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FEATURES OF STRESS-STRAIN BEHAVIOUR OF BASALT FIBRE REINFORCED CONCRETE BEAM STRUCTURES

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Abstract. The paper deals with the results of multi-method test studies of the bearing capacity, stress-strain behaviour and crack resistance of the 2000x200x100 mm reinforced concrete beams and basalt fibre reinforced concrete beams subjected to high-level static and low-cycle loads. Specifically, the test-statistical curves illustrating strengths of the inclined cross-sections (collapsing transverse force). There are examined moments and the developed transverse forces for normal and inclined cracks, the deflection and crack widths subjected to service and collapsing loads. The projection lengths of the dangerous inclined cracks on the longitudinal axis and the average distances between normal cracks along the element lengths versus the design factors of the concrete beams similarly reinforced with steel and basalt-plastic were compared. Comparative analysis was made to check the impact of the main design factors on the indicated load-bearing capacity parameters of the reinforced concrete beams and basalt fibre reinforced concrete beams manufactured and tested in accordance with the experimental design theory and D-optimum plan of Box B3.

Keywords: *basalt-plastic and steel reinforcement, bearing capacity, stress-strain behaviour, crack resistance, static and low-cycle loading.*

Introduction

During recent decades the structures with non-metallic composite reinforcements (NCR) find the ever growing use in the construction practice, particularly in the special purpose buildings and facilities.

Due to high strength, resistance to physical and chemical corrosion, dielectric and diamagnetic properties, little weight and low heat conductivity, the NCR replace steel reinforcement frequently. However, a wide use of the NCR to reinforce concrete structures is hindered by insufficient study of the peculiarities of their performance, inadequate regulatory support and scant experience of operating the appropriate facilities.

Experience has shown that the use of NCR is promising and economically justified when constructing roads, hydrotechnical and transport facilities, erection of bridge spans, treatment facilities, chemical installations and food industry facilities as well as special purpose buildings and arrangement of foundations in corrosive soil environment. At that, the application prospects of the basalt plastic reinforcement is explained by low cost of the main raw material – basalt fibre as far as by the fact that in the world there are considerable deposits of basalt which has unique physical and chemical properties, specifically, the better chemical resistance to corrosive environment as compared with the fiber-glass reinforcement.

Easy-to-extract basalt deposits have been explored in Ukraine and a number of plants in Kharkiv and Khmelnytskyi regions already produce high-quality basalt plastic reinforcement. It is characteristic that production of such reinforcement is less hazardous for the environment than the use of steel reinforcement.

Proceeding from the above, it is a topical task to perform experimental and theoretical research of the load-bearing capacity of the structures reinforced with basalt-plastic in order to accumulate the database and improve the existing and develop new regulatory documents that enable to a wider application of such reinforcement in the indicated spheres of special facility construction.

Review of the recent research and publications

In 1978 the Scientific Research Design and Construction Technological Institute of Concrete and Reinforced Concrete (SRIRC) [1] was one of the first to issue guidelines for calculation of the fibre-glass reinforced structures. In this document the main application of the NCR is reduced to the prestressed structures. The guidelines suggest performance coefficients that allow to take into account reduction of strength properties of NCR resulting from long loading and non-uniform distribution of stresses.

In 1980 N.P. Frolov summed up in his paper [2] the research results of the stress-strain behaviour of the fibre-reinforced concrete structures that have been made in the Soviet Union (SU) up to 1980-s. The author [2] analysed the impact of long-time operation in corrosive environment and temperature upon reduction of the bearing capacity of said structures. He substantiated expedience of the NCR use by the fact that the protective concrete layer of marine facilities is being destructed during 3 -10 years of operation, and in chemical industry facilities this process takes 4 – 7 years because of the intensive corrosion of steel reinforcement.

When developing the norms for calculation and design of composite reinforced concrete structures (CR) the US and Canada specialists based themselves on the studies performed by Dolan C.W., Hamilton H.R., Bakis C.E. and Nanni A. [3]. Their paper generalized the research results obtained when studying prestressed CR in concrete structures.

The papers [4, 5] supply diagrams and research values that show the dependencies of CR creep on the load duration and its cohesion with heavy concrete; they also contain a review of the foreign and domestic regulatory documents dealing with calculation and design of NCR structures.

The load-bearing capacity of non-prestressed basalt-plastic reinforced concrete structures were studied in the USA in 1998 - 2003 by Brik V. B. [6, 7]. The author tested 11 beams of various cross-sections that have spans of 750 - 900 mm. The obtained results were compared with the research data of the tested twin beams that has steel reinforcement. The samples containing smooth basalt-plastic reinforcement collapsed because of the insufficient cohesion of reinforcement with concrete and sliding of the reinforcement.

Thesis research of R. Fico [8] was performed in connection with the being developed Italian norms for calculation and design of NCR structures. The author made a comparative analysis of the basic requirements of various national norms dealing with design of the NCR structures. His research included mathematic simulation of the stress-strain behaviour of a great number of CR reinforced concrete samples. When conducting a numerical experiment the author accounted for the influence of a great number of variable design factors upon their bearing capacity. In doing so, the convergence of the calculated and test data was unsatisfactory.

The Ukrainian norms draft (State standards of Ukraine – DSTU present a version of the earlier published Ukrainian norms [10] as well as of the effective norms dealing with calculation of the reinforced concrete structures. The analysis of these draft norms [10] indicates that calculations of the CR reinforced structures are made in compliance with the effective norms applied for calculating reinforced concrete structures. At that, use is made of the linear strain diagram of the CR strain for the tension case. This document provides for use of the additional coefficients pertaining to the NCR operation conditions.

In 2015 A.D. Pakhmonov [11] performed an experimental research of the stress-strain behaviour of the whole beams with various content of basalt-plastic reinforcement in the support zones of the multispan beams. The span zone in the tested samples was reinforced with steel. The author proposed the improved methodology to calculate multispan whole concrete beams with mixed reinforcement and use of the realistic diagrams illustrating the condition of materials. This methodology enables to account for re-distribution of internal forces acting between the supporting and spanned normal cross-sections.

The guidelines on design of NCR reinforced concrete structures which are modifications of the existing national norms used to calculate and design of the steel reinforced structures. As regards the recommendations for specifications of the design coefficients applicable for the structures reinforced with basalt-plastic, these can be found in the Guidelines [10] only, in SP [12] added in 2015 with annex L “Calculation of the structures with composite polymer reinforcement” and in + P.M. Koval and O.Ya. Grymak [13] which concern calculation of the basalt-plastic reinforced basalt-concrete beams subjected to low-cycle high-level loads.

The research performed by Elavenit S, Saravanan S and Reddy R. [14] proved that the basalt-fibre reinforced polymer (BFRP) can be used as an alternative to steel reinforcement in those structures that are operated in sea water, alkali and other environments.

The work [15] of Serbescu A., Guadagnini M. and Pilakoutas K. [15] was devoted to durability and corrosion resistance of the BFRP. The guaranteed strength of this reinforcement was established near 1,300 MPa and the module of elasticity near 40 GPa; it was guaranteed that such reinforcement will preserve 72 – 80% of its initial strength if it interacts with concrete or cement grout during 100 years. The complex long-time model of the BFRP rods strength was proposed.

Vincent P., Ahmed E. and Benmokrane B. [16] studied the behaviour of BFRP and concrete beams with BFRP in corrosive environment. The research results proved that the BFRP meets the requirements of CSA 5807-10 as regards their physical and mechanical properties. Besides, they recommend to use coefficient k_b = 0.8 when calculating the BFRP structures.

In their work [17] Li L., Lu J., Fang S., Liu F. and Li S. Developed guidelines for the design of the BFRP concrete beams made of sea sand and concrete.

Atutis M., Valivonis J. and Atutis E. [18] remark a positive experience achieved when applying the prestressed BFRP for reinforcing large-size beams in order to reduce their sag and open normal cracks subjected to loads.

Thorhallsson E., Zhelyazov T., Gunnarsson A. and Shaebjornsson J.T. presented in their work [19] the results of experimental studies and PC simulation of the stress-strain behavior of the prestressed BFRP beams. The authors indicate that the controlled preliminary stress of the BFRP increases not only rigidity of the studies elements that have no transverse reinforcement but also the bearing capacity of their inclined cross-sections.

