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STRENGTH, CRACTIC RESISTANCE AND DEFORMATIVITY OF REINFORCED CONCRETE BEAMS DAMAGED BY THROUGH CRACKS, REINFORCED CARBON FIBER

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Abstract. The article deals with the main results of experimental studies of strength, crack resistance and informational content of the diagonal and normal sections of common damaged and brought to the critical state of the first group r. c. - beams reinforced with carbon fibre sheet in the lower tensioned zone and on the support area. According to the adopted methodology, an experiment was conducted on the four-factor three-level Box-Benkin B4 plan. The average relative deformation values of the compressed concrete in the middle part of beams after their stabilization under low-cycle static loading have been evaluated. Tests of prototypes were carried out according to the scheme of single-track free-beam, alternately loaded from above, then from below by two concentrated forces without changing its position.

Introduction

In the course of operation or armed hostilities the span r.c. structures are subject to substantial damage and considerable reduction of their bearing capacity, especially under low-cycle repeated loading. In this regard, there is a need to restore their performance and / or increase bearing capacity. However, in the current design standards there are no recommendations to determine the residual bearing capacity of such structures and calculate their gain. There are some known methods to restore performance and strengthen the structure by increasing the cross section and attaching additional metal or reinforced concrete elements. Still, the calculation methods of such reinforcement are also imperfect. It is proposed to renew operation capacity of such structures by strengthening their tensioned parts with CFRP; the performed experimental research will provide the basis to calculate bearing capacity of present structures with the aid of the deformation method improved by the authors.

Theoretical prerequisites, procedures and results of the research

Resistance of r.c. elements to the combined action of transverse forces and bending moments at low-cycle non-reversal high-level loads is one of the most significant and underexplored problems both in the r.c. theory and in actual design process [1]. Indefinite repetition in operation and a change of the reverse load can lead to the consequences that are qualitatively different from those obtained as a result of calculation for permanent loading of maximum intensity which actually is taken into account by the majority of effective design standards.

Existing design standards, even under constant load, are far from perfectionism. Significantly "lag behind" in this regard are methods to calculate strength of normal sections, when the influence of non-repeating cyclic signs of load on them is taken into account indirectly or not at all, especially at a higher level.

A survey of the available bibliography has proved that researchers still did not come to a single opinion about the impact of loads on the bearing capacity of the studied elements. Majority of authors indicate that such bearing capacity reduces under low-cycle loading. Other researchers [2, 3, 4] state that the infrequent cyclic loading of the operational level ($\eta \leqslant 0.70$) can lead up to 20% higher strength of the span r.c. elements, which needs additional clarifications and experimental confirmation.

Resistance of the span r.c. CFRP-strengthened structures subjected to low-cycle repeated high-level loading that have been damaged in operation or in military hostilities was not studied at all. Therefore, the research is important and up-to-date.

Research methodology

In accordance with the adopted methodology the in-situ test is accomplished with the use of 4-factor 3-level B4 plan of Box-Behnken. The factors have been varied according to the data elicited from the literature review which show that the most influential factor X1 is the value of the relative span of the section a/h_0, which was varied at three levels: $a = h_0$, $2h_0$ and $3h_0$.

The next influential by value factor is, as a rule, such design factor as the grade of heavy concrete: X2 → C16/20, C30/35, C40/55, and the third factor – the value (quantity) of the transverse reinforcement in the support areas: X3 → ρ_{sw}=0.0016; 0.0029; and 0.0044. The fourth factor was assumed to be the external action factor X4 and a level of the reversal load: $\eta = \pm 0.50$; ±0.65; ±0.80 of the actual bearing capacity, i.e., the transverse load value where at the opening width of the diagonal cracks wk exceeded 0.4 mm, and the span sag $f \geqslant 1/150$.

The tested beam samples were kept in normal thermal and humid conditions at the temperature 20±2°C and almost 100% air humidity during 100…110 days.

Prior to testing the side surfaces of the beams were coated with a thin layer of lime solution in order to facilitate fixation of formation and development of normal and diagonal cracks, and afterwards these beams were dried until they reached the natural humidity.

Deformations of the concrete, reinforcement and bending of the test samples were measured with the aid of dial indicators having a division value 0.001 mm and 0.01mm accordingly. The samples were tested according to the pattern of a single span simply supported beam which was intermittently loaded from the top and from the bottom by two point forces without any changes in the beam position.

Before the main experiment the 25 test beams (twin beams) of the first series were tested in turn for action of a single-time short-period stage-wise increasing loading, practically, up to destruction, when the open width of the diagonal cracks and the sag exceeded the permissible values (wk > 0.8 mm, f ≥ l/150). After that, similar research beams of the second and third series were tested under the influence of alternating low-cycle transversal loads of the indicated levels in accordance with the test base N = 20 cycles, after which the sample was pumped to destruction or reaching the ultimate state, if this did not happen earlier on the previous ones cycles. The criteria for the destruction of the prototypes were the achievement of ultimate strain values in concrete or reinforcement, an excessively large opening (up to 1 mm) of inclined (more often) or normal (less often) cracks, a significant increase (up to 15 mm) in the deflection boom, no increase or decrease (by 15% and more) displays of the manometer of the power plant pumping station [5]. In the fourth series the tested sample beams of the 2nd series were brought to their limit state and then reinforced with a metal casing and tested by reversal and repeated loading.

After the tested samples of series 3 beams were brought to the limit state according to the 1st and 2nd groups, the damaged lower tensioned zone and almost destructed support areas were strengthened with CFRP sheets Sika® Wrap® -231C according to the Sika Russie [6] technology (series 5). The construction of this strengthening is shown in Figure 1.

