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DEFORMABILITY OF REINFORCED CONCRETE BEAMS UNDER THE ACTION OF CYCLIC LOADING

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Abstract. The aim of the article is an experimental research of the influence of low-cycle sign-constant loading, as well as the most significant design factors on the deformability of reinforced concrete beam elements. In this regard, for experimental research, the authors developed a four-factor three-level Boxing plan B4. The experimental factors of the plan were varied according to the literature review, which showed that the most significant factors are the following: the value of the relative shear span a/h_0, the concrete class C, the value (amount) of transverse reinforcement on the beams support sections ρ_{sw}, the level of sign-constant loading η. The samples were tested according to the scheme of a single-span beam, alternately loaded with two centre-point forces. The number of cycles of sign-constant loading was accepted as 10.

According to the results of the experiment, using the COMPEX program, adequate mathematical models of the basic parameters of reinforced concrete specimens-beams deformability 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 and compressed concrete deformations, as well as beams deflections in the specified conditions, were established. In particular, the factors that have the greatest influence on deformations and deflections are the relative shear span and the level of low-cycle loading. Thus, with their increase, the relative deformations of tensile reinforcement increase by 51% and 52%, the relative deformations of compressed concrete by 40% and 37%, accordingly, by series. The increase of deflections is 43% and 40% with an increase of relative shear span and 38% and 12% with an increase of loading level, accordingly, by series.

Keywords: reinforced concrete, beam, bend, deformation, deflections, cyclic loadings, mathematical model.

Introduction. The main difference between cyclic loads and static short-term loads is the occurrence of residual deformations and their further accumulation from cycle to cycle. Concrete and reinforcement deformations, as well as deflections 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 and deflections of reinforced concrete structures in comparison with the action of short-term load, that must be taken into account in the design. Therefore, the accumulation of experimental data and their analysis is an advisable and useful scientific task.

Analysis of recent researches and publications. A large number of scientists who have devoted their works to this team confirmed that low-cycle loads increase the value of deflections, on average, by 15-20%, and the value of reinforcement and concrete deformations – by 10-15% [1-7]. This is mainly due to the accumulation of residual deformations, as well as micro- and macro-cracks, as noted in [8].

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. In [9] it was noted that the higher the level of cyclic loading, the faster the processes of concrete decomposition, which reduces the initial modulus of elasticity of concrete by 15...20% and changes the type of diagram of "stress-strain" of compressed concrete, with bending to axis of deformation. Also the author in [10] on the basis of test results concludes that the subsequent loadings exceeding exploitation level increase full deflections of beams by 20-30%, deformations of reinforcement and concrete – by 15-25%. 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.

On this bases, **the aim of the work** is an experimental study of the influence of low-cycle loads level on deformability of reinforced concrete beam elements, as well as the most significant design factors both in particular and in interaction with each other.

Materials and methods of research. According to the adopted methodology, the full-scale experiment is performed according to a four-factor three-level plan of Box B4. Variation of factors was carried out according to the literature review of sources, which showed that the most influential factor X_1 is the value of relative shear span a/h_0, which varied in three levels: $a = h_0$, $2h_0$ i $3h_0$. The second influential factor is a class of heavy concrete: $X_2 \rightarrow$ C16/20, C30/35, C40/50, and the third – the value (amount) of transverse reinforcement on the near support areas: $X_3 \rightarrow \rho_{sw} = 0{,}0016$; 0,0029; 0,0044. As the fourth factor of external action X_4 is accepted level of sign constant loading: $\eta = 0…0{,}50$; 0…0,65; 0…0,85 of the actual bearing capacity, i.e. the value of the transverse load, when the width of the opening of inclined cracks w_k exceeded 0.4 mm, and the deflections are $f \geq l/150$ [11].

Test specimens-beams were stored in normal thermal and humid conditions at a temperature of 20 ± 2 °C and almost 100% humidity for 100…110 days. Before the test, a thin layer of lime mortar was applied to the side surfaces of the beams in order to facilitate the fixation of the formation and development of normal and inclined cracks, and then beams was dried to natural moisture.

The test specimens were tested according to the scheme of a single-span beam, alternately loaded by two concentrated forces.

Before the main experiment, 25 experimental beams (twin specimens) of the first series were tested under the action of a short-term load, practically to a destructive state, when the width of the inclined cracks and the deflections exceeded the allowable values. In the future, similar experimental beams of the third series were tested under the action of a sign-constant repeated transverse load within three experimental levels.