Zhu H., Wu G., Zhang L., Zhang J. and Hui D. [20] investigated fire resistance both of the BFRP and of the concrete beams with BFRP. It was established that application of the polymer matrix with high T_g value and good compatibility (collaboration) with basalt fibres after pultrusion solidification increases fire resistance of the BFRP and span structures provided the BFRP rod ends have been protected against fire with concrete or have been wrapped with fire-extinguishing panels.

In their paper [21] Hofman S., Graubner C.-A. and Prosket T. Point out that the load-bearing capacity of the normal cross-sections of the BFRP concrete beams is not sufficiently studied while the shear strength of the support areas remains, practically, not studied at all. In this connection the authors prepared and tested concrete beams having low coefficient of the longitudinal reinforcement with BFRP and no transverse reinforcement in the three-point bend machine. In the course of the tests they were checking sags in the span middle point, crack widths and deformation of the upper fibres of the compressed concrete. In the authors' opinion this data will make the basis for the development of the BFRP shear model in the beam support zones.

Scmidt A., Kampmann R., Telikapalli S., Emparanza A.R. and De Caso F. analysed the market and current state of production and use of the BFRP reinforcement in their work [22]. Their review of state of the art and practical experience concerned American and international manufacturers and suppliers of the BFRP reinforcement in the logistics dimension. In order to generalize the data required by civil engineers and designers, we manufacturers of the BFRP from 10 various countries were questioned. The questioning results indicated that the majority of the BFRP manufacturers produce whole rods of the round cross-section covered with sand or a spiral winding. It became clear that the BFRP differ little by their shapes and types, which simplifies standardization. The breaking strength of such reinforcement is higher as well as the elasticity modulus as compared with the glass fibre-reinforced plastic (GFRP). It happened that only two out of ten BFRP manufacturers started their production before 2000. Moreover, more than 50% of the manufacturers began to produce the BFRP reinforcement after 2007. It is emphasized that production of such reinforcement in Asia and Europe is greater than in the USA. The authors [22] recommend continuing research of the BFRP structures so as to develop the general guidelines for their production and the design code.

Definition of the earlier unresolved parts of the general problem

The main normative documents and guidelines dealing with calculation of the structures with NCR have been developed in the USA, Canada, Japan, Great Britain and Italy for the last 23 years on the basis of the standards for calculation and design of the steel reinforced concrete structures. In Ukraine and Russia the developed are, accordingly, the Guidelines [10] and Annex Л to SP [12] which can be considered as the drafts of future normative documents.

The main principles governing the calculation have been preserved the same as for the reinforced concrete structures with due account of the linear performance of the NCR. Specific performance of the NCR-containing structures is taken into account by introduction of special decreasing coefficients that characterize work conditions and the standardization of the material characteristics. The formulae for determination of the design parameters of the NCR-containing structures repeat, on the whole, the formulae applied for the structures with steel reinforcement. Still, in the majority of cases the design requirements have been taken more cautious as compared with the reinforced concrete structures.

The aspects pertaining to the standardization of the requirements to fiber-glass, organic plastic and carbon fibre reinforcement have been studied to a greater extent. Application of the basalt plastic reinforcement is still not quite standardized.

Based on the analysis of the results obtained when studying chemical resistance, physical and mechanical properties and the practical experience of the CR application, it is evident that it is expedient to use the BFRP in civil and road construction, in hydrotechnical structures and in the facilities that necessitate special requirements.

Comparison of the published test data with the calculated results of the load-bearing capacity of basalt-fibre reinforced structures made according to the effective domestic and foreign standards as well as to the authors' methodologies proves, on the whole, their poor convergence. At that, as the above mentioned analysis has shown, the lion's share of the publications deals with determination of the load-bearing capacity of the normal cross-sections of NCR structures according to the first and second groups of boundary conditions while the study of strengths of the inclined cross-sections still remains in an embryonic state and remains, practically, not addressed.

Goal of the work and tasks of the study

This work is aimed at experimental study of strength, crack resistance and stress-strain behaviour of the BFRP concrete beams and establishment of the appropriate databank for further development of the physical and mathematical models of the bearing capacity of the normal and transverse cross-sections of the BFRP spanned concrete structures with due account of the action of static and low-cycle high level loads by analogy to similar models [23-25] that have been developed for the reinforced concrete structures.

The tasks of the study:

- to investigate the stress-strain behaviour, the nature of collapsing, load-bearing capacity, width of the normal cracks and sags of basalt fibre reinforced concrete elements in the course of their static and low-cycle loading with the use of the experimental design theory;
- to study the impact of the main design factors on the load-bearing capacity of the support zones of the studied elements, their crack resistance, and stress-strain

behaviour with the aid of experimental and statistical dependencies obtained in the course of processing the obtained data;

- to make a comparative analysis of the impact of the main design factors on said parameters of the similarly reinforced with steel and BFRP test beams with due account of the static and low-cycle loading.

Methodology of the experiments, materials and equipment

In connection with the above, the system experimental research [23-25] of the load-bearing capacity of support zones of complex loaded reinforced concrete beam structures are being performed in Odesa State Academy of Construction and Architecture.

To achieve this goal two more series of field studies were additionally accomplished by testing single-span BFRP concrete beams subjected to static and low-cycle repeated loads of high level in accordance with the central government budget research projects (state registration Nos.0107U000809 and 0108U000559) with the use of the experimental design theory and efficient PC software COMPEX of Prof. V.A. Voznesenskyi.

It is known from literary sources that the main performance parameters of steel, fibre and basalt fibre reinforced concrete structures are governed by the Gaussian law and that it is possible to process the results with the least square method. As the studied factors can influence the output function in a non-linear manner, it is expedient to approximate it with the second order polynomial. That is why the test samples were prepared with the use of the three-factor three-level D-optimum Box plan B3 [26] which ensures the same accuracy of the output parameter prediction within the area that is described with the radius that equals the conventional “1” with respect of the “zero” point.

The following factors (design factors) were chosen as the test ones that were changing 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 – the concrete grade C, MPa, C16/20, C30/35, C40/50; X_3 – transverse reinforcement coefficient ρ_{fw} (ACB-800 (composite basalt-plastic reinforcement)) = 0.0029; 0.0065; 0.0115 for basalt fibre reinforced concrete beams and ρ_{sw} (BpI) = 0.0016; 0.0028; 0.0044 for the reinforced concrete samples. Coefficients of the upper and low longitudinal reinforcement ρ_{lf}=ρ_{ls}=0.0176 for both beam types with the design spans L_0=$9h_0$=1,575 mm and width b=100 mm.

Each study of the field test provided for two twin beams having four support areas. Altogether there were tested 30+30=60 basalt concrete beams subjected to, accordingly, stepped increase of the static and low-cycle repeated loading. For the sake of comparison, we used the test results of similar reinforced concrete beams [25].

The tested beams were reinforced with basalt fibre plastic in kind of two flat tied frames. These elements were produced with the use of heavy concrete of the above indicated grades plus the 5-10 mm granite chips and 1.5 mm fineness modulus quartz sand. Portland cement grade 500 without additives was used as a binder. In order to reduce the water/cement ratio, make it more convenient to place concrete mix and shorten the cure period, all tests were conducted with Relaxol-Super M (ISO 9001 № 04.156.26) complex additive in quantity of 1% of the cement weight as recalculated to dry substance.

Special power installations were designed, manufactured and certified for testing the sample beams. Loads were applied according to the four-point scheme with the aid of the DG-50 hydraulic jack and the load distribution traverse beam; the concentrated forces were applied in stages: with the step (0.04…0.06) F_{ult} until appearance of the first normal and inclined cracks, and afterwards with the step (0.08…0.12) F_{ult} until rupture. The time exposure on a step was up to 15 minutes, and all measurements were made at the beginning and at the end of each step.

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

Deformation of the test concrete samples were measured with the aid of wire and foil strain gauges with the 40 and 50 mm base according to the generally adopted methodology; the strain gauges were glued on one lateral and the top polished sides. The transfer from the strains of the reinforcement measured during testing was accomplished according to Hooke law, and the strains in the concrete were measured through the sectional elasticity modulus. Deformations of the concrete located in the compressed zone and in the tensioned reinforcement were checked with the aid of the dial gauges and the vertical displacements were measured with deflection indicators.

