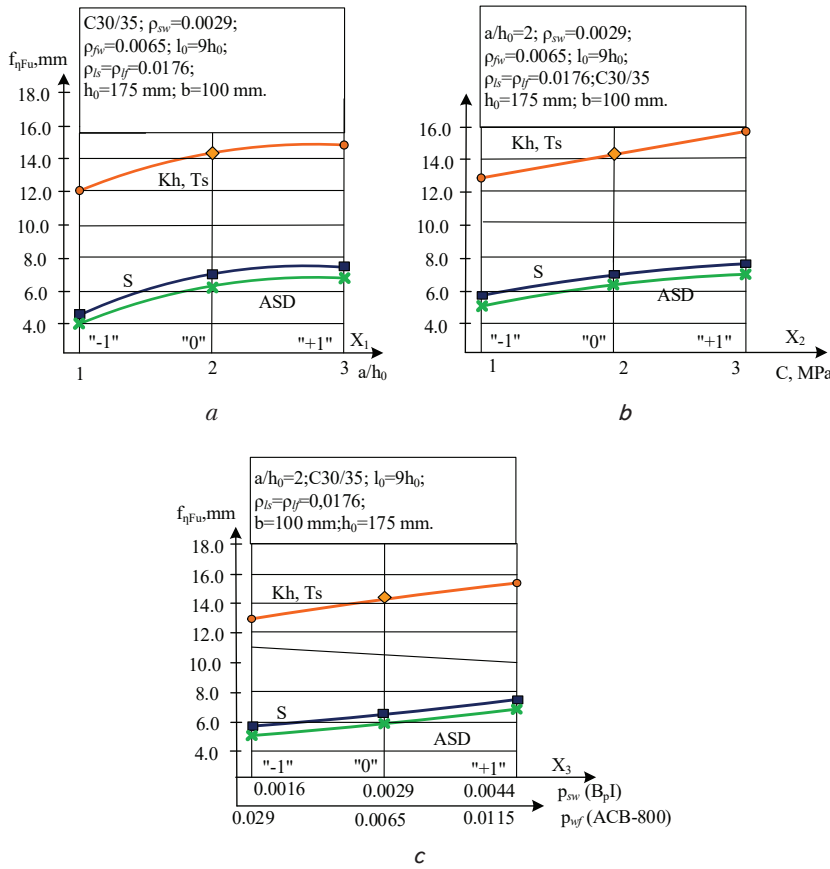


Fig. 5. Influence of design factors on a deflection in beams before their failure ( $\eta \approx 0.95 F_u$ ):  $a$  – the magnitude of shear span;  $b$  – concrete class;  $c$  – the quantity of transverse reinforcement; ASD – according to [22]; S – according to [22]; Ts – at static loading; Kh – at low-cycle reloading

Before failure, deflections in basalt-concrete beams reached on average  $\left(\frac{1}{110}\right)l_0$  and exceeded deflections in reinforced concrete beams approximately 2.2...2.4 times. Similar experimental results are described in [27].

#### 5.4. Formation of normal and oblique cracks in basalt-concrete beams

Formation of normal and oblique cracks in basalt-concrete beams is characterized by corresponding dependences (11) and (12). It is graphically represented in Fig. 6.

$$\hat{Y}(M_{crf}^{\perp}) = 3.25 + 0.98x_2 + 0.14x_3, \text{ kNm},$$

$$\bar{\sigma} = 5.1\%, \tag{11}$$

$$\hat{Y}(V_{crf}^{\perp}) = 20.5 - 9.6x_1 + 3.3x_2 + 0.8x_3 + 5.1x_1^2 - 0.5x_2^2 - 0.6x_3^2 - 2.4x_1x_2,$$

$$\bar{\sigma} = 8.0\%. \tag{12}$$

The obtained data satisfactorily coincide with the results of experimental studies in [25].