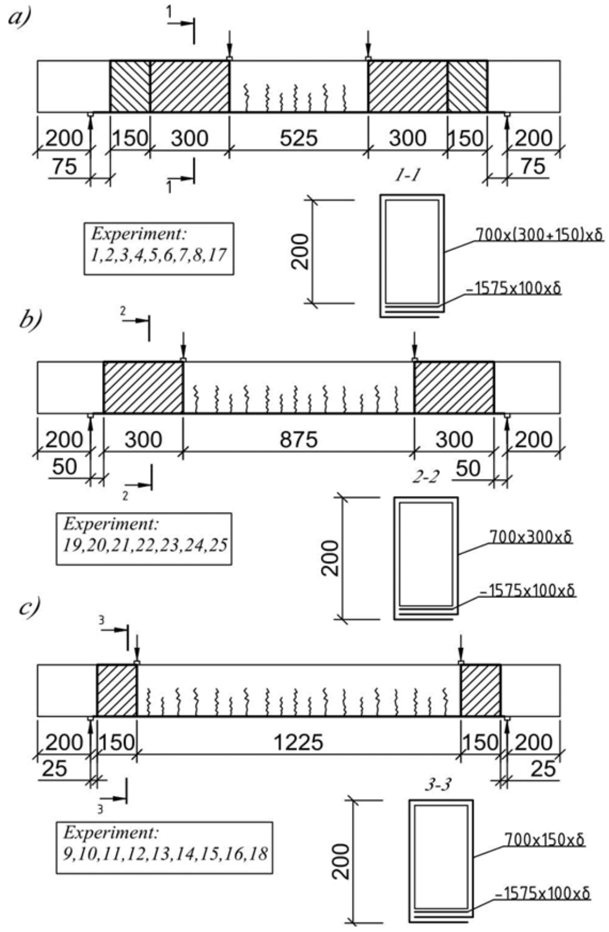

Figure 1. Patterns of strengthening the lower tensioned zones and support areas of the damaged r.c. beams of 3rd series with large (a), medium (b) and small (c) shear spans.

The strengthened with external CFRP beams of series 5 were tested according to the same methodology as the beams of series 3.

Strength of the tested beam samples

As a result of processing the obtained experimental data of the first, third and fifth series, the removal of insignificant and recalculation of those coefficients that remained with the help of the effective COMPREX computer program were developed under the guidance of prof. Voznesensky V.A., that obtained adequate mathematical models of strength, i.e., destructive transverse Vu, i loads in natural or reduced to cross-sectional expressions that have sufficient informational benefit and show satisfactory convergence with experimental data and characterize the strength of research elements:

- reference (series1) with the stage-wise gradually increasing loading.

$$\hat{Y}\left(V_{u,1}\right) = 98 - 41x_1 + 12x_2 + 6x_3 + 16x_1^2 - 7x_2^2 - 5x_3^2 - 7x_1x_2, \text{ кН}, \ \upsilon\text{=5.2\%}$$

$$\text{Variability coefficient } \mho = 5.2\%; \qquad (1)$$

$$\hat{Y}\left(\frac{V_{u,1}}{bh_0}\right) = 5.60 - 2.3x_1 + 0.69x_2 + 0.34x_3 + 0.91x_1^{\ 2} - 0.40x_2^{\ 2} - 0.29x_3^{\ 2} - 0.40x_1x_2, \qquad \text{(1a)}$$

- similar beams (series 3) with the low-cycle non-reversal high-level loading.

$$\hat{Y}\left(V_{u,3}\right) = 90 - 36x_1 + 10x_2 + 7x_3 - 3x_4 + 18x_1^{\ 2} - 6x_2^{\ 2} - 6x_3^{\ 2} - 2x_4^{\ 2} - 8x_1x_2 + 2\,\mathrm{x}_1\mathrm{x}_4, \text{ кН},$$

$$\text{Variability coefficient } \mho = 5.1\%;\text{(2)}$$

$$\hat{Y}\left(\frac{V_{u,3}}{bh_0}\right) = 5.14 - 2.06x_1 + 0.57x_2 + 0.40x_3 - 0.17x_4 + 1.03x_1^{\ 2} - 0.34x_2^{\ 2} - 0.34x_3^{\ 2} - 0.11x_4^2 - 0.46x_1x_2 \qquad \text{(2a)}$$
$$+0.11\mathrm{x}_1\mathrm{x}_4, \text{МПа}$$

- 3 CFRP-strengthened beams (series 5) brought to the critical state according to the 1st group subject to similar loading.

$$\hat{Y}\left(V_{u,\mathrm{f}}\right) = 153 - 69x_1 + 12x_2 + 4x_3 + 9x_1^{\ 2} - 8x_2^{\ 2} - 7x_1x_2,$$

$$\text{Variability coefficient } \mho = 5.2\%;\text{(3)}$$

$$\hat{Y}\left(\frac{V_{u,\mathrm{f}}}{bh_0}\right) = 8.74 - 3.94x_1 + 0.69x_2 + 0.23x_3 - 0.51x_1^{\ 2} - 0.46x_2 - 0.40x_1x_2, \text{Мпа} \qquad \text{(3a)}$$

Mathematical models (1), (2) and (3) characterize the bearing capacity of the tested elements support zones in the natural form, and (1a), (2a) and (3a) reflect the strength of their oblique sections reduced to the dimensions of their cross sections only.

The presented adequate mathematical models have a significant advantage over other statistical dependencies that make possible to evaluate the influence of each research factor on the output parameter not only in particular, but also in interaction with each other, and also to compare the magnitude of this influence both in a single series and for all the indicated series together, that is a comprehensive analysis. A geometric interpretation of the actual and reduced bearing capacity of the supporting sections of the prototype beams is partially presented in Figure 2.

The concrete grade is the next factor according to the impact value. As the grade improves from C16/20 to C30/35, the strength of oblique sections raises more intensively.

With the upgrade of the concrete, from C30/35 to C40/50, the bearing capacity of the support zones changes slightly. The similar pattern is observed with respect of the transverse reinforcement coefficient ρw when it changes from 0.0016 to 0.0044. Low-cycle loading and increase of the levels from 0.5 to 0.8 of destructive load produces a negative effect on the test element bearing capacity.