Statement of basic materials and results

Deformation, cracking and destruction of the tested basalt fibre reinforced beams and reinforced concrete beams occurred in accordance with the construction mechanics rules and was predictable. The normal cracks were the first to appear within the zone of the maximum bending moments. As the transverse loading increased, the normal cracks developed deeper in the beam, their widths also increased and new normal cracks were appearing. Then new normal cracks appeared. The further increase of loading has led to the development of normal and inclined cracks with the prevailing opening of the inclined cracks until rupture took place along the dangerous inclined cracks.

The tested beam samples were designed almost of equal strength in the normal and inclined cross-sections, however, they were made so that their collapse was still taking place in along the inclined cracks under action of the collapsing transverse forces and the associated bending moments at the final stage of beam performance.

On the basis of the obtained test data, removal of the insignificant coefficients and re-calculation of the remaining coefficients, the adequate experimental and statistical dependencies of the main test sample performance parameters were obtained with the aid of the efficient computer software program COMPEX.

This data presents a good and useful information and show good convergence with the test data.

Strength (load-bearing capacity) of the studied elements

It can be characterised by the following dependencies:

$$\hat{Y}(V_{us}) = 98 - 41x_1 + 12x_2 + 6x_3 + 16x_1^2 - 7x_2^2 - 5x_3^2 - 7x_1x_2, \text{кН}, \mho = 5.1\%; \quad (1)$$

$$\hat{Y}\left(V_{us}^{cyc}\right) = 90 - 36x_1 + 10x_2 + 7x_3 + 18x_1^2 - 6x_2^2 - 6x_3^2 - 8x_1x_2, \text{кН}, \mho = 5.1\%; \quad (2)$$

$$\hat{Y}\left(V_{uf1}\right) = 51{,}8 - 30.1x_1 + 11.8x_2 + 5.5x_3 + 15.9x_1^2 - 5.5x_2^2 - 2.3x_3^2 - 10.6x_1x_2 - -4.8x_1x_3, \text{кН}, \mho = 5.0\%; \quad (3)$$

$$\hat{Y}\left((V_{uf2}^{cyc}\right) = 44.3 - 27.0x_1 + 10.4x_2 + 4.5x_3 + 17.3x_1^2 - 4.0x_2^2 - 2.4x_3^2 - 10.2x_1x_2 - 2.9x_1x_3, \text{кН}, \mho = 5.5\%, \quad (4)$$

where, V_{us}, V_{us}^{cyc} – collapsing transverse force at, accordingly, static and low-cycle repeated loading of reinforced concrete beams according to [25];

V_{uf1}, $V_{uf2}^{\boldsymbol{cyc}}$ – collapsing transverse force at, accordingly, static and low-cycle repeated loading of the BFRP concrete beams at the same values of the design factors.

The presented adequate experimental and statistical dependencies (1)…(4), which Prof. V.A. Voznesenskyi called mathematical models [26], have essential advantage over correlation and other dependencies because they enable to comprehensively evaluate the influence of each above indicated factor upon the key output parameters, and not only by themselves but also in their interaction with each other. It is also possible to compare the value of such influence both on the reinforced concrete beams and on the BFRP reinforced concrete elements subjected to step-like increasing static and low-cycle repeated loading. Geometric interpretation of the load-bearing capacity of the tested sample beam support areas is, partially, presented in Figure 1.

The greatest influence on the load-bearing capacity of the tested elements among the design factors is produced by the value of the relative shear span (Figure 1, a). On the whole, the regularity of decrease of the inclined cross-sections strength in the beams reinforced both with steel and basalt (BFRP) reinforcement in parallel with the non-linear increase of the shear span, which was found by O.S. Zalesov, Yu.A. Klymov [27], V.M. Karpiuk [23 - 25] and other researchers, is confirmed.

The concrete grade is the next factor according to the influence value. At that, when the concrete grade increases from C16/20 to C30/35, the load-bearing capacity of the inclined cross-sections grows more intensively.

The similar picture is observed when the transverse reinforcement coefficients $\rho_{sw}$and $\rho_{\boldsymbol{fw}}$increase.

Analysis of the dependencies (1)…(4) indicates that they are qualitatively of the same type, and the impact of the design factors and the factor of low-cycle repeated loading are qualitatively similar. Variations are observed in quantitative values only.

Hence, the load-bearing capacity of the inclined cross-sections in the test beam samples is expressed via the collapsing transverse force V_u and increases relative to their average values (constant terms b_0) to make, accordingly, 98; 90; 51.8; and 44.3:

- as the relative shear span a/h_0 decreases from 3 to 1 in the indicated series - by 84%, 80%, 116% and 122%, accordingly;
- as the concrete grade increases from C16/20 to C40/50 - by 24%, 22%, 46% and 47%, accordingly;
- as the quantity of the transverse steel reinforcement ρ_{sw}increases from 0.0016 to 0.0044 (expressions (1), (2)) and that of the BFRP $\rho_{\boldsymbol{fw}}$ from 0.0029 to 0.0115 - by 12%, 16%, 21% and 20%, accordingly;
- as the relative shear span a/h_0decreases in parallel with the increase of the concrete grade C - by 7%, 9%, 20% and 23%, accordingly;
- as the relative shear span a/h_0decreases in parallel with the increase of the quantity of the transverse basal-plastic reinforcement $\rho_{\boldsymbol{fw}}$ - by 9% and 7%, accordingly.

Appearance of the quadratic effects at factors X_1^2, X_2^2, X_3^2 of the signs that are opposite to the direct impact of said factors indicates that, beyond the boundaries of the test factor changes (a/h_0>3, C>40/50МПа, ρ_{sw}>0.0044 і ρ_{fw}>0.0115), any further increase of a/h_0 will not lead to a considerable decrease of the load-bearing capacity (collapsing transverse fore (Figure 1, a), so any further increase of the concrete grade C (Figure 1. b) and the quantity of the transverse steel ρ_{sw} and basalt-plastic ρ_{fw} reinforcement (Figure 1, c) are not expedient because the process of V_u increase is, in this case, of the fading nature.

