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DEFORMABILITY OF STEEL REINFORCEMENT OF DAMAGED CFRP-STRENGTHENED BEAMS UNDER THE ACTION OF CYCLIC LOADING

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Abstract. In the article are presented the main results of experimental studies of deformability of the reinforcement of common damaged and brought, in the course of the previous tests, to the critical state by the 1st group r.c. beams reinforced with carbon fibre (CFRP) sheet in the lower tensioned zone and on the support area.

Namely, according to the results of the experiment, using the COMPEX program, adequate mathematical models of the deformations of steel reinforcement of CFRP-strengthened reinforced concrete specimens-beams under the action of low-cycle sign-constant loading were derived, that reflect the influence of these factors both individually and in interaction with each other. Analyzing these models, the features of the development of tensile reinforcement in the specified conditions, were established. In particular, the factors that have the greatest influence on deformations are the relative shear span and the level of low-cycle loading. As compared with the series of tests of ordinary r.c. samples, presence of the external CFRP strengthening reduced deformation of the tensioned steel reinforcement by 1.65 times on the average. There occurs a re-distribution of the tension forces between them.

Keywords: steel reinforcement, beam, carbon fibre-reinforced polymer sheet (CFRP), cyclic loading, deformations, mathematical model.

Introduction. The main difference between cyclic loads and static short-term ones is the occurrence of residual deformations and their further accumulation from cycle to cycle. Concrete and reinforcement deformations in bending elements are stabilized and gain a slight increase before the destruction stage at certain load cycles within the exploitation levels. However, for example, when reinforced concrete beams works outside the exploitation levels, the development of the main deformability characteristics of these elements may not be so predictable. Furthermore, the influence of cyclic loads of different levels increases the values of deformations of reinforced concrete structures in comparison with the action of short-term load that must be taken into account in the design. Moreover, there is no studies about workability of steel reinforcement in structures with strengthening their tensioned parts with CFRP. Therefore, the accumulation of experimental data and their analysis is an advisable and useful scientific task.

Analysis of recent researchs and publications. A large number of scientists who have devoted their works to this team confirmed that low-cycle loads increase the value of reinforcement and concrete deformations – by 10-15% [1-5]. This is mainly due to the accumulation of residual deformations. Besides, most authors tend to idea that the strength and deformation characteristics of concrete and reinforced concrete structures under cyclic loads are significantly influenced by the load mode [6, 7]. However, scientists have not established a clear limit of the cyclic load levels, which changes the stress-strain state of the experimental elements that thus requires additional study. Resistance of the span r.c. CFRP-strengthened structures subject to low-cycle repeated high-level loading that have been damaged in operation or in military hostilities was not studies at all. Therefore, the research along this line is important and up-to-date.

Materials and methods of research. 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 shown that the most influential factor x_1 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: $x_2 \rightarrow$ C16/20, C30/35, C40/55, and the third factor – the value (quantity) of the transverse reinforcement in the support areas: $x_3 \rightarrow \rho_w = 0.0016$; 0.0029; and 0.0044. The fourth factor was assumed to be the external action factor x_4 and a level of the reversal load: $\eta = \pm 0.50$; ± 0.65; ± 0.80 of the actual bearing capacity.

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. Deformations of the reinforcement of the test samples were measured with the aid of dial indicators having a division value 0.001 mm and 0.01mm accordingly.

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. Afterwards, the similar beams of the second and third series were tested subject to reversal and non-reversal low-cycle transverse loading of the defined levels according to the test assumption N = 20 cycles; afterwards the sample was additionally loaded, practically, until destruction or achievement of the critical level, if that had not happened earlier during the previous cycles. After the tested samples were strengthened with CFRP sheets Sika® Wrap® - 231C according to the Sika technology (ser. 5). The construction of strengthening is shown in Fig. 1.