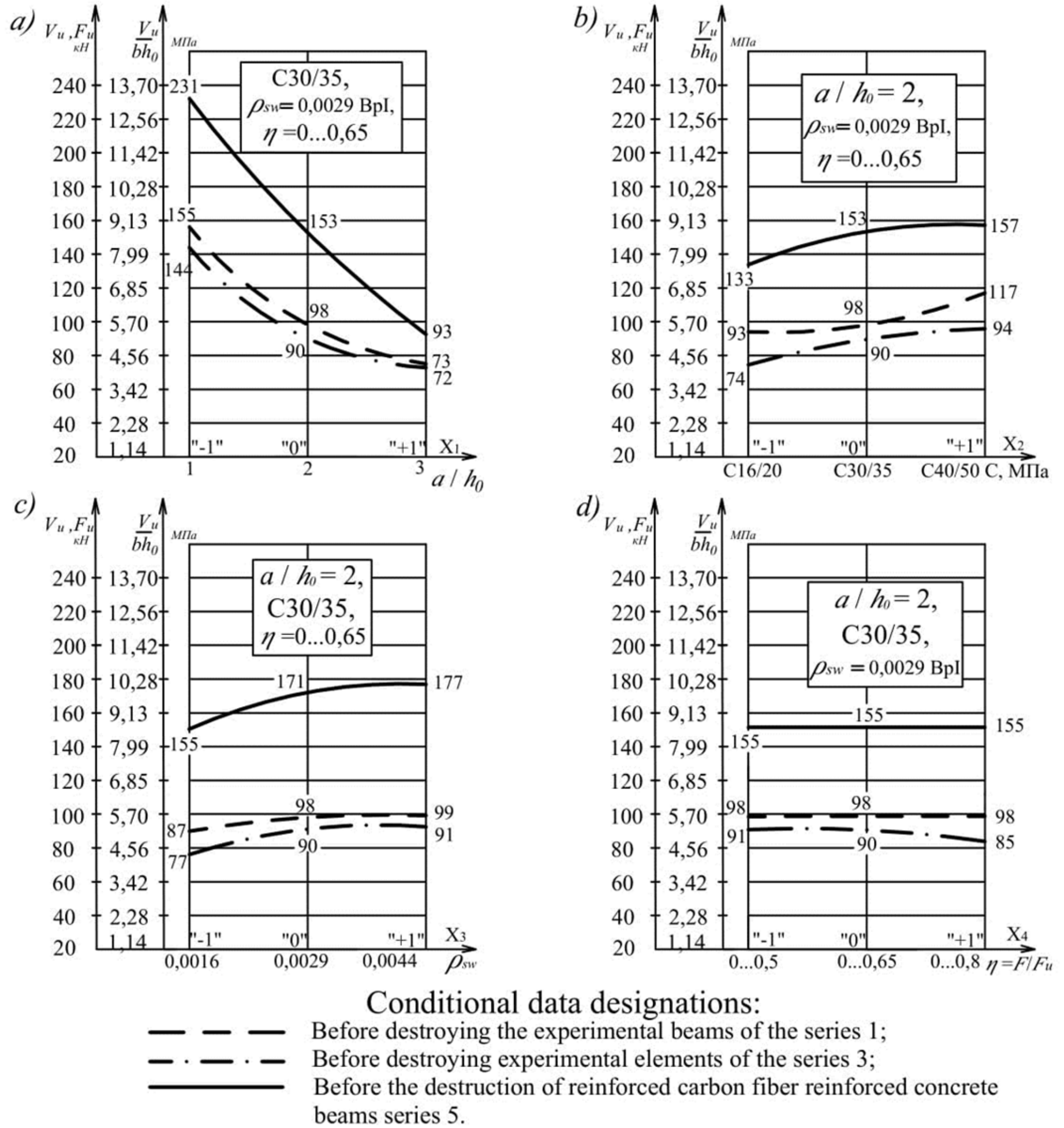

Figure 2. Destructive transverse force Vu or transverse loading (Fu) of the tested sample beams prior to their failure vs the value of the relative shear span a/h_0 (a), concrete grade C (b), quantity of the transverse reinforcement ρ_{sw} (c) and level of the low-cycle repeated loading η (d).

Analysis of mathematical models (1)...(3a) shows that they are of the same type by quality, and the impact of the design factors and external factors are similar by quality. The differences are in the quantitative indicators only.

Thus, the strength of the oblique sections of the tested sample beams of the first, third and fifth series, that was reduced to working area of the transverse section, increases relatively to their reduced average values 5.60; 5.14 and 8.74, accordingly:

- with reduction of the relative shear span a/h0 from 3 to 1 in the indicated series by 84, 80 and 90%, accordingly;

- with the change of the concrete grade from C16/20 to C40/50 25, 22 and 16%, accordingly;

- with the increase of the quantity of transverse reinforcement ρsw from 0.0016 to 0.0044 by 12,16 and 5%, accordingly;

- with reduction of the non-reversal loading η from 0...0.8 to 0...0.5 in the third series;

at single-time reduction of the relative shear span a/h_0 and increase of the concrete grade within the above indicated limits by 7% in the first, 9% in the third and 5% in the fifth series;

- with a single-time reduction of the relative shear span a/h_0 and a level of the non-reversal low-cycle loading in the third series.

It is evident that the main cause of the bearing capacity reduction in low-cycle non-reversal loading lies in the structural disturbance of concrete, particularly in the support zones, its decompaction and partial loss of cohesion with the reinforcement.