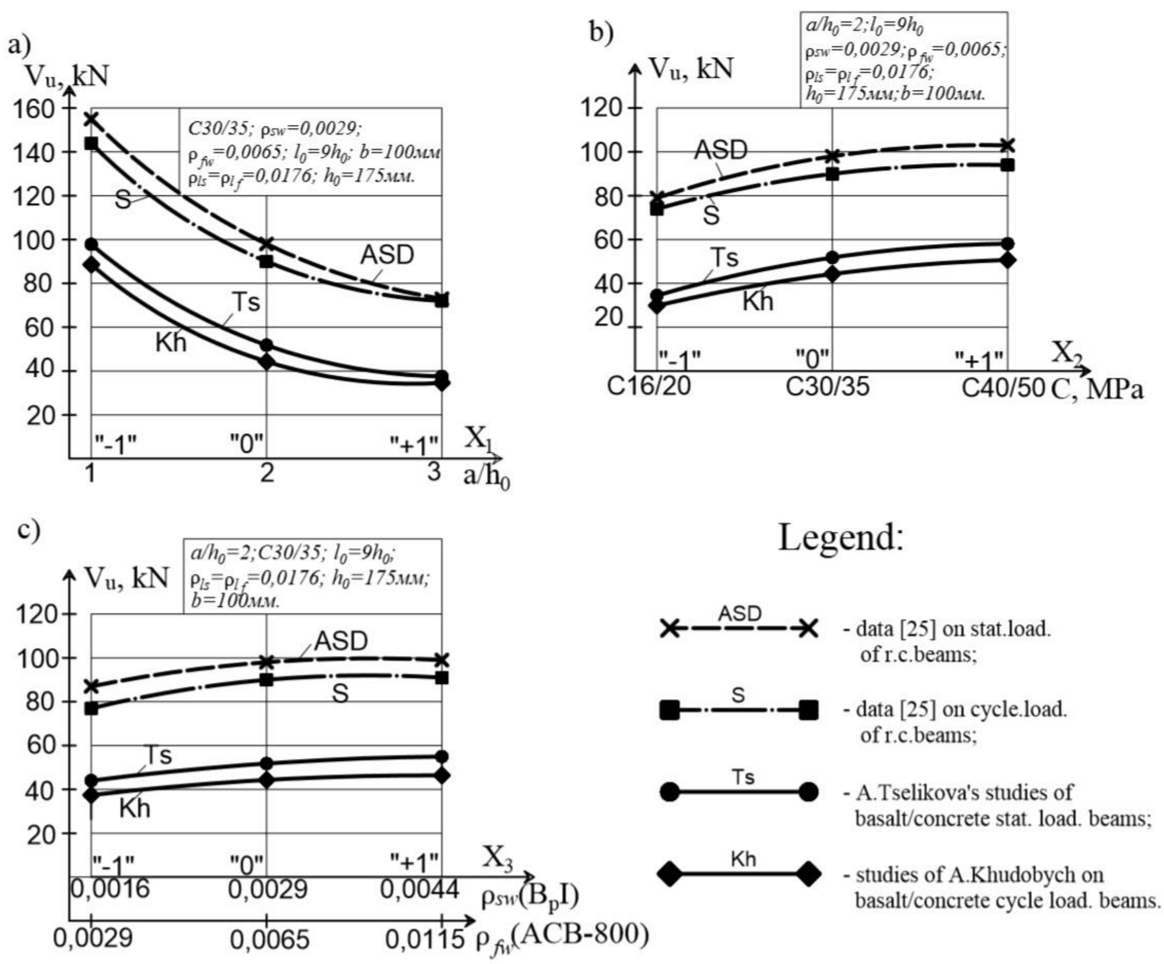

Figure 1. Impact of the relative shear span (a), concrete grade (b) and quantity of the transverse reinforcement (c) on the load-bearing capacity of the test element support areas.

Due to a considerably higher deformability (4.44 times) replacement of the steel reinforcement with the BFRP reinforcement, all other design factors being equal, has led to a decrease of the collapsing transverse force V_u at static loading of the tested beam samples by 47% on the average, and in case of the low-cycle repeated loading – by 51%. It is characteristic that such decrease of their load-bearing capacity is common within the entire range of the design factor variation (Figure 1).

The low-cycle repeated loading reduces the load-bearing capacity of the reinforced concrete beam support areas on the average by 8%, which is confirmed by numerous papers of Prof. Ye.M. Babych, Prof. G.Kh. Masyuk and their followers, and of the BFRP concrete elements – by 14%, as it became evident.

The repeated loading cycles number in the performed tests was dictated by the Ye.M. Babych criterion of the deformation stabilization in concrete, and was at least 10, if the tested beam samples have not collapsed at the smaller number of cycles.

The absolute majority of the tested beams collapsed in the inclined cross-sections in both or one (more frequently) shear spans. The criterion of the test samples collapse was:

achievement of the ultimate deformations in concrete or reinforcement that had evident signs of the plastic deformation appearance, excessive opening of the inclined cracks (to 1 mm and more) (more frequently) or the normal cracks (less frequently), essential increase of the bending deflection ($f \geq \frac{1}{100} l_0$) and absence of an increment or certain decrease (to 15%0 of the pressure gauge of the power installation pumping station.

It is evident that the main reason of the load-bearing capacity reduction in the test samples at the low-cycle repeated loading is due to disturbance of the concrete structure, particularly in the support area zones, loss of the concrete density and partial loss of the cohesion with the reinforcement.

The greatest increment of the residual deformations in concrete and transverse reinforcement is observed during the first two-three cycles and, as a rule, these stabilize until the fifth-sixth cycles at the loading levels η = 0…0.50 - 0…0.65. In some samples with the minimum concrete grade and the minimum transverse reinforcement quantity at loading levels N = 0…0.8 said deformations did not stabilize and the beams collapsed during 6…9 cycles because of reaching the fatigue strength or because of possible reduction of the strength parameters resulting from statistical error when determining the collapsing static step-wise increasing loading.

Not overreinforced (ρ_{sw}⩽0.003(BpI), $\boldsymbol{\rho_{ls}}$⩽0.018(A500C)) reinforced concrete sample beams that were tested by step-wise increasing static and low-cycle repeated loading [25] collapsed, as a rule, according to B/MM [23] pattern, i.e., along the inclined cross-sections with the prevailing action of the bending moment resulting from the yield of the longitudinal working reinforcement in the mouth of the dangerous inclined crack and the transverse reinforcement which crosses it. As the quantity of the transverse reinforcement $\rho_{sw} \geq 0.0044$increases, the similar test elements having the average (a/h_0=2) values and large (a/h_0=3) shear spans were collapsing according to C/V [23] pattern, i.e., along an inclined crack with the prevailing action of the transverse force resulting from the yield of the transverse reinforcement and shear or crushing of the concrete located in the compressed zone above the top of the dangerous inclined crack. With small shear spans (a/h_0⩽1) the studied reinforced concrete beams collapsed, as a rule, according to D//cm pattern [23] along the inclined compressed strip between two inclined cracks because concrete crushed in this strip along the path of the main compressing stresses or concrete shear subjected to the maximum tangential stresses. Taking into consideration a relatively big quantity of the longitudinal BFRP reinforcement **(**$\boldsymbol{\rho_{lf}}$=0.0176), the BFRP beams collapsed along the inclined cracks in the concrete as a result of its crushing in the artificially reduced, due to a shift of the neutral line of the compressed up to the top zone above the apex of the dangerous inclined crack. At that, the stress and deformations in the transverse BFRP rods which are crossed by this inclined crack reach the maximum values.

Deflections of the experimental samples at the operational ($N = \mathbf{0.65}F_u$) loading level

These can be represented by the following experimental and statistical dependencies:

$$\hat{Y}\left(f_{s,\eta F_u}\right) = 4.5 + 0.8x_1 + 0.35x_2 + 0.25x_3 - 0.35x_1^2 - 0.15x_2^2 + 0.30x_1x_3, \text{мм}, \mho = 6.0\%, \quad (5)$$

$$\hat{Y}\left(f_{s,\eta F_u}^{cyc}\right) = 5.00 + 0.85x_1 + 0.40x_2 + 0.25x_3 - 0.40x_1^2 - 0.15x_2^2 + 0.30x_1x_2, \text{мм}, \mho = 6.4\%, (6)$$

$$\hat{Y}\left(f_{f1,2,\eta F_u}^{cyc}\right) = 10.20 + 0.91x_1 + 1.04x_2 + 0.73x_3 - 0.74x_1^2, \text{мм}, \mho = 5.3\%, \quad (7)$$

which show that the BFRP concrete beam deflections are more than 2 times greater than the deflections of similar reinforced concrete elements having the same design factors and reach, on the average, 1/154 of the design length of the span.

As the collapsing transverse load at low-cycle repeated loading decreases by about 14%, as compared with the statistical value, and the deformability of the compressed concrete increases at the same value, then, as it became clear, the impact of the low-cycle loading at this level did not produce effect on the deflections.

The graphical representation of deflections in basalt-concrete and reinforced concrete beams subjected to operational loads is shown in Figure 2.