The number of cycles of sign-constant loading is dictated by the criterion of stabilization of deformations, first of all, in concrete of E.M. Babich and his students [12] and is at least 10, if the test specimens-beams did not destruct with a smaller number of cycles.

During the experimental studies, direct measurements of deformations of the extreme, most compressed concrete fibers in this cycle and, accordingly, tension working reinforcement in the middle of spans (in the zone of pure bending) were performed. The indirect assessment of transverse reinforcement deformations of near support areas of specimens-beams was made. For all tested reinforced concrete elements, graphs of experimental and calculated relative deformations after the action of each cycle of repeated loading of corresponding levels were constructed, including the stage before failure.

Research results. It is experimentally established that the values of relative deformations of materials after the action of each cycle of repeated loading at a certain level increase significantly, residual deformations are accumulated until their stabilization, which usually occurs after 4… 8 load cycles and is 60…80% of general residual deformations of compressed concrete zone. The second and third load cycles usually account for another 15-25%, and for 4…8 cycles – only 5…10% of these deformations. In this case, the action of low-cycle loads significantly affects the stress-strain state of the experimental beams. In particular, the stress diagram of the compressed zone gradually changes due to the compaction of concrete, there is a redistribution of internal efforts between the compressed concrete and tensioned reinforcement, in which the corresponding deformations change. The presented data are in good agreement with the results of research by P.S. Homon [2], O.I. Korniychuk [13] and others.

In some specimens with a large shear spans at high levels of repeated loading (η = 0.8) stabilization of residual deformations of concrete or reinforcement and sometimes both concrete and reinforcement did not occur and their destruction as non-reinforced elements occurred in normal sections due to the yielding of longitudinal working reinforcement or due to the both yielding of the reinforcement, and the crushing of the concrete compressed zone.

Similarly, to compressed concrete at repeated loading there was a deformation of longitudinal tensioned working reinforcement. Tests have shown that the residual deformations in it at unloading the beams to zero in the first cycles reach values (20…50) $\cdot 10^{-5}$ and stabilize up to 4…8 cycles.

Residual deformations in transverse reinforcement and concrete of inclined sections were 25… 60% of the total. Their largest increase was observed in the first cycle (≈20…50%) and during reloading in the last cycle. Due to the reduction of plastic deformations, the process of accumulation of residual deformations in the materials of the support sections at a constant level of low-cycle transverse load gradually attenuates. Up to 4…8 cycles of such loading both in cross reinforcement, and in concrete of near support areas, as a rule, there is a stabilization of deformations.

The relative deformations of working tensioned reinforcement in the middle of the span of test elements. Processing of experimental data on the relative deformations of working reinforcement in the beams zone of pure bending after their stabilization at the appropriate level of low-cycle load, as well as before their destruction at η=0,95F_u by this method allowed to obtain the following mathematical models:

$$\hat{Y}\left(\varepsilon_{s,1}^{\eta F_u}\right)=\begin{pmatrix}195+48X_1+10X_2+9X_3+32X_4-25X_1^2-9X_2^2-5X_3^2-15X_4^2+15X_1X_3+\\+10X_1X_4\end{pmatrix}\cdot 10^{-5}, \tag{1}$$

$$\upsilon=5,3\%,$$

$$\hat{Y}\left(\varepsilon_{s,1}^{0,95F_u}\right)=\left(239+77X_1+24X_2+33X_3+20X_4-13X_1^2-4X_2^2-3X_4^2+10X_1X_3\right)\cdot 10^{-5}, \tag{2}$$

$$\upsilon=7,1\%,$$

$$\hat{Y}\left(\varepsilon_{s,3}^{\eta F_u}\right)=\begin{pmatrix}210+52X_1+16X_2+10X_3+34X_4-26X_1^2-10X_2^2-5X_3^2-16X_4^2+16X_1X_3+\\+10X_1X_4\end{pmatrix}\cdot 10^{-5}, \tag{3}$$

$$\upsilon=5,1\%,$$

$$\hat{Y}\left(\varepsilon_{s,3}^{0,95F_u}\right)=\left(258+84X_1+34X_2+35X_3+21X_4-13X_1^2-3X_2^2-3X_4^2+10X_1X_3\right)\cdot 10^{-5}, \tag{4}$$

$$\upsilon=5,3\%.$$

The geometric representation of these models is presented in Fig. 1.