The maximum growth of the residual deformations in concrete and transverse reinforcement of the tested beams of the first and third series was recorded during the first 2-3 cycles and, as a rule, they were stabilized before the fifth-sixth cycles at the loading levels η=0...0.50 – 0...0.65. In some samples made of the lowest concrete grade and the minimum transverse reinforcement at loading η=0...0.8 these deformations were not stabilized and the samples failed in 6...9 cycles because of reaching the structural fatigue or due to possible reduction of their strength characteristics caused by a statistical error when determining the destructive high-level loads.

The tested sample beams of the fifth series that were strengthened with external composite reinforcement were deformed almost elastically until reaching the limit state in the compressed concrete or in the tensioned metal or composite reinforcement.

Not overreinforced ($\rho_{sw} \leqslant 0.003$ (BpI); $\rho_f \leqslant 0.018$ (A500C)) tested sample beams subjected to a single-time static stage-wise increase (first series) and low-cycle non-reversal (third series) loading failed, as a rule, according to B/M pattern, i.e., in oblique sections and the prevailing action of the bending moment as a result of the yield of the longitudinal working reinforcement in the unsafe diagonal crack mouth and the transverse reinforcement that crosses such crack [8]. As the quantity of the transverse reinforcement increases $\rho_{sw} \geqslant 0.0044$, the similar test elements having medium ($a/h_0=2$) and large ($a/h_0=3$) shear spans failed according to C/V pattern, i.e., in the diagonal crack under the prevailing action of the transverse force due to yield of the transverse reinforcement and shear or bearing of the compressed zone of concrete above the top of unsafe diagonal crack; with the small shear spans ($a/h_0 \leqslant 1$) the similar test samples failed sometimes according to Д/cm pattern beyond the oblique compressed strip located between two diagonal cracks as a result of crush of this strip concrete that follows the trajectory of the main compressing stresses.

Destruction of the normal sections of the test beam was strengthened in the fifth series by CFRP and was accompanied, as a rule, by yield of the metal and composite structure, possible detachment of the protective concrete layer and breaking CFRP external reinforcement [9].

Destruction of the support zones of the fifth series beams that have small shear span also began from excessive deformation and detachment of the external composite reinforcement along with the protective concrete layer and crushing of concrete beyond the oblique compressed strip.

Basic parameters of test elements crack resistance

During testing sample beams for short-term single-time and low-cycle load we monitored creation, development and opening width of the cracks on their surface. The width of normal crack opening was determined at the level of tensioned working reinforcement, and that of the diagonal cracks – in the mid-height of the beam in those places where visually was the greatest [10].

The normal cracks appeared the first within the pure bend zone and under the focused forces at the loading levels ɳ=0.15…0.25 of the breaking level. As loading was being increased these cracks developed towards the compressed zone, their opening width was being increasing as well and new cracks were formed in the zone of joint action of the bending moment and the transverse force and they gradually were becoming more inclined towards the point where the concentrated load was applied.

First diagonal crack appeared at loading ɳ=0.4…0.6 of the breaking load in the middle height of the beams having small or medium shear spans, or they developed out of normal cracks in the samples having large shear spans, maximum quantity of the transverse and minimum quantity of the longitudinal working reinforcement.

The process of the normal and diagonal cracks in the beams of the first and third series developed as forecast: in parallel with the internal stress growth new cracks were formed, lengths and opening width of the existing cracks increased and subsequent development of these cracks depended on intensity of the transverse reinforcement in the shear spans. If its quantity was sufficient, the tested samples failed in the normal sections, the working reinforcement yield [11], and if the reinforcement quantity was insufficient – the earlier formed diagonal cracks merged together to dorm one major or several almost parallel cracks to form a strip; failure began beyond the cracks associated with a possible yield of the transverse and longitudinal rods and subsequent shear or crushing of the concrete compressed zone.

With the fifth series beams strengthened with external composite reinforcement we noted further development of the earlier formed cracks and appearance of new cracks, so-called secondary normal cracks, in middle part of the beams, and in the support areas wrapped in CFRP the diagonal crack appeared.

The mathematical models of the normal crack opening in the pure bend zone in the middle part of the beams at the level of the tensioned reinforcement are as follows:

- in common beams subjected to stage-wise static increasing loading (series 3) of the corresponding levels.

$$\hat{Y}\left(W^{\eta_1 F_{u,1}}_{\mathrm{cr},\perp,1,2,3}\right)=0.14-0.02x_1+0.03x_2+0.01x_3+0.05x_4+0.01x_1{}^2-0.03x_2{}^2+0.02x_4{}^2+$$
$$+0.01x_1x_3+0.01x_1x_4+0.02\,\mathrm{x}_2\mathrm{x}_4+0.01\,\mathrm{x}_3\mathrm{x}_4,mm$$

$$\text{Variability coefficient } \mho = 6.2\%; \tag{4}$$

- in damaged and brought to the limit state beams of the 1st group in series 3 of the tested samples – the beams strengthened with CFRP sheets (series 5) subjected to, accordingly, low-cycle loading η1Fu,1 and prior to their failure at 0.95Fu,f:

$$\hat{Y}\left(W_{\mathrm{cr},\perp,\mathrm{f}}^{\eta_1 F_{u,1}}\right)=0.31+0.18x_1+0.02x_2+0.03x_3+0.09x_4+0.02x_1x_3+0.06x_1x_4, mm$$

$$\text{Variability coefficient } Ʊ = 10.5\%; \tag{5}$$

$$\hat{Y}\left(W_{\mathrm{cr},\perp,\mathrm{f}}^{0,95F_{u,f}}\right)=0.46+0.28x_1+0.03x_2+0.03x_3+0.05x_4+0.03x_1x_3+0.03x_1x_4, mm$$

$$\text{Variability coefficient } Ʊ = 10.4\%; \tag{6}$$

Geometrical interpretation of the above mathematical models is shown in Fig. 3.

The conducted research proved that the opening width of normal cracks in the middle part of the damaged beams at the loading levels preset by the test schedule was, on the average, 2.2 times greater than that one in the continuous beams of the first and third series.