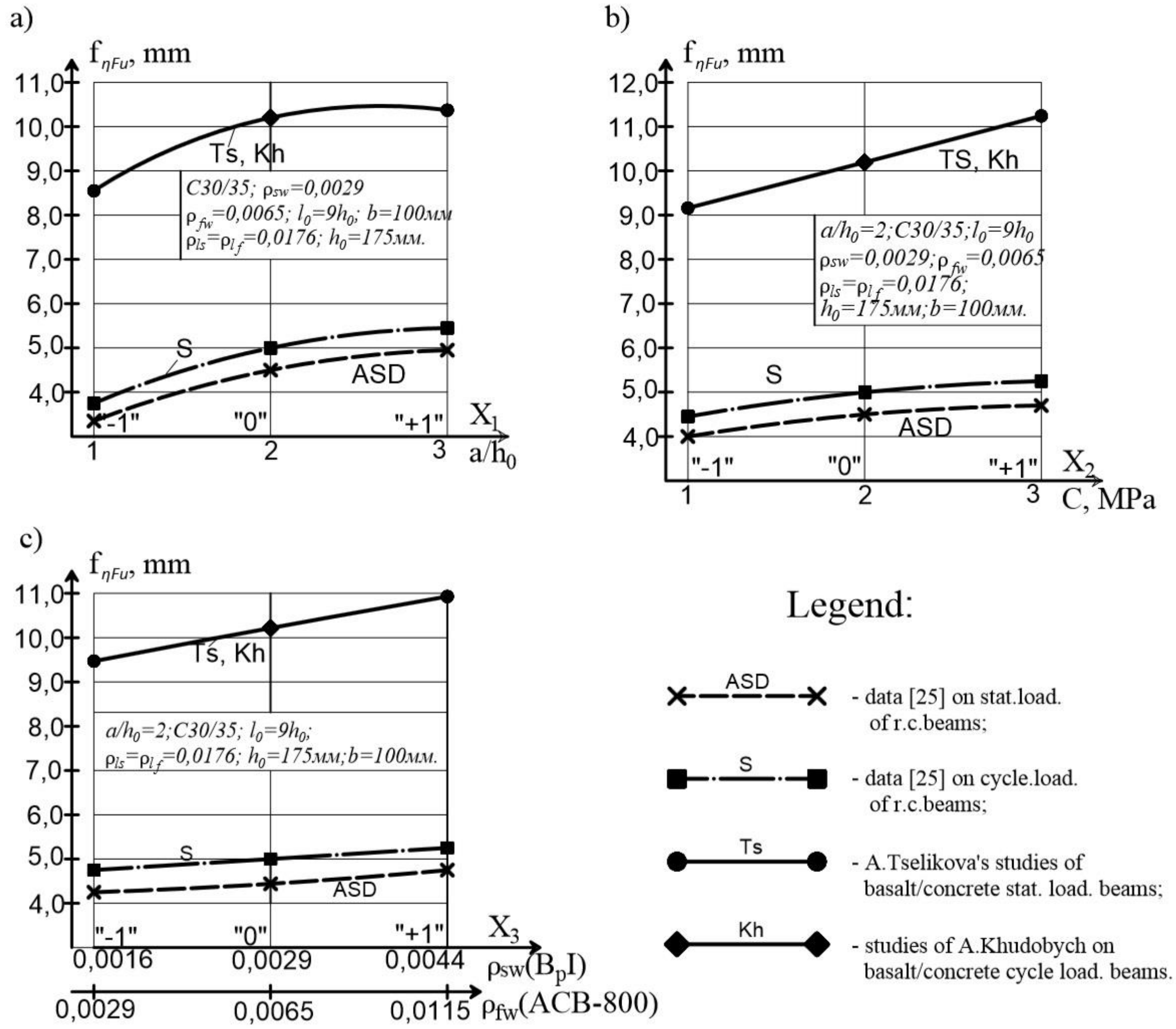

Figure 2. Beam deflections at the operational ($\eta = 0.65F_u$) level of transverse loading versus the relativeshear span (a), concrete grade (b) and quantity of the transverse reinforcement (c).

Deflections of the test beams before their collapse

They are characterized by the following expressions:

$$\hat{Y}(f_{us}) = 6.00 + 1.50x_1 + 0.65x_2 + 0.70x_3 - 0.50x_1^2 + 0.20x_1x_3, \text{мм}, \mho = 5.8\%; \quad (8)$$

$$\hat{Y}(f_{us}^{cyc}) = 6.5 + 1.5x_1 + 0.75x_2 + 0.75x_3 - 0.55x_1^2 + 0.20x_1x_3, \text{мм}, \mho = 5.1\%; \quad (9)$$

$$\hat{Y}(f_{uf1,2}^{cyc}) = 14.28 + 1.34x_1 + 1.46x_2 + 1.01x_3 - 1.03x_1^2, \text{мм}, \mho = 5.6\%, \quad (10)$$

which geometrical interpretation is shown in Figure 3.

Before the collapse the deflections of the BFRP concrete beams have reached, on the average, and exceeded the deflections of the reinforced concrete beams by about 2.2…2.4 times.

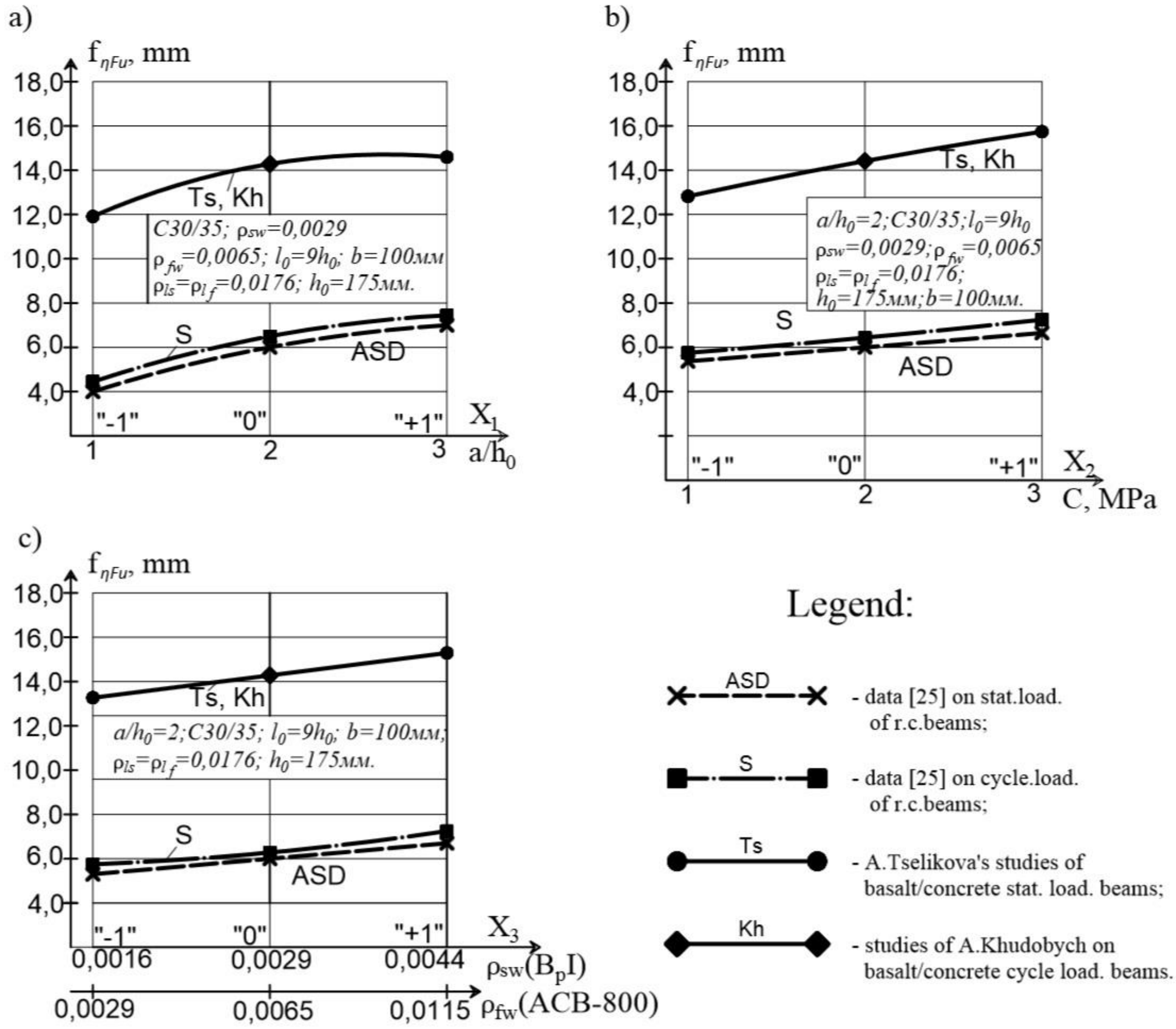

Figure 3. Impact of the design factors (relative shear span (a), concrete grade (b) and quantity of the transverse reinforcement (c) on the test beam sample deflections before their collapse ($\eta \cong 0.95F_u$).