Analysis of mathematical models (1) … (4) shows that the average values of the relative deformations of tensioned reinforcement in the middle of the beams after their stabilization at low-cycle sign-constant loads increase. In this case, the influence of experimental factors on this parameter in experimental series is significant and the same. Thus, the relative deformations of tensioned reinforcement of 1st series specimens-beams at the specified load levels and before failure increase relative to the average values with increasing:

– relative shear span a/h_0 from 1 to 3 on 49% and 64%;

– concrete class from C16/20 to C40/50 on 10% and 20%;

– amount of transverse reinforcement ρ_{sw} from 0,0016 to 0,0044 on 9 and 28%;

– transverse load level η from 0,5 to 0,8 on 33 and 17%,

and 3d series, accordingly, with increasing:

– relative shear span a/h_0 from 1 to 3 on 50% and 65%;

– concrete class from C16/20 to C40/50 on 15% and 26%;

– amount of transverse reinforcement ρ_{sw} from 0,0016 to 0,0044 on 10 and 27%;

– transverse load level η from 0,5 to 0,8 on 32 and 16%.

– at simultaneously increasing of relative shear span and amount of transverse reinforcement on 4…5%.

Characteristic is also the presence of negative signs in the quadratic effects of these factors, which indicates that with their increase beyond these limits, the further increase in tensile deformation will be damped.

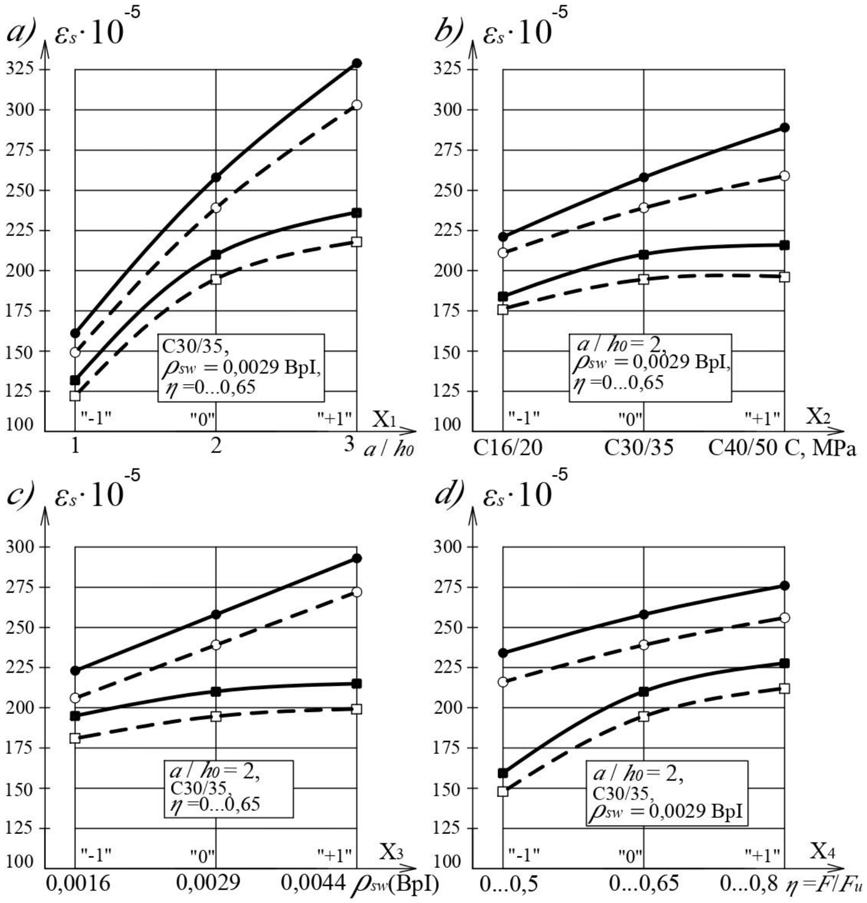

Fig. 1. The influence of constructive factors (a), (b), (c), and transverse load level (d) on reinforcement deformations at short-term load (– –□– –) and low-cycle loading (——■——) of set level (η), and also before failure (0,95F$_u$) under gradually increasing load (– –○– –) and after stabilized low-cycle (——●——) loading