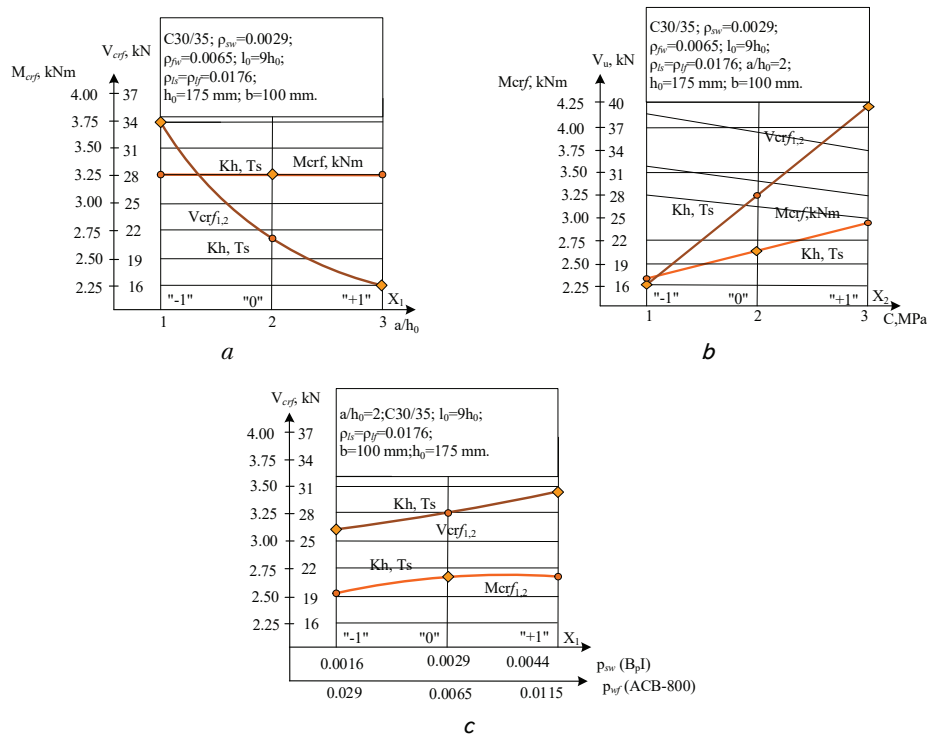


Fig. 6. Dependence of the moment  $M_{cr1,2}$  and transverse force  $V_{crf1,2}$  taking part in formation of normal and oblique cracks, respectively, in experimental basalt-concrete beam specimens on:  $a$  – the size of shear span;  $b$  – concrete class;  $c$  – quantity of transverse reinforcement; Ts – at static loading; Kh – at low-cycle reloading

**5. 5. Width of the opening of normal cracks in experimental elements at low-cycle loading at an operational level**

The width of the crack opening can be described by dependences (13), (14). It is presented in Fig. 7.

$$\hat{Y}(W_{ks}^{\perp cyc}) = 0.14 + 0.02x_1 + 0.03x_2 + 0.01x_3 + 0.01x_1^2 - 0.03x_2^2 + 0.01x_1x_3, \quad \bar{\sigma} = 6.2\%, \quad (13)$$

$$\hat{Y}(W_{kf1,2}^{\perp cyc}) = 0.35 + 0.06x_1 + 0.10x_2 + 0.05x_3 + 0.02x_1x_3, \quad \text{mm}, \quad \bar{\sigma} = 11.5\%. \quad (14)$$

As can be seen from Fig. 7, the width of the opening of normal cracks in experimental specimens at the operational loading level does not exceed permissible values, namely, 0.5 mm for design reasons.

**5. 6. Width of the opening of oblique cracks in experimental beams during static and low-cycle loading at operational levels**

The width of the opening of oblique cracks is described by static dependences (15) to (18). It is shown in Fig. 8.

$$\hat{Y}(W_{ks}') = 0.35 - 0.06x_1 - 0.03x_2 - 0.01x_3 - 0.01x_1x_3, \quad \text{mm}, \quad \bar{\sigma} = 10.4\%, \quad (15)$$

$$\hat{Y}(W_{ks}^{cyc}) = 0.40 - 0.05x_1 - 0.03x_2 - 0.03x_1x_3, \quad \text{mm}, \quad \bar{\sigma} = 6.0\%, \quad (16)$$

$$\hat{Y}(W_{kf1}') = 0.30 - 0.08x_1 - 0.15x_2 + 0.07x_3 + 0.03x_1^2 + 0.03x_2x_3, \quad \text{mm}, \quad \bar{\sigma} = 13.7\%, \quad (17)$$

$$\hat{Y}(W_{kf2}^{cyc}) = 0.45 - 0.08x_1 - 0.18x_2 + 0.13x_3 - 0.05x_2^2 - 0.04x_1x_2 + 0.04x_2x_3, \quad \text{mm}, \quad \bar{\sigma} = 14.5\%. \quad (18)$$