Formation of the normal and inclined cracks in BFRP concrete beams

It is characterized by the corresponding dependencies (11) and (12) which are shown in Figure 4.

$$\hat{Y}\left(M_{crf}^{\perp}\right) = 3.25 + 0.98x_2 + 0.14x_3, \text{кНм}, \mho = 5.1\%; \quad (11)$$

$$\hat{Y}\left(V_{crf}^{/}\right) = 20.5 - 9.6x_1 + 3.3x_2 + 0.8x_3 + 5.1x_1^2 - 0.5x_2^2 - 0.6x_3^2 - 2.4x_1x_2, \mho = 8.0\%, \quad (12)$$

Opening width of the normal cracks in the test elements at low-cycle loading of the operational level.

It can be described by the dependencies (13)…(14) and is represented in Figure 5.

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

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

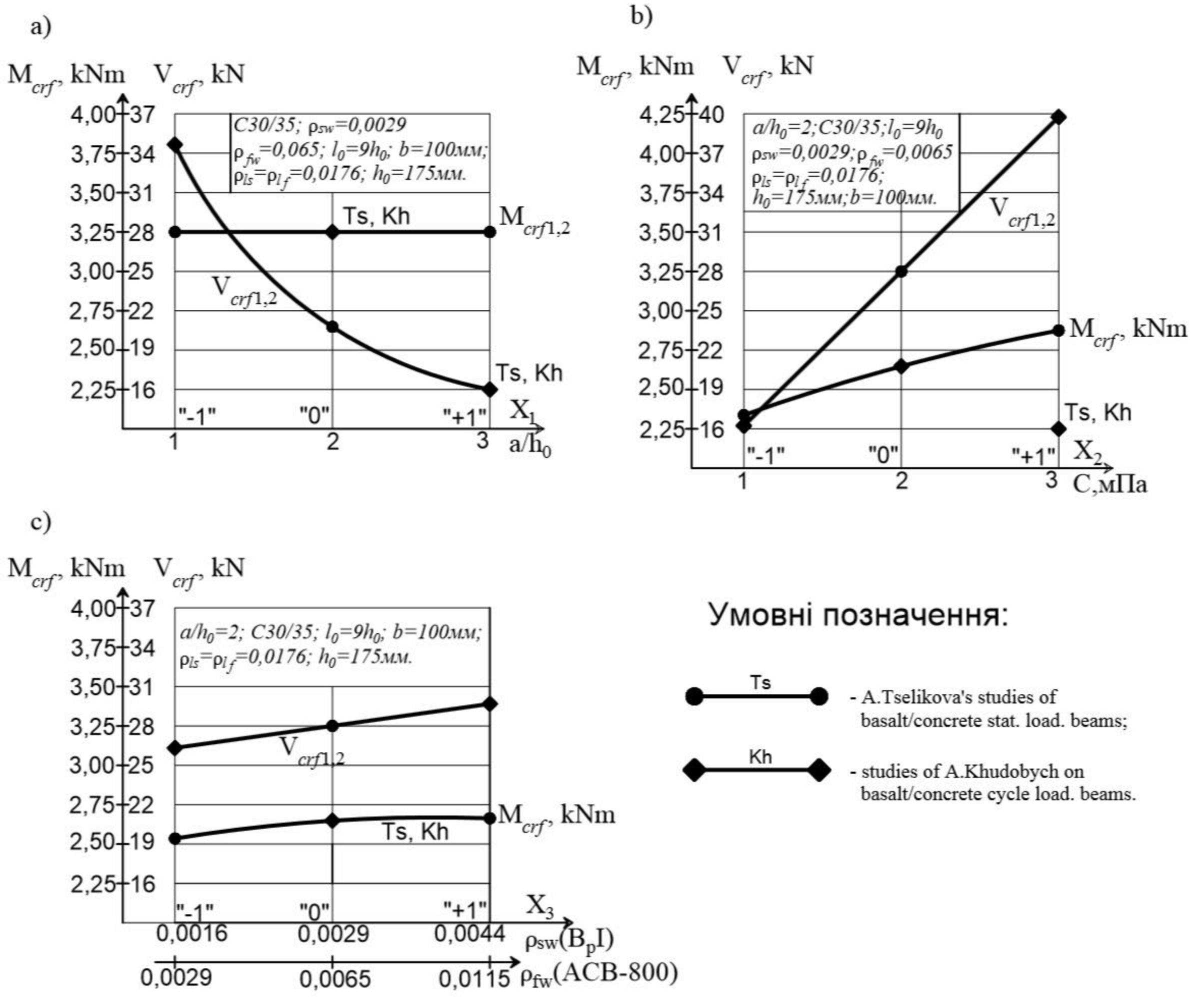

Figure 4. Moment $M_{cr1,2}$ and transverse force $V_{crf1,2}$ in the formation of, accordingly, normal and inclined cracks in the studied BFRP concrete beam samples versus the shear span (a), concrete grade (b) and quantity of the transverse reinforcement (c) subjected to static (index 1) and low-cycle (index 2) repeated loading.

As it is shown in Figure 5, the opening width of the normal cracks in the test samples subjected to the operational loading does not exceed permissible levels.

Opening width of the inclined cracks in the test beams at static and low-cycle loading of the operational level.

It is described by the dependencies (15)...(18) and is represented in Fig. 6.

$$\hat{Y}\left(W_{ks}^{/}\right) = 0.35 - 0.06x_1 - 0.03x_2 - 0.01x_3 - 0.01x_1x_3, \text{мм}, \mho = 10.4\%; \quad (15)$$

$$\hat{Y}\left(W_{ks}^{/cyc}\right) = 0.40 - 0.05x_1 - 0.03x_2 - 0.03x_1x_3, \text{мм}, \mho = 6.0\%; \quad (16)$$

$$\hat{Y}\left(W_{kf1}^{/}\right) = 0.30 - 0.08x_1 - 0.15x_2 + 0.07x_3 + 0.03x_1^2 + 0.03x_2x_3, \text{мм}, \ \mho = 13.7\%. \quad (17)$$