Relative deformations of compressed concrete in the zone of pure bending of test beams. Processing of experimental data on deformations of compressed zone concrete in the middle of spans of experimental elements after their stabilization at the corresponding level of low-cycle loading, and also before beams destruction at η=0,95Fu by the accepted technique allowed to deduce the following mathematical models:

$$\hat{Y}\left(\varepsilon_{c,1}^{\eta F_u}\right)=\left(84+17X_1+10X_2+7X_3+21X_4+4X_1X_3+5X_1X_4\right)\cdot 10^{-5},\upsilon=5,1\%, \quad (5)$$

$$\hat{Y}\left(\varepsilon_{c,1}^{0,95F_u}\right)=\left(129+30X_1+15X_2+11X_3+6X_1X_3\right)\cdot 10^{-5},\upsilon=6,5\%, \quad (6)$$

$$\hat{Y}\left(\varepsilon_{c,3}^{\eta F_u}\right)=\left(92+17X_1+10X_2+7X_3+21X_4+4X_1X_3+5X_1X_4\right)\cdot 10^{-5},\upsilon=6,7\%, \quad (7)$$

$$\hat{Y}\left(\varepsilon_{s,3}^{\eta F_u}\right)=\left(149+30X_1+11X_2+11X_3-4X_1^2-2X_2^2+6X_1X_3\right)\cdot 10^{-5},\upsilon=6,1\%, \quad (8)$$

geometric interpretation of which is presented in Fig. 2.

Analysis of the presented models (5) … (8) shows that the deformations of compressed concrete and, accordingly, compressive stresses in it, at the given load levels of the experiment, usually do not reach extreme values, and the destruction of test specimens (if this happens without increasing the level load) occurs, as a rule, by inclined sections or (much less often) by normal sections and begins with yielding of longitudinal work reinforcement.

The average values of the relative deformations of compressed concrete in the middle of the beams after their stabilization at low-cycle sign-constant loads increase in comparison with the short-term static load. The relative deformations of compressed concrete of reinforced concrete beams of the 1st series at the specified load levels and before failure increase relative to the average values of $84\cdot10^{-5}$ і $129\cdot10^{-5}$ with increasing of:

– relative shear span a/h_0 from 1 to 3, accordingly, on 40% and 47%;
– concrete class from C16/20 to C40/50 on 24% and 23%;
– amount of transverse reinforcement ρ_{sw} from 0,0016 to 0,0044 on 17 and 18%;
– transverse load level ƞ from 0,5 to 0,8 on 50%,

and 3d series, accordingly, with increasing:

– relative shear span a/h_0 from 1 to 3, accordingly, on 37% to 40%;
– concrete class from C16/20 to C40/50 on 22% and 15%;
– amount of transverse reinforcement ρ_{sw} om 0,0016 to 0,0044 on 15 and 16%;
– transverse load level ƞ від 0,5 до 0,8 на 46%.

