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CALCULATED RELIABILITY OF ECCENTRICALLY COMPRESSED CONCRETE COLUMNS UNDER THE ACTION OF LOW CYCLE LOADING WITH ALTERNATING ECCENTRICITES

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The paper gives definition of design reliability of eccentric compressed reinforced concrete columns under the action of low-cyclic loads with alternating eccentricities. Based on theoretical researches and using the experimental data the numerical example of defining the design reliability of aforesaid elements was made. The value of eccentricity, level and loading conditions influence essentially on reversal of physical and mechanical properties of materials, since these parameters are considered as random variables from which reliability, constructive reliability and long-term durability of eccentric compressed elements are depended. During estimating the column reliability, it was used the existed method of reliability calculation of building constructions under the action of single-stage steady loads in accordance with existing norms. It was justified statistically the definition of the reversal of physical and mechanical properties of concrete during determining the coefficient of operating conditions. These reversals were taking into account during operating the eccentric compressed elements under action of low-cyclic alternating loads.
Keywords: eccentric compression, low-cyclic loads, alternating eccentricity, reliability.

Introduction. Construction is one of the materials-intensive manufacturing industries, the development of which requires continuous improvement of calculation methods and design of reinforced concrete structures, aimed at ensuring their reliability in operation while reducing material consumption and other costs. The limit state method, which is contained in the current regulatory documents, allows providing bearing capacity of the reinforced concrete eccentrically compressed elements due to the use of various coefficients of reliability and responsibility of the structure. However, the sufficient bearing capacity of the element does not guarantee its sufficient reliability, the quantitative assessment of which is unknown at the stage of the design of a building. Reliability and economy are the prerequisites for the design, construction and operation of buildings and structures. The need to ensure a high level of reliability of buildings, structures and their structural elements is quite obvious, since their failure, including possible accidents and destruction, leads to great economic losses, dangerous environmental consequences, and sometimes catastrophic casualties. The experience in the construction and operation of construction sites shows that the same type of buildings and structures that are constructed and operated under similar conditions, or their separate structural elements, fail with different random occurrence. It is almost impossible to accurately determine the service life of a building structure or building as a whole, and it is only possible to estimate the likelihood that this building or structure will be used for a given period. Therefore, the methods of assessing the reliability of structural elements requires credible information about the variability of the strength parameters of building materials, the magnitude of loads and their nature as random deviations from the calculation models, etc. Of all the factors that affect the reliability of structures and buildings in general, loading and its actions are the most uncertain values with large statistical errors. Therefore, the study of the variability of loading regimes plays a major role in the issues of reliability and structural safety of structural units, buildings and structures.

Analysis of recent publications on this topic. Formation and development of reliability fundamentals in construction originated in the late twenties of the last century in the works of M. Mayer [1] and M. F. Khotsialov [2]. Later, in the late forties of the last century, the modern interpretation of the concept of reliability in the field of construction industry is associated, first and foremost, with the works of M. S. Streletsky [3] and A. R. Rzhanitsyn [4]. It was in these works that the fundamental definitions of the modern theory of the reliability of buildings and structures were laid, in which not only the statistical nature of variability of the strength characteristics of materials, but also the loading parameters were considered, and the necessity of the probabilistic assessment of the reliability of a building or structure was proved. It was A.R. Rajcinin who formulated the basic principles of the concept of security of a building or structure, which are the basic principles of the whole theory of reliability. Somewhat later, basic research on the problem of reliability using probabilistic models was conducted by such scientists as V. V. Bolotin [5], V. D. Reiser [6,7], A. P. Kudzis [8]. Variability studies of the main factors affecting the reliability of structural elements, including statistical analysis of the physical and mechanical characteristics of concrete and reinforcing steel, were carried out by A.Ya. Barashikov [9,10], M. M. Zastava [11], O. S Lychev [12] and others. The significant contribution to the improvement of the methods of calculating the reliability of structures was made by V. A. Perlmuter [13,14], A. I. Lantuh-Lyashchenko [15], S. F. Pichugin [16,17], O. V. Semko [18], V. A. Pashinsky [19], S. B. Usakovsky [20], R. I. Kinash [21] and others. Among the foreign scientists working in the field of reliability, a significant role belongs to A. H - S. Ang [22], A. M. Frendenhal [23], O. Ditlevsen and H. O. Madsen [24], R. E. Melchers, M. A. Ahammed [25] and others.