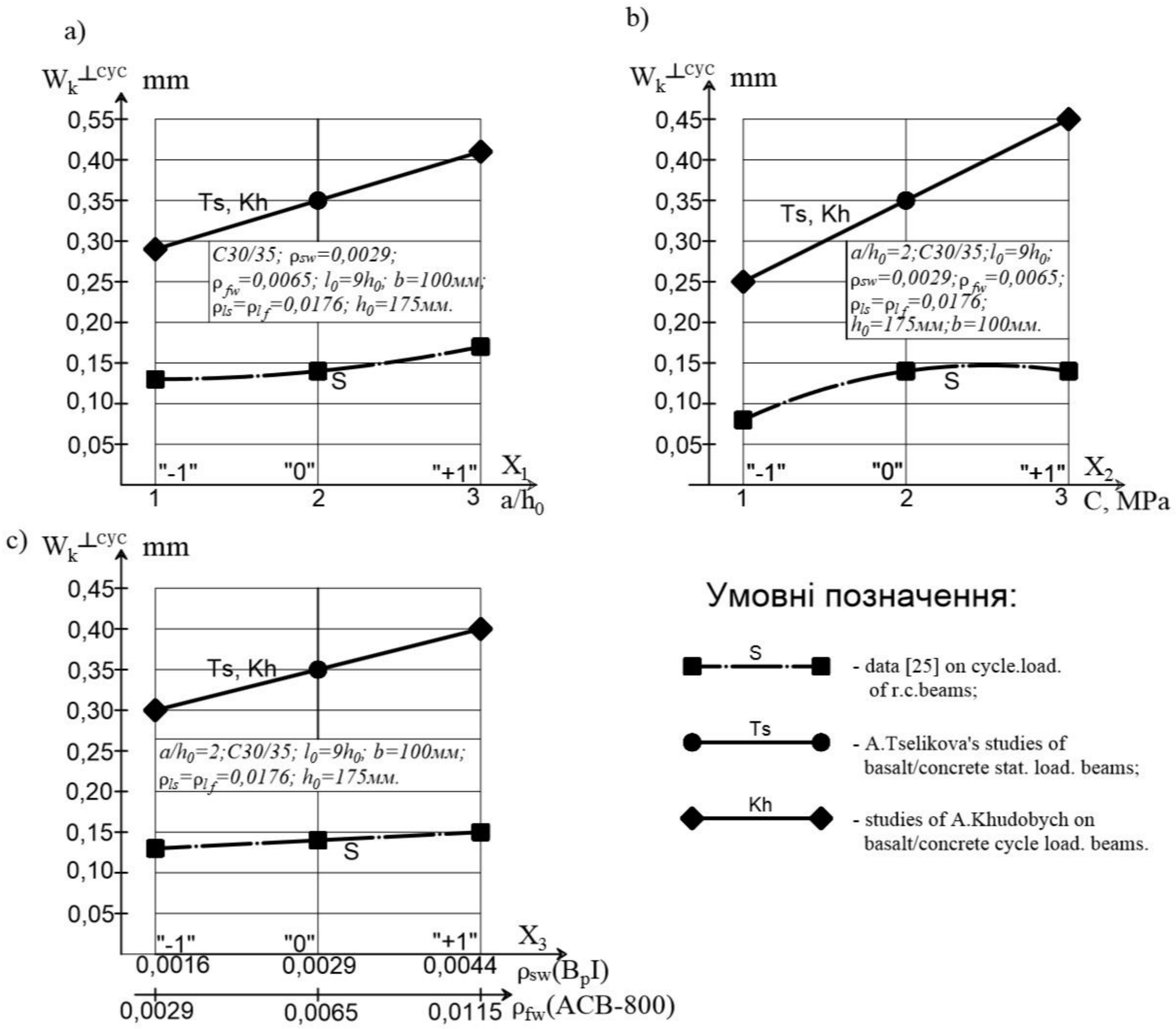

Figure 5. Impact of the design factors on the opening width of normal and inclined cracks in the tested reinforced concrete and BFRP concrete beams subjected to static low-cycle loading of the operational level ($\eta \cong 0.65F_u$).

Conclusions:

1. The accomplished system approach to the experimental and theoretical study of the stress-strain behaviour of beam structures reinforced with steel and basalt-plastic (BFRP) enabled, for the first time, to perform reliable quantitative and qualitative evaluation of the impact of design factors and external factors on their load-bearing capacity, stiffness, crack resistance and other performance parameters taken both individually and in interaction with each other, to considerable specify the physical model of how said structures work when subjected to static and low-cycle repeated loading. In particular, it was established that the strength of the studied elements is increasing in a non-linear manner:

- as the relative shear span a/h_0 decreases from 3 to 1 in the indicated series – by 80...122%;
- as the concrete grade increases from C16/20 to C40/50 - by 24...47%, accordingly;

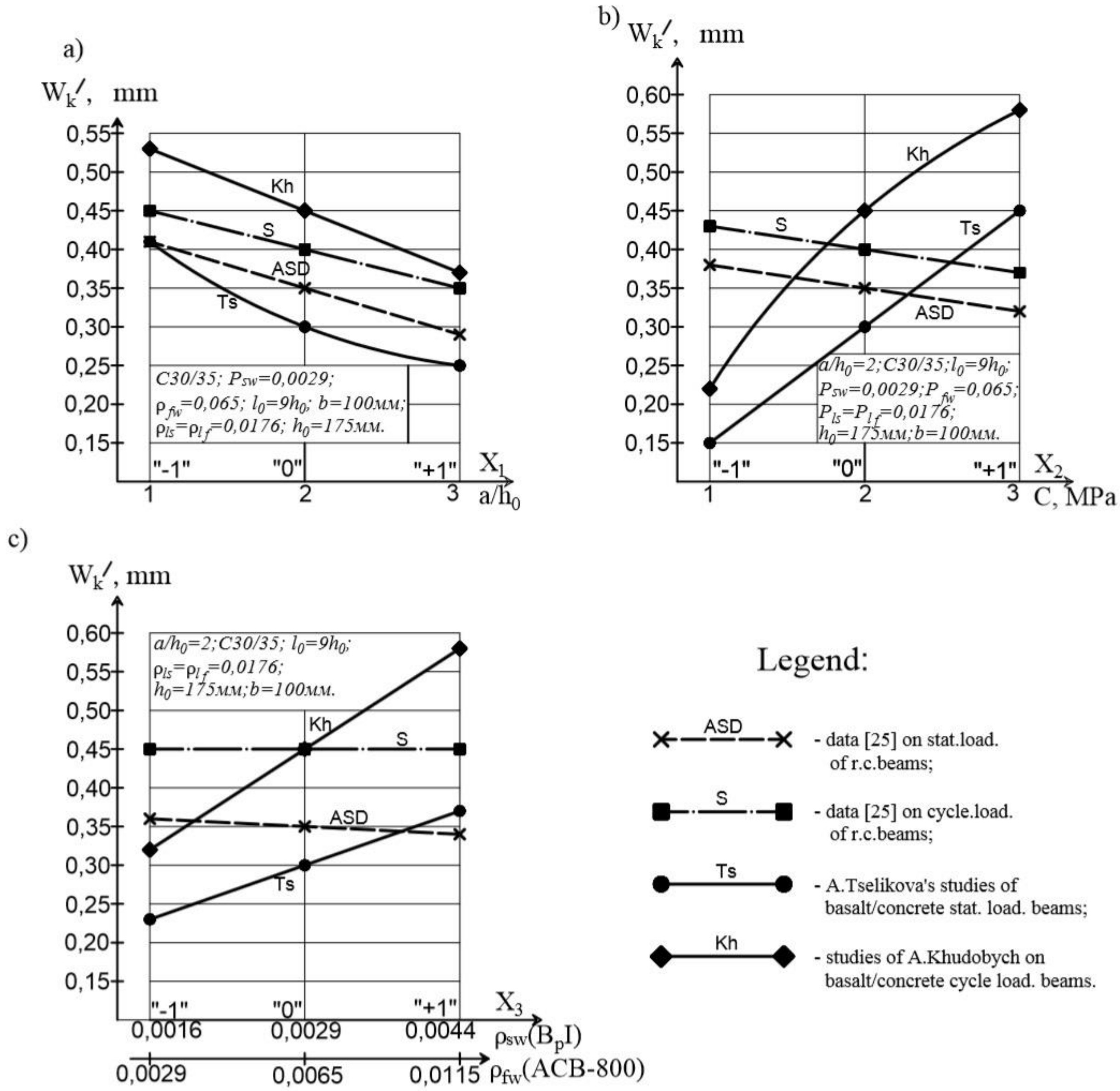

Figure 6. Opening width of the inclined cracks in the test beam samples subjected to the operational load level ($\eta \cong 0.65F_u$) versus the relative shear span value (a), concrete grade (b) and the quantity of the transverse reinforcement (c).

- as the quantity of transverse reinforcement ρ_{sw} increases from 0.0016 to 0.0044 and BFRP reinforcement ρ_{fw} from 0.0029 to 0.0115 – by 12… 16% and 20…21%, accordingly;
- as the relative shear span decreases and, in parallel, the concrete grade increases by 7…23%;
- as a/h_0 decreases and ρ_{fw} increases by 7… 9%.

2. Replacement of the steel reinforcement with the more yielding BFRP reinforcement leads, all other design factors being similar, to a decrease of the load-bearing capacity of the inclined cross-sections in the tested beam samples subjected to static loading by, on the average, 47%, and to low-cycle repeated loading – by 51%..

3. Low-cycle repeated loading decreases the load-bearing capacity of the reinforced concrete beam support areas by, on the average, 8%, and that of the BFRP reinforced concrete elements – by 14%.

4. Deflections of the BFRP reinforced concrete beams more than twice exceed the deflections of similar reinforced concrete elements with the same design factors and reach, on the average, 1/154 of the design length of the span at the operational loading level ($0.65F_u$), and are increasing to 1/110 before collapse ($0.95F_u$).

5. Opening width of the normal cracks in reinforced concrete beams subjected to operational level of the low-cycle repeated loading equals, on the average, 0.14 mm, and that of the BFRP reinforced beams – 0.35 mm. Accordingly, the average opening width of the inclined cracks in the reinforced concrete equals 0.40 mm, and in the BFRP reinforced beams - 0.45 mm at the similar loading.