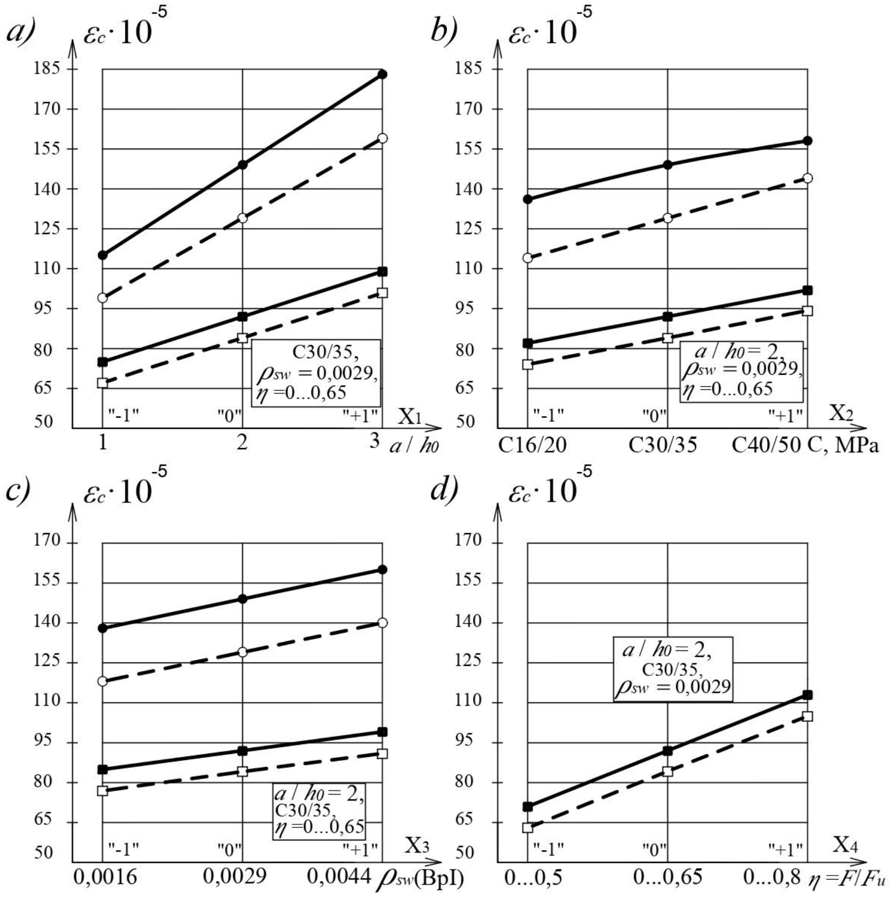

Fig. 2. Dependence of deformations of extreme compressed concrete fibers on constructive factors (a), (b), (c) and of transverse load level (d) at short-term load (– –□– –) and low-cycle loading (——■——) of set level (ƞ), and also before failure ($0{,}95F_u$) under gradually increasing load (– –○– –)and after stabilized low-cycle (——●——) loading

Deflections of the test reinforced concrete elements. During the test, it was found that repeated low-cycle loads at the set levels negatively affect on the beams deflections due to the accumulation of residual deformations in compressed zone of concrete and tensioned reinforcement.

Processing of the deflections measurement results in samples-beams after their stabilization at the specified load levels ($ƞF_u$), as well as before their destruction ($\approx0{,}95F_u$) allowed to obtain the following mathematical models:

$$\hat{Y}\left(f_1^{\eta F_u}\right)=\begin{pmatrix}4,5+0,8X_1+0,35X_2+0,25X_3+0,85X_4-0,35X_1^2-0,15X_2^2-0,2X_4^2+\\+0,3X_1X_3+0,2X_1X_4\end{pmatrix}\cdot 10^{-5}, \tag{9}$$

$$\upsilon=6,0\%,$$

$$\hat{Y}\left(f_1^{0,95F_u}\right)=\left(6+1,5X_1+0,65X_2+0,7X_3+0,35X_4-0,5X_1^2+0,2X_1X_3\right)\cdot 10^{-5},\upsilon=5,8\%, \tag{10}$$

$$\hat{Y}\left(f_3^{\eta F_u}\right)=\begin{pmatrix}5+0,85X_1+0,4X_2+0,25X_3+0,9X_4-0,4X_1^2-0,15X_2^2-0,25X_4^2+\\+0,3X_1X_3+0,2X_1X_4\end{pmatrix}\cdot 10^{-5}, \tag{11}$$

$$\upsilon=6,4\%,$$

$$\hat{Y}\left(f_1^{0,95F_u}\right)=\left(6,5+1,5X_1+0,75X_2+0,75X_3+0,35X_4-0,55X_1^2+0,2X_1X_3\right)\cdot 10^{-5},\upsilon=5,1\%, \tag{12}$$

that shown in Fig. 3.