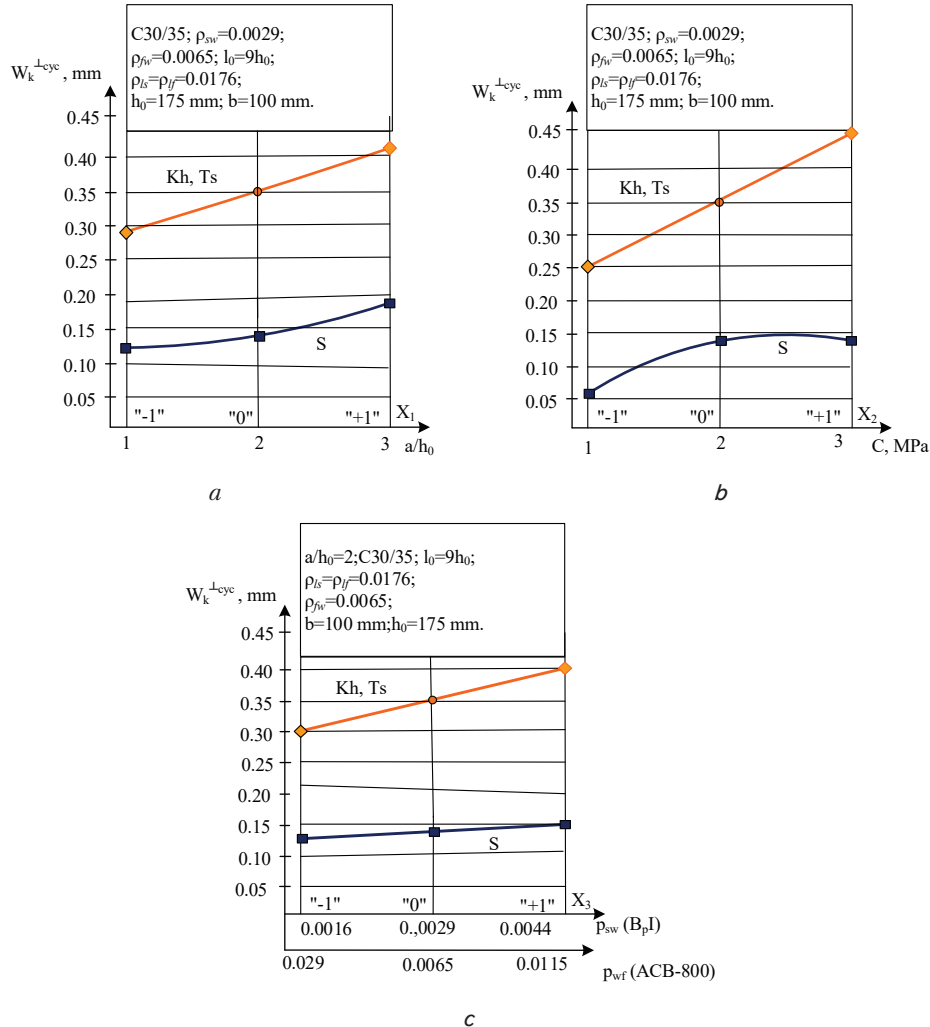


Fig. 7. Dependence of the width of the opening of normal cracks in experimental reinforced concrete and basalt-concrete beams at their static and low-cycle loading at an operational level:  
 a – the magnitude of shear span; b – concrete class; c – the quantity of transverse reinforcement;  
 S – according to [22]; Ts – at static loading; Kh – at low-cycle reloading