The analysis indicates that the maximum opening width of the normal cracks in the pure bend zone of the indicated series is increasing as compared with the average values of 0.14, 0.31 and 0.46 mm at the average values of the studied factors:

- with increase of the relative shear span a/h_0 from 1 to 3 b 29, 116 and 122%;
- with the change of the concrete grade from C16/20 to C 40/50 (actually to C 30/35) by 43, 13%;
- with the increase of the quantity of transverse reinforcement ρ_{sw} from 0.0016 to 0.0044 by 14, 19 and13%;
- with the increase of loading η from 0.5 to 0.8F_u by 71 and 58%, and on achievement of η = 0.95 $F_{u,f}$ – by 22%;
- at single-time increase of:
- the relative shear span value and quantity of the transverse reinforcement within the indicated limits by 7, 13 and 13%, accordingly;
- the relative shear span value and the loading by 7%;
- the concrete grade due to the increase of the bearing capacity and loading level by 14 and 13% in the fifth series;
- quantity of the transverse reinforcement by the same reason and the loading level increase by 7% in the first series.

Main parameters of material deformability and the test beam samples

When performing experimental studies direct measurements of deformations in the extreme, most compressed concrete fibres in this cycle and, accordingly, the tensioned working reinforcement in the span middle (in the pure bend zone) were made, as well as the averaged evaluation of the deformation of the support zone transverse reinforcement in the tested beam samples.

Diagrams illustrating experimental and analytical relative deformations were constructed for each tested r.c. elements after each cycle of the corresponding levels repeated loading, including the stage immediately preceding the failure [12].

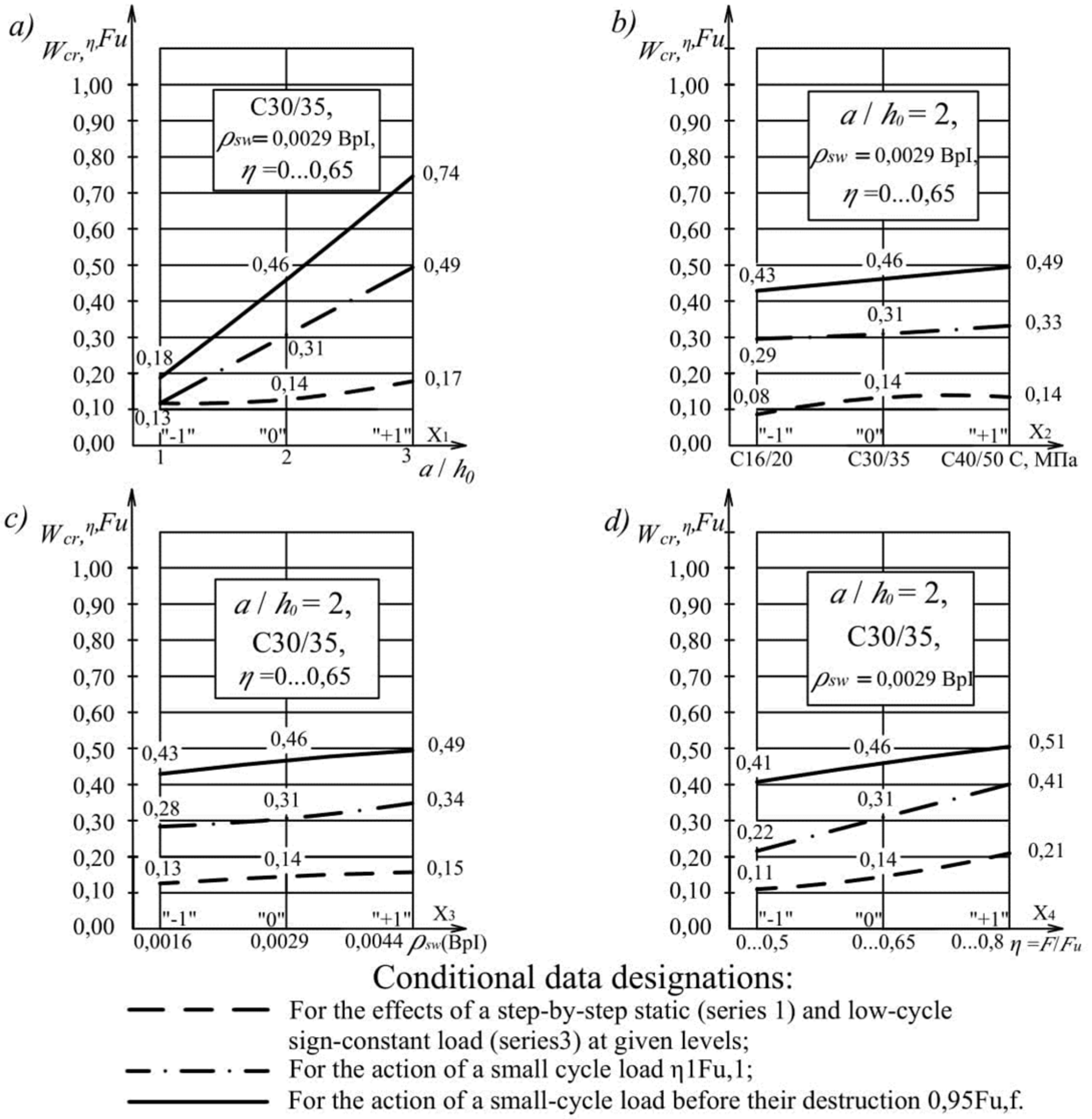

Figure 3. Impact of the relative shear span value a/h$_0$ (a), concrete grade C (b), quantity of transverse reinforcement ρ$_{sw}$ (c) and level of low-cycle repeated loading η (d), on the opening width of normal cracks in the "pure bend" zone in the middle of the beams at the level of tensioned reinforcement.