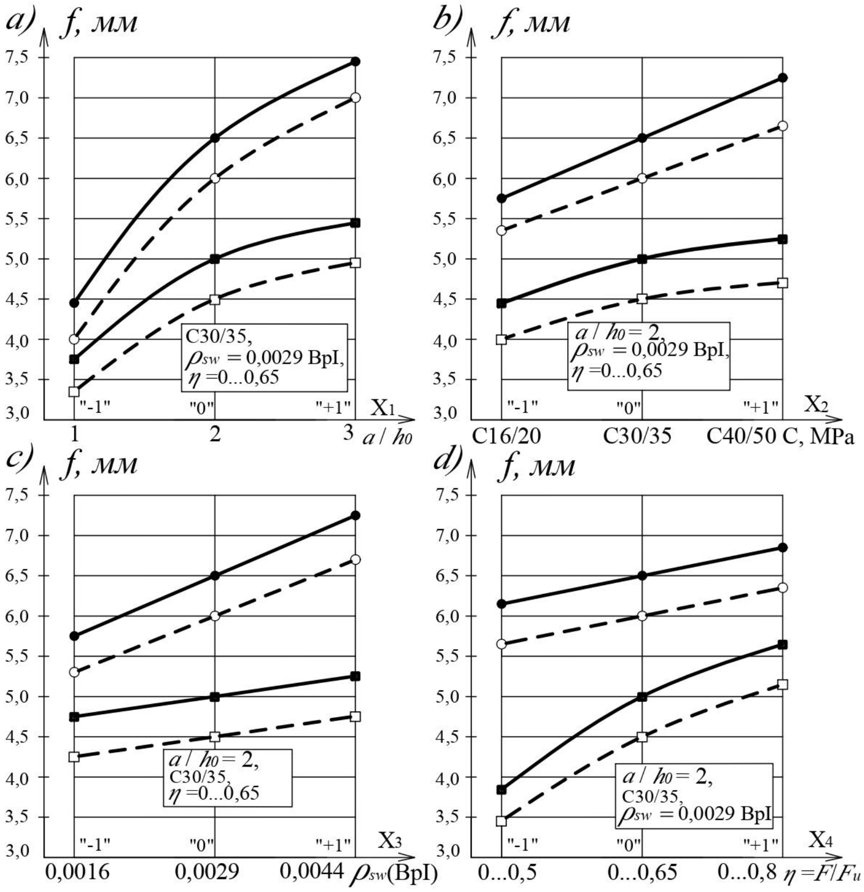

Fig. 3. Dependence of deflections on constructive factors (a), (b), (c) and of transverse load level (d) at short-term load (– –□– –) and low-cycle loading (——■——) of set level (η), and also before failure (0,95F$_u$) under gradually increasing load (– –○– –) and after stabilized low-cycle (——●——) loading

Analysis of mathematical models (9) and (11) and Fig. 3 shows that the test samples deflections values of the 1st and 3d series at the appropriate load levels increase, on average, by 11% relative to the average values of 4,5 and 5,0 mm with the increasing of:

– relative shear span a/h$_0$ from 1 to 3 on 36% and 34%;

– concrete class from C16/20 to C40/50 on 16%;

– amount of transverse reinforcement ρ_{sw} from 0,0016 to 0,0044 on 11 i 10%;

– transverse load level η from 0,5 to 0,8 on 38 and 14%.

A comparison of models (10) and (12) shows that the deflections of the samples of the 1^{st} and 3^{d} series before the destruction increase, on average, by 8% relative to the average values of 6,0 and 6,5 mm with the increasing of:

– relative shear span a/h_0 from 1 до 3 on 50% and 46%;
– concrete class from C16/20 to C40/50 on 22 і 23%;
– amount of transverse reinforcement ρ_{sw} from 0,0016 to 0,0044 on 23%;
– transverse load level η from 0,5 to 0,8 on 12 and 11%.

Conclusions:

1. Analysis mathematical models of the tensioned reinforcement relative deformations in the test elements span middle, it is found that increasing the relative shear span increases the effect of bending moment and they increase by 51% and 52% respectively. The increase of the values of other experimental factors leads to an increase of the tensioned reinforcement deformations to 24% in both series. As for the relative deformations of compressed concrete in the area of pure bending of the samples, the most influential are two factors: the relative shear span and the transverse load level. Namely, with their increase, the compressed concrete deformations value increases by 40% and 37%, respectively.

2. The values of the deflections of reinforced concrete specimens-beams mostly depend on the value of the relative shear span. When it increases, the deflections increase by 43% and 40%, respectively, according to the series. In second place is the level of transverse load. With its increase, the increase of deflections is 38% and 12%. The growth of the concrete class and the transverse reinforcement coefficient increases the deflections by 23%.

3. In general, the influence of low-cycle sign-constant loading on the deformability of reinforced concrete specimens-beams differs significantly from the influence of a short-term static load. Namely, the specified type of load increases the value of relative deformations of the tensioned reinforcement by 8%, the value of relative deformations of compressed concrete by 10%, the value of deflections by 11%.

Quite an urgent scientific problem today is the restoration and reconstruction of damaged constructions of buildings and structures in emergency situations, hostilities etc. Therefore, among the prospects for further research are repeated tests of reinforced with modern composite materials inclined and normal sections of almost destroyed test specimens of 3^{d} series beams under the action of a similar load and as a result, the development of techniques to restore damaged beam structures.