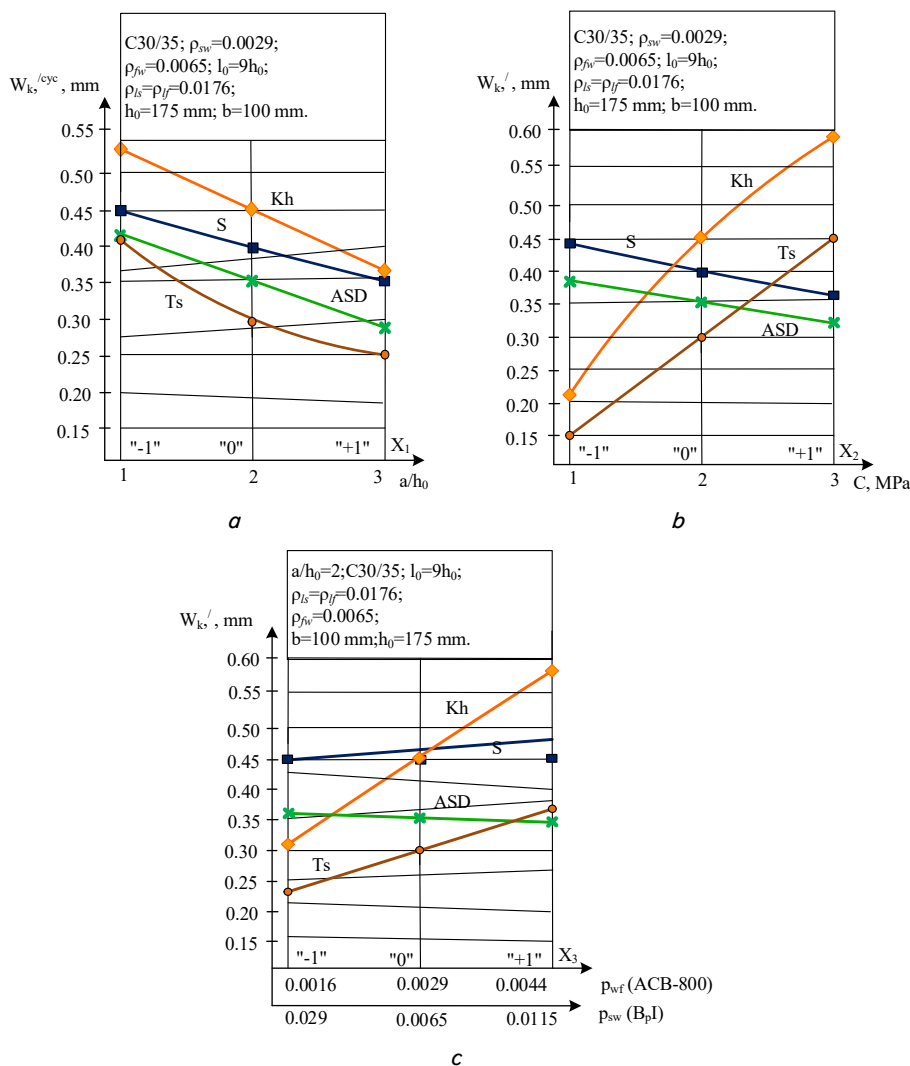


Fig. 8. Dependence of width of the opening of oblique cracks in experimental beam specimens before their failure ( $\eta \approx 0.95F_u$ ) on: a – the size of shear span; b – concrete class; c – the quantity of transverse reinforcement; ASD – according to [22]; S – according to [22]; Ts – at static loading; Kh – at low-cycle reloading

Experiments have shown that the width of the opening of oblique cracks did not exceed admissible values at average values of design factors. These data are consistent with the results of study [29].

### 6. Discussion of the results obtained in the study of strength, deformability, and crack resistance

Analysis of dependences (1) to (4) shows that they are qualitatively of the same type and influence of design factors and the factor of low-cycle reloading is qualitatively similar. Differences were observed in quantitative indicators.

Bearing capacity of oblique cross-sections in experimental beam specimens expressed through the destructive transverse force  $V_u$  increases in relation to average values (free members  $b_0$ ), respectively 98; 90; 51.8; 44.3;

- with a decrease in the relative shear span  $a/h_0$  from 3 to 1 in these series: by 84 %, 80 %, 116 %, 122 %, respectively;

- with an increase in concrete class from C16/20 to C40/50: by 24 %, 22 %, 46 % and 47 %, respectively;

- with an increase in quantity of transverse steel reinforcement  $\rho_{sw}$  from 0.0016 to 0.0044 (expressions (1), (2)) and basalt-plastic BFRP  $\rho_{sw}$  from 0.0029 to 0.0115: by 12 %, 16 %, 21 % and 20 %, respectively;

- at a simultaneous reduction of relative shear span  $a/h_0$  and increase in concrete class C: by 7 %, 9 %, 20 % and 23 %, respectively;

- at a simultaneously reduction of relative shear span  $a/h_0$  and increase in quantity of transverse basalt-plastic reinforcement  $\rho_{fw}$ : by 9 % and 7 %, respectively.

Presence of quadratic effects at factors  $X_1^2$ ,  $X_2^2$ ,  $X_3^2$  with signs opposite to the direct influence of these factors indicates that outside the limits of change of experimental factors ( $a/h_0 > 3$ ,  $C > 40/50$  MPa,  $\rho_{sw} > 0.0044$  and  $\rho_{fw} > 0.0115$ ), a further increase in  $a/h_0$  will not lead to a significant decrease in load-bearing capacity (destructive transverse force) (Fig. 1, a) and a further increase in concrete class C (Fig. 1, b) and quantity of transverse steel  $\rho_{sw}$  and basalt-plastic  $\rho_{fw}$  reinforcement (Fig. 1, c) is impractical because the process of increasing  $V_u$  is of damping nature in this case.