It was experimentally established that the values of relative deformation of the materials after each repeated loading cycle considerably increase upon reaching a certain level and residual deformation accumulate until their stabilization which, as a rule, takes place after 4…8 loading cycles and reaches 60…80% of the total residual deformation of the compressed concrete zone. Generally, in the second and third loading cycles occur 15…25% more, and in the 4…8 cycles – only 5…10% of these deformations. At that, the low-cycle loading action considerably impacts the stress-strain state of the tested beams. In particular, the stress diagram of the compressed zone changes gradually due to concrete compaction and re-distribution of inner stresses takes place between the compacted concrete and tensioned reinforcement wherein the corresponding deformations change. In some tested samples that had large shear spans and were subjected to high levels of repeated loading (η=0,8) there occurred no stabilization of the residual deformations of the concrete or reinforcement, sometimes both of the concrete or reinforcement, and their failure, as non-overreinforced elements, took place in the normal sections as a result of the yield of the longitudinal working reinforcement or both due to the reinforcement yield and crushing the compressed zone concrete.

Similarly to the compressed concrete under repeated loading, deformation of the tensioned longitudinal working reinforcement takes place [13]. The tests proved that the residual deformations in such reinforcement reach (20…50)·10^{-5} and are stabilized to 4…8 cycles when the beams were unloaded to zero in the first cycles.

Residual deformations in the transverse reinforcement and the concrete in oblique sections comprised 25…60% of the total deformations [14]. Their greatest increment was recorded in the first cycle (≈20…50%) and at additional loading in the last cycle. Due to reduction of plastic deformations the accumulation process of residual deformations in the support zone at stable level of low-cycle transverse loading fades gradually. Deformations in the transverse reinforcement and in the support zone concrete stabilize, as a rule, before the 4…8 cycle of such loading.

Relative deformations of the compressed concrete in the pure bend zone of the tested beams

Mathematical models of the relative deformations of the compressed concrete in the tested samples of common beams and strengthened beams of 1, 3 and 5 series in accordance with the loading levels $\eta_1 F_{u,1}$ preset by the schedule are as follows:

$$\hat{Y}\left(\varepsilon_{c,1}^{\eta Fu1}\right) = \left(84 + 17x_1 + 10x_2 + 7x_3 + 21x_4 + 4x_1x_3 + 5x_1x_4\right)\cdot 10^{-5},$$

Variability coefficient $\mho = 5.1\%$;(7)

$$\hat{Y}\left(\varepsilon_{c,3}^{\eta Fu1}\right) = \left(92 + 17x_1 + 10x_2 + 7x_3 + 21x_4 + 4x_1x_3 + 5x_1x_4\right)\cdot 10^{-5},$$

Variability coefficient $\mho$=6.7%; (8)

$$\hat{Y}\left(\varepsilon_{\mathrm{c,f}}^{\eta_1 F_{u,1}}\right) = (91 + 21x_1 + 5x_2 + 14x_3 + 21x_4 - 4x_1{}^2 - 2x_3{}^2 - 12x_1x_2 + 8x_1x_3 + 11\mathrm{x}_1\mathrm{x}_4 -$$
$$7\,\mathrm{x}_2\mathrm{x}_3 + 4\,\mathrm{x}_3\mathrm{x}_4)\times 10^{-5},$$

Variability coefficient $\mho$=9.6%;(9)

Their geometrical interpretation is shown in Figure 4.

The processing of experimental data on the deformation of the compressed zone concrete in the center of the spans of the research elements after their stabilization at the appropriate level of low-cycle load, as well as before the destruction of the beams at η = 0.95Fu allowed to derive the following mathematical models:

$$\hat{Y}(\varepsilon_{c,1}^{0,95F_{u,1}}) = (129 + 30\mathrm{X}_1 + 15\mathrm{X}_2 + 11\mathrm{X}_3 + 6\mathrm{X}_1\mathrm{X}_3)\cdot 10^{-5}$$

Variability coefficient $\mho$=6.5%; (10)

$$\hat{Y}(\varepsilon_{c,3}^{0,95F_{u,3}}) = (149 + 30\mathrm{X}_1 + 11\mathrm{X}_2 + 11\mathrm{X}_3 - 4\mathrm{X}_1^2 - 2\mathrm{X}_2^2 + 6\mathrm{X}_1\mathrm{X}_3)\cdot 10^{-5}$$