Research objective. To determine, on the basis of experimental and theoretical studies, a calculated estimate of the reliability of reinforced concrete eccentrically compressed columns under the action of low cycle loading with alternating eccentricities.

Research findings. The use of eccentrically compressed elements is quite common in buildings and structures. The loads acting on such elements are quite diverse – from constant static to low cyclic repetitions and alternating ones. The latter loads cause special conditions of such elements operation, causing changes in the physical-mechanical and deformative characteristics of materials, affecting the processes of cracking, crack opening and their deformability, which in turn affects their operation reliability and durability. Eccentrically compressed reinforced concrete elements, which are tested in the course of operation, low-cycle alternating loading, include columns of single-storey and multi-storey industrial buildings and various structures, racks of crane and transport trestles, elements of buttress retaining walls. In addition, such a stressful condition in structures may occur during the reconstruction of buildings or structures, as well as in emergency situations.

In the laboratory of the Department of Industrial and Civil Construction, and Engineering Structures, the authors conducted comprehensive experimental studies of the work of eccentrically compressed columns under the action of low-cycle loading of varying intensity with alternating eccentricities. Experimental specimens of $b \times h \times l$ – 100×160×3000 mm in size were made of C16/20 and C20/25 concrete. Reinforcement of columns was carried out by spatial frames. Four rods with a diameter of 12 mm of class A400C were adopted as working reinforcement, and a cross bar of steel of class B500 with a diameter of 4 mm in 150 mm was used as transverse reinforcement. The columns were tested for eccentric compression after 30 days of exploitation and more in special settings. Longitudinal force was alternately applied with eccentricities e_0=10 cm through the steel head. The modes of low cycle alternating loads for different columns were at different levels and varied from η=0.3 to η=0.85. The methodology of experimental research is presented in detail in [26].

A detailed analysis of the experimental studies showed that alternating low cycle loading at low levels of η=0.3 slightly increase the load-carrying capacity of eccentrically compressed elements compared to those subjected to eccentric compression by a single short-term static loading. The load carrying capacity, depending on the loading level, was in the range of 8% ... 12%. This is due to a certain compaction of early-age concrete, although at higher loading levels this effect of increasing bearing capacity was counterbalanced. And at the level of η=0.85, the load carrying capacity even decreased to 7% ... 10%, as cracks appeared in the stretched zone of concrete, which violated the integrity of the section. In this case, only the central part of the section was sealed. In [27], a theoretical determination of the load carrying capacity of eccentrically compressed elements under the action of low-cycle loading with alternating eccentricities is provided, taking into account second-order effects that increase the value of the initial eccentricity of applying compressive forces. The theoretical calculations of the load carrying capacity of the above elements were performed in accordance with the current regulatory documents [28] and [29]. Therefore, let us determine the calculated reliability of eccentrically compressed elements undergoing low cycle loading with alternating eccentricities, using experimental data based on a numerical example. To determine the design reliability, we consider the data of the columns with the lowest load carrying capacity using a statistical analysis of the variability of their parameters (accepted mean values).

The estimated reliability of the columns is evaluated according to the methodology outlined in [17], in accordance with the requirements [30]. The values of [β]=4,75 and [β]=3,89 are taken as the normative indicator of reliability according to the current norms in the calculations of building structures, respectively, according to the first and second groups of limit state, considering that they belong to buildings of the CC2 consequences class and the structures of A responsibility category.