Because of much greater deformability (4.44 times), replacement of steel reinforcement with basalt-plastic BFRP at all other design factors being equal led to an average 47 %

decrease in destructive transverse force  $V_u$  under static loading of the experimental beam specimens and a 51 % decrease at low-cycle reloading. It is characteristic that such a reduction of the beam bearing capacity is inherent in the entire range of change of design factors (Fig. 5, a).

Low-cycle reloading reduces the bearing capacity of the near-support sections of basalt-concrete beams by an average of 8 % which is confirmed by the data of [22].

The number of cycles of reloading in the tests was determined by the criterion of stabilization of deformations in concrete and was not less than 10 if the experimental beam specimens did not fail at a smaller number of cycles.

Absolutely most of the experimental beams failed behind the oblique sections in both or one (what was more often) of the shear spans. The criteria for failure of the experimental beams included achievement of limit deformations in concrete or reinforcement with obvious signs of occurring plastic deformations in them, excessive (up to 1 mm or more) opening of oblique (what was more often) or normal (less often) cracks, a significant increase in deflection ( $f \geq (1/100)l_0$ ), no increase or some decrease (up to 15 %) in readings of the manometer of the power unit's pumping station.

Obviously, the main cause of a decrease in bearing capacity of the experimental beam specimens during low-cycle reloading was a violation of the concrete structure, especially in the near-support sections, decompaction of concrete and partial loss of adhesion to reinforcement.

The largest growth of residual deformations in concrete and transverse reinforcement was observed in the first two or three cycles and, as a rule, they stabilized before the fifth or sixth cycle at loading levels  $\eta=0\ldots 0.50-0\ldots 0.65$ . In some specimens made of a low-class concrete and at a minimum transverse reinforcement, these deformations were not stabilized at loading levels  $\eta=0\ldots 0.8$  and the beams failed in 6...9 cycles from the loss of fatigue strength.

As a rule, experimental reinforced concrete beams with irredundant reinforcement ( $\rho_s \leq 0.003$  (BpI),  $\rho_{fs} \leq 0.018$  (A500C)) failed according to the  $B/M$  scheme [20] at static and low-cycle loads. Such failure occurred behind oblique sections under the predominant action of the bending moment because of a creep of longitudinal main reinforcement at the mouth of a dangerous oblique crack and transverse reinforcement along this crack length. With an increase in the quantity of transverse reinforcement  $\rho_{sw} \geq 0.0044$ , similar experimental beams with medium ( $a/h_0=2$ ) and large ( $a/h_0=3$ ) shear spans were destroyed according to the scheme  $C/V$  [20], that is, behind an oblique crack at a predominant action of transverse force because of creep of the transverse reinforcement and shear or crushing of concrete in the compressed zone above the nose of a dangerous oblique crack. At small distances between the load and the support ( $a/h_0 \leq 1$ ), experimental reinforced concrete beams usually failed according to the scheme  $D$  [20] behind an oblique compressed band. Beams can also fail from shear under the action of maximum tangential stresses.

Failure of basalt-concrete beams took place across concrete behind oblique sections because of concrete fragmentation over the apex of a dangerous oblique crack. In this case, stresses and strains in the transverse BFRP rods intersected by this oblique crack reach limit values.

Comparison of experimental data of similarly reinforced concrete and basalt-concrete beams has shown that the specimens with steel reinforcement demonstrated the best indicators (up to twice) of their bearing capacity for the first and second groups of boundary conditions. However, as the review of published data has shown, the actual service life of reinforced concrete structures in corrosive media is reduced because of corrosion of steel reinforcement several times more than specified in standards. Therefore, the use of NCR in the construction of special-purpose facilities is indispensable. As shown in [16] and other studies, to increase the efficiency of structures with BFRP, it is advisable to make them pre-stressed. This needs additional experimental and theoretical studies.

The results of the study of bearing capacity of basalt-concrete beams were obtained in standard tests of experimental beam specimens of recommended dimensions for strength, deformability, and crack resistance under the action of single static and repeated cyclic loading. The available publications on this topic are not enough to create a reliable method of calculating such structures.

The peculiarity of the obtained study results consists in a systematic approach to the problem under study and application of the mathematical planning theory during experiments and processing of obtained data. This has made it possible to objectively assess the influence of design

factors on main parameters of the load-bearing capacity of basalt-concrete structures not only separately but also in interaction to compare the results of experiments of different series. Such a procedure for studying the bearing capacity of basalt-concrete structures was not found in the literature available to the authors.