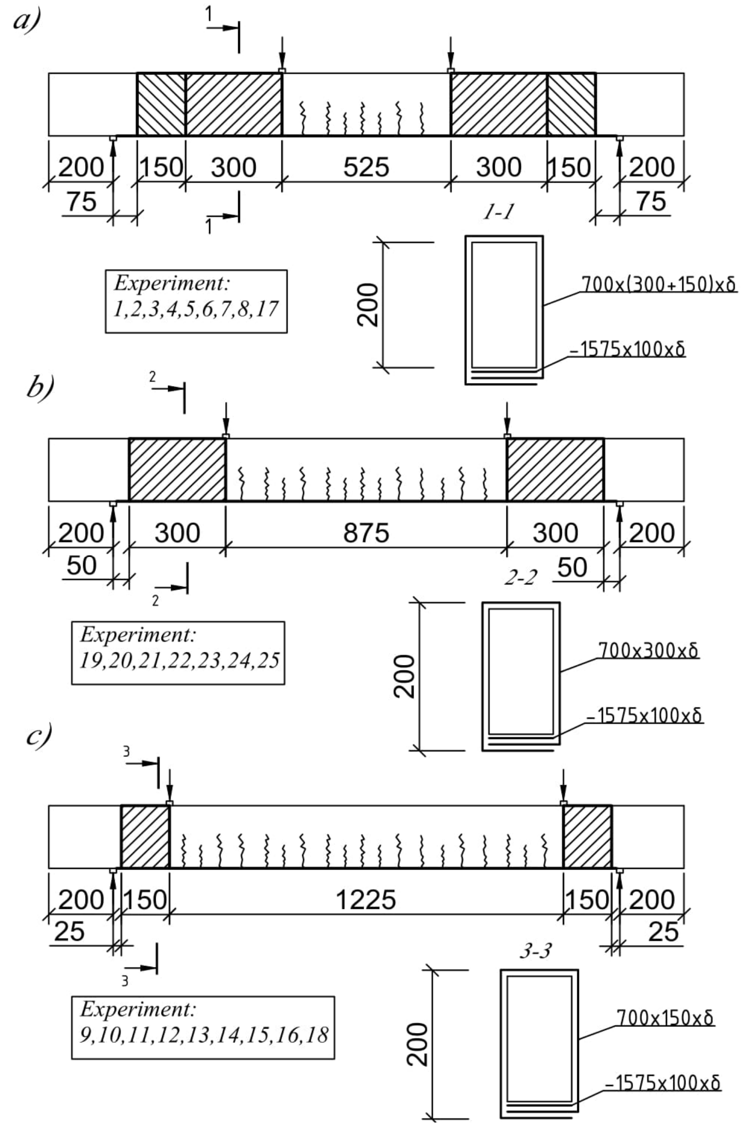

Figure 1. Patterns of strengthening the lower tensioned zones and support areas of the damaged r.c. beams of 3rd series with large (a), medium (b) and small (c) shear spans

The strengthened with external CFRP beams of series 5 were tested according to the same methodology as the beams of series 3 [6].

Research results. When performing experimental studies direct measurements of deformations of 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 repeated loading of the corresponding levels, including the stage immediately preceding the failure [7].

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. 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 some tested samples that had large shear spans and were subjected to high levels of repeated loading (ɳ=0,8) there occurred no stabilization of the residual deformations of the 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 of the compressed zone concrete.

Deformation of the tensioned longitudinal working reinforcement takes place. 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 comprised 25…60% of the total deformations. 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 stabilize, as a rule, before the 4…8 cycle of such loading.