6. In order to considerably increase the load-bearing capacity of the inclined cross-sections in span BFRP reinforced structures and to decrease their deflections and the opening width of the normal and inclined cracks, we consider it expedient to manufacture them out of the prestressed BFRP and to ensure the appropriate scientific and technical support.

References

1. *Recomendacii po raschety construkciy so stekloplasticovoi armaturoi* [Recommendations for the calculation of constructions with fiberglass reinforcement]. Moscow. NIIJB, P 16-78, 978, pp 20.
2. Frolov N.P. *Stekloplastikovaya armature i stekloplastbetonnie construkcii: uchebnik* [Fiberglass reinforcement and fiberglass concrete structures: a textbook]. Stroyinzdat, 1980, pp. 104.
3. Dolan C.W., Hamilton H.R., Bakis C.E., Nanni A. Design Recommendations for Concrete Structures Prestressed with FRP Tendons. Final Report, University of Wyoming, 2000.
4. Kuzevanov D.V. *Nauchno-tehnicheskiy otchet "Konstrukcii s kompositnoj nemetalicheskoj armaturoj. Obzor i analiz zarubegnih i otechestvennyh normativnuh dokumentov"* [Scientific and technical report "Designs with composite non-metallic reinforcement. Review and analysis of foreign and domestic regulatory documents] [online]. 2012, [accesat (15.10.2018)].
   Disponibil: http://fordewind.org/wiki/tib/exe/fetch.php?media=img:nka2012.pdf
5. Kustikova J.O. *Napryazgonno-deformirovannoe sostoyanije scepleniya bazaltoplastikovoj armatury s betonom: dissertacija na soiskanie nauchnoj stepeni kandidata tehnicheskih nauk* [The stress-strain state of adhesion of basalt-plastic reinforcement with concrete: a dissertation for the degree of candidate of technical sciences]. Moscow, 2014, pp. 181.
6. Brik V.B. Performance Evaluation of 3-D Basalt Fiber Reinforced Concrete Basalt Rod Reinforced Concrete, Washington: Transportation Research Board, 1998.
7. Brik V.B. Advanced Concept Concrete Using Basalt Fiber, BF Composite Rebar Reinforcement, Washington: Transportation Research Board, 2003, pp. 30.
8. Fico R. Limit states design of concrete structures reinforced with frp bars. PHD Thesis, University of Naples Federico II, 2007.
9. Technology group "Ekipag" *"Otcheti o provedennih ispitanijah stekloplastikovoj i bazaltoplastikovoj armatury"* [Test reports of fiberglass and basalt-plastic reinforcement]. 2008-2011 [acces at (18.12.2019)]. Disponibil: http://www.frp-rebar.com/frp–rebar–test.html
10. Government Standards of Ukraine N B V.2.6- 185:2012 of 1 April 2013 on the design and manufacture of concrete structures with non-metallic composite reinforcement based on basalt and glassware. Kyiv: Ministry of Regional Development, Construction and Housing and Communal Services of Ukraine [online]. 2012, pp. 28. [accesat (10.01.2020)]. Disponibil:
    https://dbn.co.ua/load/normativy/dstu/dstu_n_b_v_2_6_185/5-1-0-1173
11. Rahmonov A.D. *Prochnost, giostkost i treschenostojkost nerazreznih betonnih balok s kombinirovannim armirovanijem: dissertacija na soiskanije nauchnoj stepeni kandidata nauk* [Strength, Stiffness and Crack Resistance of Non-Cut Concrete Beams with Combined Reinforcement: Dissertation for the Candidate of Science Degree]. Kazan, 2015, pp. 160.
12. Concrete and reinforced concrete structures. The main provisions. Set of rules: СП63.13330.2012 / TK 465 "Building" of 01.01.2013 in Building regulations 52-01-2003 – M:2012. [online]. 2013, pp. 79 [acces at (25.10.2019)]. Desponibil:

http://docs.cntd.ru/document/1200095246

13. Koval P.M. Vrahuvanja diji malociklovih navantajen pri rozrahunku bazaltobtonnih balok, armovanih bazaltoplatikovoju armaturoju [Considering the number of low-cycle loads at the basing base, reinforced basalt-plastic fittings]. In: *Bridges and tunnels: theory, research, practice*, 2018, 16(13), pp. 37-45.
14. Elavenit S., Saravanan S., Reddy R. *Investigation of structural members with basalt rebar reinforcement as an effective alternative of standard steel rebar* [online]. 2017, [accesat (10.01.2020)]. Disponibil: http://www.icontrolpollution.com/articles/investigation-of-structural-members-with-basalt-rebar-reinforcement-as-an-effective-alternative-of-standard-steel-rebar-.pdf
15. Serbescu A., Guadagnini M., Pilakoutas K. Mechanical characterization of basalt FRP rebars and long-term strength predictive model. In: *Journal of Composites for Construction*, 2015, 19(2).
16. Vincent P., Ahmed E., Benmokrane B. Characterization of Basalt Fiber – Reinforced Polymer (BFRP) reinforcing bars for concrete structures. In: *Proceedings, Annual Conference Canadian Society for Civil Engineering* – 2013, 5 January 2013. pp. 4489 – 4498.
17. Li L., Lu J., Fang, S., Liu, F., Li, S. Flexural study of concrete beams with basalt fibre polymer bars. In: *Proceedings of the Institution of Civil Engineers: structures and Buildings*, 2018, 171 (7), pp. 505 – 516.
18. Atutis M., Valivonis J., Atutis, E. Experimental study of concrete beams prestressed with basalt fiber reinforced polymers. Part 1: Flexural behavior and serviceability. Composite Structures, 2018, pp. 114 – 123.
19. Thorhallsson E., Zhelyazov T., Gunnarsson A., Shaebjornsson J.T. Concrete beams reinforced with prestressed basalt bars. Concrete – innovation and Design: fib Symposium Proceedings, 2015, pp. 277 – 278.
20. Zhu H., Wu G., Zhang L., Zhang J., Hui D. Experimental study on the fire resistance of RC beams strengthened with near surface – mounted high – T_g BFRP bars. Composites Part B: Engineering 60, 2014, pp. 680 – 687.
21. Hofmann S., Graubner C.-A., Proske T. Load – bearing performance of concrete beams with basalt fibre reinforced polymer (BFRP) rebars. Proceedings of the 12th fib International PhD Symposium in Civil Engineering, 2018, pp. 419 – 426.
22. Scmidt A., Kampmann R., Telikapalli S., Emparanza A.R. De Caso F. Basalt FRP production: Market analysis and state – of – the – art report. Proceedings of the fib Symposium 2019: Concrete – Innovations in Materials, Design and Structures, 2019, pp. 189 – 196.
23. Karpiuk V.M., Somina Y.A., Antonova D.V. Calculation models of the bearing capacity of span reinforced concrete structure support zones, vol, 968 MSF, 2019.
24. Karpiuk V., Somina, Y., Maistrenko O., Engineering Method of Calculation of Beam Structures Inclined Sections Based on the Fatigue fracture Model. Lecture Notes in Civil Engineering 47, 2020, pp. 135 – 144.
25. Karpiuk V.M., Somina Y.A., Kostiuk A.I. *Osoblivosti napruzheno-deformovanogo stanu i rozrahunku zalizobetonnih konstrukcij za diji ciklichnogo navantagenja visokih rivniv: monografija* [Features of stress-strain state and calculation of reinforced concrete structures under the action of cyclic loading of high levels: monograph]. Odesa, Odesa Government Academy of Building and Engineering, ISBN 978-617-7195-54-1 2018. pp. 273.
26. Voznesenskij V.A. *Statisticheskii metody planirovanija eksperimenta v tehniko-ekonomicheskih issledovanijah* [Statistical methods of experiment planning in feasibility studies]. 1981. pp. 215.
27. Zalesov A.S., *Klimov Yu.A. Prochnost Gelezobetonnih konstrukcij pri dejstvii poperechnih sil* [Strength of reinforced concrete structures under the action of transverse forces]. Kiev: Budivelnik, 1989. pp. 104.