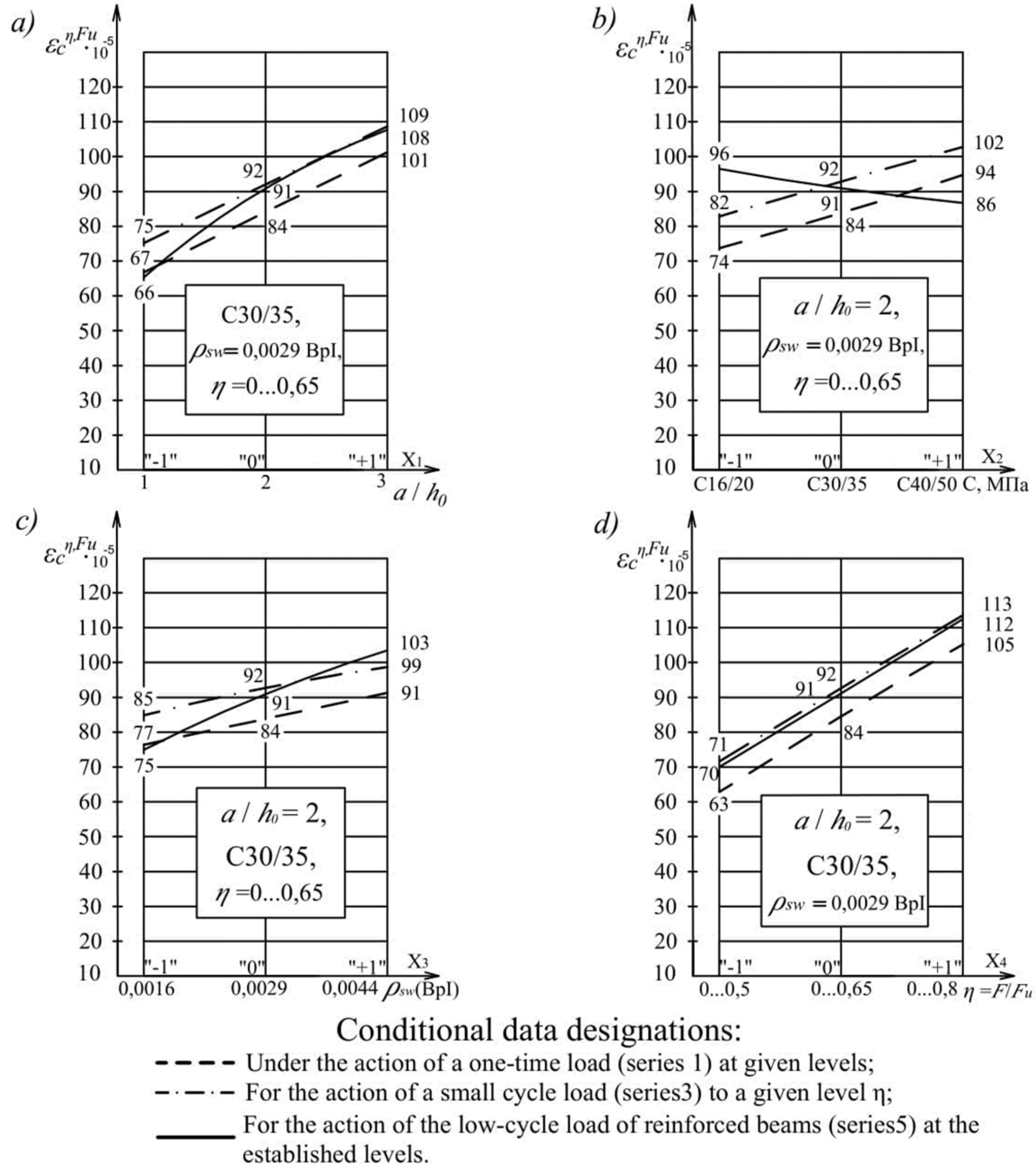

Figure 4. Relative deformations of the compressed concrete in the tested beam samples vs the value of the relative shear span, a/h$_0$ (a), concrete grade C (b), quantity of the transverse reinforcement ρ$_{sw}$ (c) and level of the low-cycle repeated loading η (d).

Variability coefficient Ʊ=6.1%;(11)

$$\hat{Y}(\varepsilon_{c,f}^{0,95F_{u,f}}) = (264+94X_1-25X_2+7X_4-4X_1^2-23X_1X_2)\cdot 10^{-5}$$

Variability coefficient Ʊ=5.1%; (12)
Their geometrical interpretation is shown in Figure 5.