Processing of the obtained data on the relative deformations of the working reinforcement in the pure bend zone of beams after their stabilization at a corresponding level of low-cycle loading as well as before their failure at ɳ=0.95F$_u$ following the indicated methodology allowed of obtaining the following mathematical models:

- for the working steel reinforcement of A500C class in common and strengthened beams subject to the preset levels of loading η_1 of series 1, 3 and 5, accordingly:

$$\hat{Y}\left(\varepsilon_{s,1}^{\eta Fu1}\right)=\left(195+48x_1+10x_2+9x_3+32x_4-25x_1^2-9x_2^2-5x_3^2-15x_4^2+15x_1x_3+10x_1x_4\right)\cdot 10^{-5}, \quad \upsilon=5,3\%, \tag{1}$$

$$\hat{Y}\left(\varepsilon_{s,3}^{\eta Fu1}\right)=\left(210+52x_1+16x_2+10x_3+34x_4-26x_1^2-10x_2^2-5x_3^2-16x_4^2+16x_1x_3+10x_1x_4\right)\cdot 10^{-5}, \quad \upsilon=5,1\%, \tag{2}$$

$$\hat{Y}\left(\varepsilon_{s,f}^{\eta Fu1}\right)=\left(127+25x_1+10x_2+17x_3+32x_4-26x_1^2-6x_1x_2+8x_1x_3+14x_1x_4+6x_2x_4+5x_3x_4\right)\cdot 10^{-5} \quad \upsilon=5,5\%, \tag{3}$$

- for the external CFRP composite strengthening subjected to the same loading:

$$\hat{Y}\left(\varepsilon_{f}^{\eta Fu1}\right)=\left(162+33x_1+14x_2+24x_3+39x_4-11x_1x_3+14x_1x_4+6x_4x_2+6x_3x_4\right)\cdot 10^{-5}, \quad \upsilon=5,7\%, \tag{4}$$

Their geometrical mages are shown in Fig. 2.