Numerical example of calculation. Output data: column cross section dimensions – $b\times h$=100×160 mm; $a=a'$=15 mm; working longitudinal reinforcement – 2 rods on each side with a diameter of 12 mm of A400C class ($A_s=A'_s$=2,26 cm^2), f_{yd}=365 MPa, f'_{yd}=300 MPa (the value is taken from the experimental data); concrete grade C20/25, f_{cd}=17 MPa; height of columns H=300 cm. The compressive force acting on the columns is applied with eccentricity e_0=10 cm. The destruction of the column began at N_u=130 kN. The collapse of the column occurred at the bending moment. $M_u=N_u\cdot e_0$=130·10=1300 kNcm=13 kNm.

Statistical characteristics of materials: concrete C20/25

- mathematical expectation

$$\bar{\sigma}_c=\frac{f_{cd}}{1-1.64V_c}=\frac{17}{1-1.64\cdot 0.135}=21.83\,\text{MPa}=2.18\,\text{kN/cm}^2,$$

where V_c - coefficient of variation;

- standard

$$\hat{\sigma}_c=\bar{\sigma}_c\cdot V_c=21.83\cdot 0.135=2.95\,\text{MPa}=0.295\,\text{kN/cm}^2;$$

reinforcing steel A400C

- mathematical expectation

$$\bar{\sigma}_s=f_{yd}=365\,\text{MPa}=36.5\ \text{kN/cm}^2;$$

$$\bar{\sigma}_{sc}=f'_{yd}=300\,\text{MPa}=30\,\text{kN/cm}^2;$$

- standard

$$\hat{\sigma}_s=\bar{\sigma}_s\cdot V_s=365\cdot 0.0436=15.91\,\text{MPa}=1.59\ \text{kN/cm}^2;$$

$$\hat{\sigma}_{sc}=\bar{\sigma}_{sc}\cdot V_s=300\cdot 0.0436=13.08\,\text{MPa}=1.31\,\text{kN/cm}^2,$$

where $V_s=0.0436$ according to table 2.31 [17] – coefficient of variation.

Numerical characteristics of stresses:

- mathematical expectation of resisting moment

$$\bar{M}_u = \bar{\sigma}_s A_s d - \bar{\sigma}_{sc} A'_s a' - 0.5\frac{(\bar{\sigma}_s A_s - \bar{\sigma}_{sc} A'_s)^2}{\bar{\sigma}_c b} =$$

$$= 36.5\cdot 2.26\cdot 14.5 - 30\cdot 2.26\cdot 1.5 - 0.5\frac{(36.5\cdot 2.26 - 30\cdot 2.26)^2}{2.18\cdot 10} = 1089.45\,\text{kN cm};$$

- resisting moment standard

$$\hat{M}_u = \hat{\sigma}_s A_s d - \hat{\sigma}_{sc} A'_s a' - 0.5\frac{(\hat{\sigma}_s A_s - \hat{\sigma}_{sc} A'_s)^2}{\hat{\sigma}_c b} =$$

$$= 1.59\cdot 2.26\cdot 14.5 - 1.31\cdot 2.26\cdot 1.5 - 0.5\frac{(1.59\cdot 2.26 - 1.31\cdot 2.26)^2}{0.295\cdot 10} = 46.95\,\text{kN cm};$$

- mathematical expectation of compression force

$$\bar{N}_u = \bar{\sigma}_s A_s + \bar{\sigma}_{sc} A'_s + \bar{\sigma}_c bh = 36.5\cdot 2.26 + 30\cdot 2.26 + 2.18\cdot 10\cdot 16 = 499.07\,\text{kN};$$

- compression force standard

$$\hat{N}_u = \hat{\sigma}_s A_s + \hat{\sigma}_{sc} A'_s + \hat{\sigma}_c bh = 1.59\cdot 2.26 + 1.31\cdot 2.26 + 0.295\cdot 10\cdot 16 = 56.75\,\text{kN};$$

Geometric characteristics of the cross section of columns: A=160cm^2, W=426.7cm^3, i_x=2.67cm.