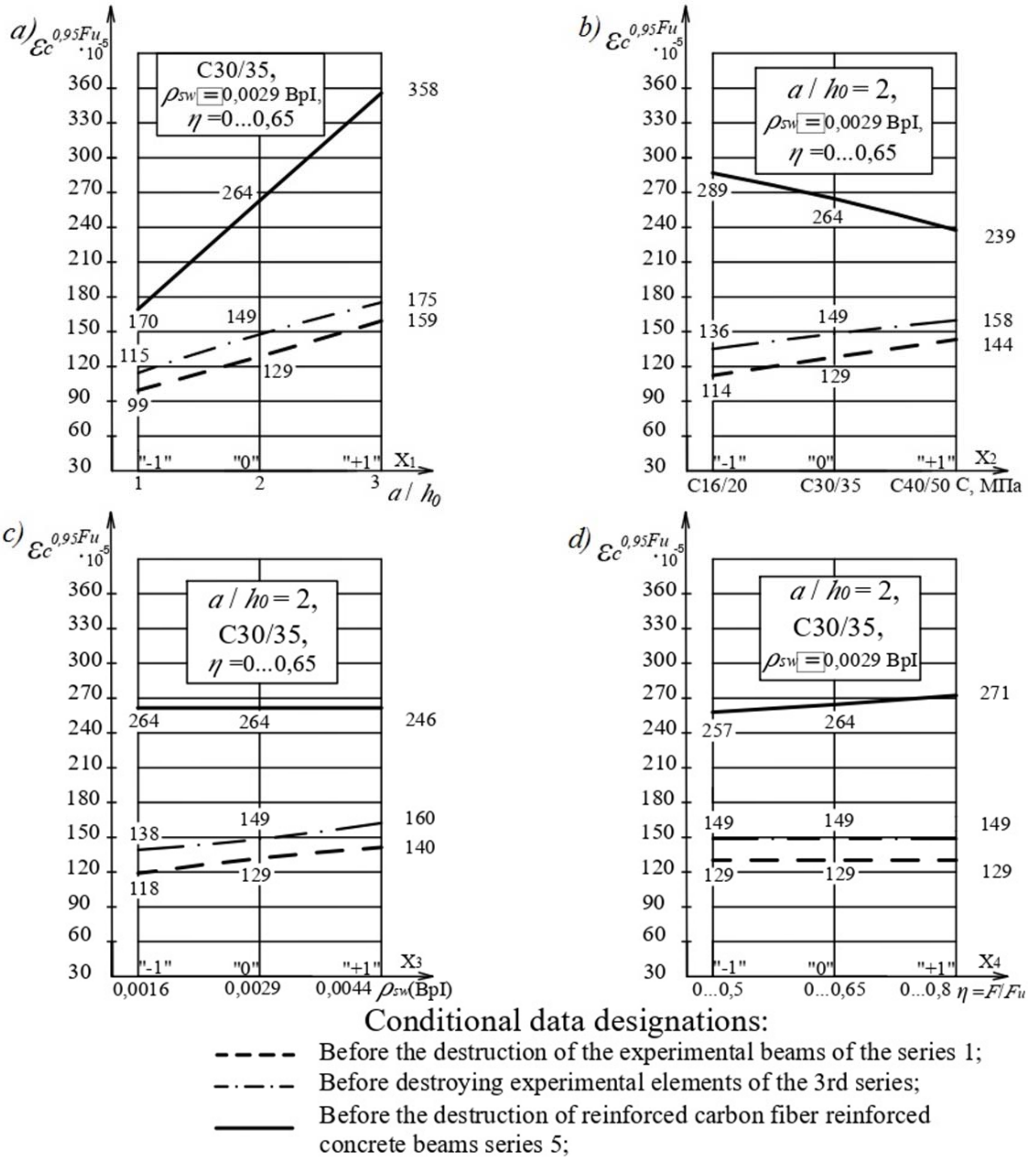

Figure 5. Dependence of relative deformations of compressed concrete test specimens-beams on the magnitude of the relative passage of the slice, a/h$_0$ (a), the class of concrete C (b), the number of transverse reinforcement ρ$_{sw}$ (c), the level of low-cycle reloading (d).

Average relative deformation values of the compressed concrete in the middle part of beams after their stabilization under low-cycle static loading.

Relative deformations of the compressed concrete in r.c. beams of 1, 3 and 5 series prior to failure increase upwards as compared with the average values:

- relative shear span *a*/h$_0$ from 1 to 3 - by 47%, 40% and 71%, accordingly;
- concrete grade from C16/20 to C40/50 - by 23%, 15% and 19%;
- quantity of transverse reinforcement ρ$_{sw}$ from 0.0016 to 0.0044 - by 17 and 15%;
- level of transverse loading η from 0.5 to 0.8 - by 15% and 5%.

Conclusions

1. Peculiarities of the stress-strain state of the tested beam samples are presented. Dependence of the nature and kind of their failure on the relevant ratio of the design factors and factors of external impacts, particularly presented and kind of external strengthening with composite materials was established for the first time.

2. Due to the adopted methodology new experimental data was obtained in order to essentially specify physical models reflecting behaviour of oblique sections of the span r.c. structures subjected to high-level low-cycle repeated loading which resulted in description for the first time of the system impact of the shear span a/h_0, concrete grade C, transverse reinforcement coefficient ρsw and level of repeated loading η on crack resistance, deformability and strength of the tested beam samples.

3. Application of the mathematical theory of planning, adopted plan and levels of changing design factors and external impact factors make it possible to apply a system approach to analyse the events and compare the obtained data.

4. Presence of the external carbon fibre-reinforced polymer strengthening in the lower tensioned zone of the beams in the 5th series and on their support zones makes it possible to enhance bearing capacity of the beams as compared with similar beams of the 3rd series, subjected to similar low-cycle loading, by 1.7 times on the average, and partially change the nature of their failure. In doing so, the average value of the normal crack opening width in the “pure bend” zone is increased from 0.31 to 0.46 mm; the average relative deformations and tensioned steel reinforcement of A500C class increase from 258 10^{-5} to 546 10^{-5}.

5. Increase of the shear span a/h0 from 1 to 3 not only reduces by 2 and 2.5 times the destructive transverse low-cycle loading, accordingly, in common (series 3) and CFRP reinforced (series 5) r.c. beams but also defines the nature of such failure. With a small shear span (a/h0 =1) a” tested beam samples failed in the support zones because of oblique cracks or strips accompanied with detachment of the carbon fibre sheet in the average and large shear spans (a/h0 = 2 or 3); increase of the quantity of external composite reinforcement in these areas leads, as a rule, to destruction of the tested elements in the normal sections within the “pure bend” zone, which is accompanied by yield of the tensioned metal and composite reinforcement, and the concrete of the compressed zone is subjected to critical deformations. The maximum opening width of the normal cracks increased by 0.49 mm in the common beams of the third 3rd series to 0.74 mm in the carbon fibre reinforced elements.

6. The performed research proved that upgrading concrete from C16/20 to C40/50 results in higher bearing capacity of the common beams of the 3rd series by 22% only. In the carbon-reinforced beams – only by 15%, because the tensile strength increase of the concrete and “lags behind” the compression strength growth of the concrete when the concrete grade is upgraded. The maximum opening width of the normal cracks accompanied with a change of the concrete grade within the indicated limits and at average values of other design factors increases from 0.33 mm in common beams to 0.49 mm in reinforced elements with upgraded concrete grade within the indicated limits. Similarly to bearing capacity of the tested beam, deformations of steel and composite reinforcement also increase.

7. Along with a greater quantity of transverse steel reinforcement - from ρsw =0.0016 to ρsw =0.0044, the bearing capacity of common beams (series 3) is increasing in a non-

linear way, the same as the carbon-fibre strengthened elements (series 5), on the average by 15%. With a change of this factor within the preset limits the opening width of normal cracks is also increasing by 15% and reaches the maximum value of 0.49 mm in the strengthened beams while the average values of other design factors are preserved. With the common beams the increase of the transverse reinforcement increases deformations in steel reinforcement by 18%, however, with the strengthened beams the deformations of steel and composite reinforcement remain stable and sufficiently high until failure.

8. A change in the low-cycle transverse loading levels η from 0…0.5 to 0…0.8 with the common beams (series 3) results in reduction of their bearing capacity by up to 10% while with the strengthened beams (series 5) their strength remains stable. Higher level of said loading within the indicated limits increases the opening width of normal cracks in common beams by 60%, and in the strengthened beams – by 22% while average values of the design factors remain the same. Deformations of the steel and external composite reinforcement increase in all series by 10% on the average when the levels of such loading change within the indicated limits. While the present factor did not influence the deformations in the compressed concrete of common beams, such impact in the strengthened elements comprised by 6% only.

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