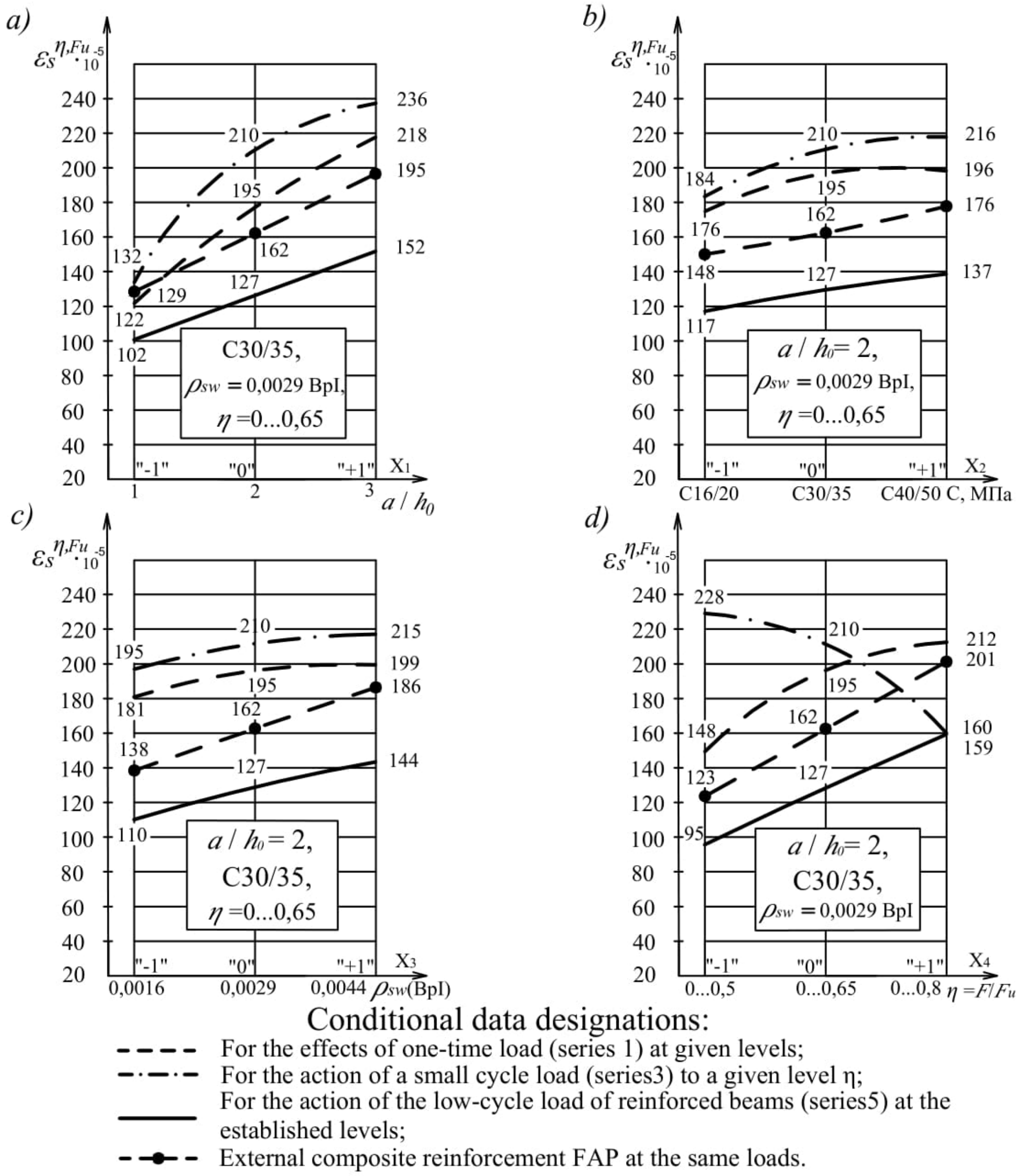

Figure 2. Relative deformations of the steel reinforcement and external CFRP vs the value of the relative shear span (a), concrete grade (b), quantity of the transverse reinforcement (c) and level of the low-cycle load (d)

Conclusions:

1. Due to the 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 the average relative deformations of tensioned steel reinforcement of A500C class increase from $258 \cdot 10^{-5}$ to $546 \cdot 10^{-5}$.

2. 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 steel and composite reinforcement, and the concrete of the compressed zone is subject to critical deformations.

3. 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. Higher level of transverse reinforcement within the set limits leads to greater by 10% sags in common and strengthened beams.

4. As compared with the 3rd series of tests, presence of the external CFRP strengthening reduced deformation of the tensioned steel reinforcement by 1.65 times on the average. There

occurs a re-distribution of the tension forces between them.

Among the prospects for further research is the study of the serviceability of steel reinforcement of reinforced concrete span elements, strengthened with CFRP under the the action of a high-cycle repeated loading.

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ДЕФОРМАТИВНІСТЬ СТАЛЕВОЇ АРМАТУРИ ПОШКОДЖЕНИХ ЗАЛІЗОБЕТОННИХ БАЛОК, ПІДСИЛЕНИХ ВУГЛЕПЛАСТИКОМ, ЗА ДІЇ ЦИКЛІЧНОГО НАВАНТАЖЕННЯ

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Анотація. У статті наведено основні результати експериментальних досліджень деформативності сталевої арматури як звичайних залізобетонних балок, так і пошкоджених в ході попередніх випробувань до критичного стану зразків, посилених вуглепластиковим полотном у нижній розтягнутій зоні та на приопорній ділянці.

А саме, за результатами експерименту за допомогою програми COMPEX отримано адекватні математичні моделі деформацій сталевої арматури підсилених вуглепластиком залізобетонних зразків-балок під дією малоциклового знакопостійного навантаження, які відображають вплив цих факторів як окремо, так і у взаємодії один з одним. Аналізуючи ці моделі, встановлено особливості розвитку деформацій розтягнутої, а також поперечної арматури в заданих умовах. Зокрема, факторами, які найбільше впливають на деформації, є відносний прольот зрізу та рівень малоциклового навантаження. Встановлено, що у порівнянні з серією випробувань звичайного залізобетонного зразка-балки, наявність зовнішнього армування вуглепластиком знизила величини деформацій розтягнутої сталевої арматури в середньому в 1,65 рази внаслідок перерозподілу зусиль розтягу.

Ключові слова: сталева арматура, балка, згин, деформації, циклічні навантаження, математична модель.