The study results characterize the bearing capacity of only  $2000 \times 200 \times 100$  mm concrete beams with basalt-plastic reinforcement (BFRP). They cannot be automatically applied to basalt-concrete structures of other sizes. For this purpose, it is necessary, at least, to reduce basic initial parameters of the above experimental and statistical dependences to an effective area ( $b/h_0$ ) and replace the coded values of experimental factors  $X_i$  with natural values. These limitations are determined by the generally accepted method of conducting experimental studies in the laboratory. They are to show, first of all, qualitative and relative quantitative characteristics of the phenomenon under study.

In this study of bearing capacity of basalt-concrete elements, coefficients of longitudinal reinforcement of experimental specimens were not changed at three levels but taken as constant:  $\rho_{fs} = \rho_{lf} = 0.0176$ . In addition, the low-cycle loading was only sign-constant, not sign-variable one that is capable to significantly change the nature of the failure of the experimental elements. This shortcoming of the study can be remedied by adopting, e. g. a five- or six-factor experimental plan instead of a three-factor one. At the same time, the number of tests will increase several times. This shortcoming can also be partially remedied by performing additional experiments at "zero" points of the main three-factor experiment described above.

Based on the presented study results, a physical model of resistance of the near-support section of the basalt-concrete beam to external static and low-cycle loads will be developed first and then an analytical method for calculating the bearing capacity will be developed. Difficulties may arise at the stage of implementation of this method in the building design standards because the truss analogy dominating in them is far from the real picture of work of the basalt-concrete structures.

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## 7. Conclusions

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1. The studies have allowed us to establish a qualitative and quantitative picture of deformation, crack formation, and failure of experimental beams presented in a form of experimental-statistical dependences under the action of one-time static and low-cycle reloading. A comprehensive description of basic parameters of bearing capacity of identical beams with basaltoplastic (BFRP) and steel reinforcement was given. Since the real coefficient of longitudinal reinforcement BFRP ( $\rho_{fb} = 0.0176$ ) was almost twice the limit one ( $\rho_{fb} = 0.0086$ ), the failure of all basalt-concrete beams occurred in the compressed zone of concrete above apex of the dangerous oblique crack.

2. The presented experimental-statistical dependences make it possible to assess qualitatively and quantitatively influence of experimental factors on bearing capacity of the abovementioned beams both individually and in interaction with each other. In particular, it was found that the strength of experimental beam specimens increases relative to the average values (free members) in the presented dependences:

– with a decrease in the value of relative shear span  $a/h_0$  from 3 to 1 in the above series: by 80...122 %;

– with an increase in the concrete class  $\rho_{sw}$  from C 16/20 to C 40/50: by 24...47 %;

– with an increase in the quantity of transverse reinforcement  $\rho_{sw}$  from 0.0016 to 0.0044 and basalt-plastic reinforcement  $\rho_{fw}$  from 0.0029 to 0.0115: by 12...16 % and 20...21 %; respectively;

– with a simultaneous reduction of the relative shear span and increase in the concrete class: 7... 23 %;

– with a simultaneous decrease in  $a/h_0$  and increase in  $\rho_{fw}$ : by 7...9 %.

3. Comparison of the study results has shown the following:

– replacement of steel reinforcement with BFRP one resulted in a decrease in load-bearing capacity of oblique sections of the experimental beams under static loading. Low-cycle reloading reduced bearing capacity of the near-support sections on average by 8 % for reinforced concrete beams and by 14 % for concrete elements with BFRP reinforcement;

– deflections in concrete beams reinforced with BFRP were more than twice the deflections of similar reinforced concrete elements with the same design factors. Vertical displacements of the beams reached on average  $(1/154)l_0$  at operational loading level  $(0.65Fu)$  and increased to  $(1/110)l_0$  before failure;

– width of the opening of normal cracks was equal on average to 0.14 mm in reinforced concrete beams at the operational level of low-cycle reloading and 0.35 mm in basalt-concrete beams. Accordingly, the average value of the width of the opening of oblique cracks was 0.40 mm in reinforced concrete beams and 0.45 mm in basalt-concrete beams at a similar loading;

– to essentially increase the load-bearing capacity of oblique sections in span basalt-concrete structures, reduce their deflections and width of normal and oblique cracks, we consider it appropriate to manufacture them using a prestressed BFRP with an appropriate scientific and technical support.

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