Using column cross-section parameters, a number of calculations can be performed:

- relative eccentricity

$$\bar{m} = \frac{\bar{M}_u A}{\bar{N}_u W} = \frac{1089.45\cdot 160}{499.07\cdot 426.7} = 0.819;$$

- given relative eccentricity

$$\bar{m}_{ef} = \eta \bar{m} = 1.58\cdot 0.819 = 1.29,$$

where

$\eta = (1.75 - 0.1\bar{m}) - 0.02(5 - \bar{m}) = (1.75 - 0.1\cdot 0.819) - 0.02(5 - 0.819) = 1.58$ - the coefficient taking into account the shape of the cross section.

Column flexibility – $\lambda = H/b = 300/10 = 30$.

Relative flexibility – $\bar{\lambda} = \lambda\sqrt{f_{yd}/E_s} = 30\sqrt{365/(2\cdot 10^5)} = 1.28$.

We determine the numerical characteristics of the column stability reserve:

- mathematical expectation

$$\bar{Y} = \bar{f}'_{yd} - \frac{\bar{N}_u\cdot 10}{A\cdot b(1 - C\cdot \lg \bar{m}_{ef})} = 300 - \frac{499.07\cdot 10}{160\cdot 0.594(1 - 0.817\cdot 0.119)} = 241.56\text{MPa},$$

where

$$b = K_1 - K_2 \lg\bar{\lambda} = 0.7 - 0.62\cdot 0.117 = 0.627\,,$$

$$C = K_3 - K_4/b = 0.943 - 0.075/10 = 0.934\,,$$

coefficients K_1, K_2, K_3, K_4 are taken according to [17].

To determine the standard of the column stability reserve, we define the coefficients A_1, A_2, A_3 under the conditions provided in [17].

$$A_1=1,\ A_2=\frac{C\cdot\lg\overline{m}_{ef}+C\cdot d-1}{A\cdot b(1-C\cdot\lg\overline{m}_{ef})^2}=\frac{0.934\cdot 0.119+0.934\cdot 0.4343-1}{160\cdot 0.627(1-0.934\cdot 0.119)^2}=-0.61\cdot 10^{-2}\,\text{cm}^{-1},$$

$$A_3=\frac{C\cdot d\cdot\eta}{b\overline{m}_{ef}\cdot W(1-C\cdot\lg\overline{m}_{ef})^2}=\frac{0.934\cdot 0.4343\cdot 1.58}{0.627\cdot 0.119\cdot 426.7(1-0.934\cdot 0.119)^2}=-2.0255\cdot 10^{-2}\text{cm}^{-1},$$

where $d=0.4343$ is the module of transition from natural to decimal logarithms.

The standard of the column stability reserve is determined by the formula:

$$\widehat{Y}=\sqrt{\sum_{i=1}^{n}A_2^2\cdot\widehat{X}_i^2}=\sqrt{A_1^2\cdot\sigma_{sc}^2+A_2^2\cdot\widehat{N}_u^2+A_3^2\cdot\widehat{M}_u^2}=$$

$$=10\sqrt{1^2\cdot 3^2+(-0.61\cdot 10^{-2})^2\cdot 53.75^2+(-2.0255\cdot 10^{-2})^2\cdot 46.95^2}=33.924.$$

The safety characteristics proved to be equal: $\beta=\frac{\overline{Y}}{\widehat{Y}}=\frac{241.56}{33.924}=7.12$, that under the normal stability distribution gives the probability of failure of the column according to the table D3 [17] $Q=1.30\cdot 10^{-12}$.

As one can see, the discovered safety characteristics of the investigated columns significantly exceed the normative index: $\beta=7.12>[\beta]=4.75$.

Conclusions. Based on the analysis of experimental and theoretical studies of the operation of reinforced concrete eccentrically compressed columns operating under the action of low cycle loading with alternating eccentricities, the calculated reliability of such columns is numerically determined. It should be noted that the reliability of these structures under the above loading during operation will be ensured.