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ДЕФОРМАТИВНІСТЬ ЗАЛІЗОБЕТОННИХ БАЛОК ЗА ДІЇ ЦИКЛІЧНОГО НАВАНТАЖЕННЯ

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Анотація. Метою статті є експериментальне дослідження впливу малоциклового знакопостійного навантаження, а також найбільш значимих конструктивних чинників на деформативність залізобетонних балкових елементів як зокрема так і взаємодії один з одним. У зв'язку з цим, для проведення експериментальних досліджень авторами був розроблений чотирьохфакторний трирівневий план Боксу В4. Варіювання дослідних факторів плану здійснювалося за даними літературного огляду, який показав, що найбільш значимими факторами є наступні: величина відносного прольоту зрізу a/h_0, клас бетону С, величина (кількість) поперечного армування на приопорних ділянках балок ρ_{sw}, а також рівень знакопостійного малоциклового навантаження η. Зразки були випробувані за схемою однопрогінної балки, завантаженої двома зосередженими силами. Кількість циклів знакопостійного навантаження була прийнята 10.

За результатами проведеного експерименту за допомогою програми COMPEX виведені адекватні математичні моделі основних параметрів деформативності залізобетонних зразків-балок за дії малоциклового знакопостійного навантаження, які відображають вплив зазначених факторів як окремо, так і у взаємодії один з одним. В ході аналізу даних моделей встановлені особливості розвитку деформацій розтягнутої арматури та стиснутого бетону, а також прогинів балок в зазначених умовах. Зокрема, факторами, які мають найбільший вплив на деформації і прогини є відносний прольот зрізу і рівень малоциклового знакопостійного навантаження. Таким чином, при їх збільшенні відносні деформації розтягнутої арматури зростають на 51% і 52%, відносні деформації стиснутого бетону на 40% і 37% відповідно за серіями. Приріст прогинів становить 43% і 40% при збільшенні відносного прольоту зрізу і 38% і 12% при збільшенні рівня повторного навантаження відповідно за серіями. Також встановлено, що малоциклове навантаження в порівнянні з одноразовим короткочасним навантаженням збільшує відносні деформації розтягнутої арматури на 8%, відносні деформації стиснутого бетону – на 10%, прогини – на 11%.

Ключові слова: залізобетон, балка, згин, деформації, прогини, циклічні навантаження, математична модель.

ДЕФОРМАТИВНОСТЬ ЖЕЛЕЗОБЕТОННЫХ БАЛОК ПРИ ДЕЙСТВИИ ЦИКЛИЧЕСКОГО НАГРУЖЕНИЯ

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Аннотация. Целью статьи является экспериментальное исследование влияния малоциклового знакопостоянного нагружения, а также наиболее значимых конструктивных факторов на деформативность железобетонных балочных элементов. В связи с этим, для проведения экспериментальных исследований авторами был разработан четырехфакторный трехуровневый план Бокса В4. Варьирование опытных факторов плана осуществлялось по данным литературного обзора, который показал, что наиболее значимыми факторами являются следующие: величина относительного пролета среза a/h_0, класс бетона C, величина (количество) поперечного армирования на приопорных участках балок ρ_{sw}, уровень знакопостоянного нагружения η. Образцы были испытаны по схеме однопролетной балки, поочередно загруженной двумя сосредоточенными силами. Количество циклов знакопостоянного нагружения было принято 10.

По результатам проведённого эксперимента с помощью программы COMPEX выведены адекватные математические модели основных параметров деформативности железобетонных образцов-балок при действии малоциклового знакопостоянного нагружения, которые отображают влияние указанных факторов как по отдельности, так и во взаимодействии друг с другом. В ходе анализа данных моделей установлены особенности развития деформаций растянутой арматуры и сжатого бетона, а также прогибов балок в указанных условия. В частности, факторами, которые оказывают наибольшее влияние на деформации и прогибы являются относительный пролет среза и уровень малоциклового нагружения. Таким образом, при их увеличении относительные деформации растянутой арматуры возрастают на 51% и 52%, относительные деформации сжатого бетона на 40% и 37% соответственно по сериям. Прирост прогибов составляет 43% и 40% при увеличении относительного пролета среза и 38% и 12% при увеличении уровня нагружения соответственно по сериям. Также установлено, что малоцикловое нагружение по сравнению с однократной кратковременной нагрузкой увеличивает относительные деформации растянутой арматуры на 8%, относительные деформации сжатого бетона – на 10%, прогибы – на 11%.

Ключевые слова: железобетон, балка, изгиб, деформации, прогибы, циклические нагрузки, математическая модель.

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