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РОЗРАХУНКОВА НАДІЙНІСТЬ ПОЗАЦЕНТРОВО СТИСНУТИХ ЗАЛІЗОБЕТОННИХ КОЛОН ЗА ДІЇ МАЛО ЦИКЛОВИХ НАВАНТАЖЕНЬ ІЗ ЗНАКОЗМІННИМИ ЕКСЦЕНТРИСИТЕТАМИ

Стаття присвячена визначенню розрахункової надійності позацентрово стиснутих залізобетонних елементів за дії малоциклових навантажень із знакозмінними ексцентриситетами. Ці елементи є по суті самими малодослідженими з точки зору надійності будівельних конструкцій.

Таке положення обумовлене тим, що окрім труднощів з імовірнісним описом реальних навантажень, особливо тимчасових (кранових, снігових або вітрових), оцінка надійності позацентрово стиснутих елементів, в тому числі і виконаних з такого добре вивченого матеріалу, яким є залізобетон, пов'язана з урахуванням геометричної і фізичної нелінійності.

Важливо підкреслити, що імовірнісний аналіз таких елементів, особливо в частині обґрунтованого розрахунку сполучення зусиль, може дати помітний ефект, оскільки на практиці саме позацентрово стиснуті елементи (стійки, колони та інші) завантажені найбільш широким набором випадкових навантажень.

На основі теоретичних досліджень, використовуючи експериментальні дані випробуваних елементів, виконаний числовий приклад визначення розрахункової надійності вище зазначених елементів. Оскільки величина ексцентриситету, рівень і характер навантажень суттєво впливають на зміну фізико-механічних властивостей матеріалів, так як ці параметри вважаються випадковими величинами від яких і залежить надійність, конструктивна безпека і довговічність позацентрово стиснутих елементів в процесі експлуатації.

При визначенні розрахункової надійності позацентрово стиснутих колон за дії малоциклових навантажень із знакозмінними ексцентриситетами використано існуючу методику розрахунку оцінки надійності будівельних конструкцій за дії однократних статичних навантажень з дотриманням чинних нормативних документів. Визначення зміни фізико-механічних властивостей бетону і арматури, при визначенні коефіцієнта умов роботи за дії вище вказаних навантажень, обґрунтовано статистично. Ці зміни враховано у роботі позацентрово стиснутих колон за дії малоциклових знакозмінних навантажень при визначенні їх розрахункової оцінки надійності.

Ключові слова: позацентровий стиск, мало циклове навантаження, знакозмінний ексцентриситет, надійність.

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CALCULATED RELIABILITY OF ECCENTRICALLY COMPRESSED CONCRETE COLUMNS UNDER THE ACTION OF LOW CYCLE LOADING WITH ALTERNATING ECCENTRICITES

The paper gives definition of design reliability of eccentric compressed reinforced concrete columns under the action of low-cyclic loads with alternating eccentricities. In particular, these elements are underexplored in terms of building constructions reliability.

Such condition is due to the fact that, besides difficulties with the probabilistic description of actual loads, especially temporary ones (crane, snow or wind), the reliability estimation of eccentric compressed elements, including elements which were made of well-researched material such as reinforced concrete, is connected with taking into account geometric and physical nonlinearity.

It is necessary to emphasize, the probabilistic analysis of such elements, especially in part of justified calculation of coupling forces, can give significant impact since in practice the eccentric compressed elements (studs, columns, etc.) are loaded by the widest set of random loads.

Based on theoretical researches and using the experimental data the numerical example of defining the design reliability of aforesaid elements was made. Since the value of eccentricity, level and loading conditions influence essentially on change of physical and mechanical properties of materials, therefore, these parameters are considered as random variables from which reliability, constructive reliability and long-term durability of eccentric compressed elements are depended during operating process.

During defining the design reliability of eccentric compressed columns under action of low-cyclic alternating loads, it was used the existed method of calculating the estimation of building constructions reliability under the action of single-stage steady loads in accordance with normative documents. It was justified statistically the definition of the change of physical and mechanical properties of concrete and reinforcing steel during determining the coefficient of operating conditions. These changes were taking into account during operating the eccentric compressed columns under action of low-cyclic alternating loads during defining the designing estimate of reliability.

Keywords: eccentric compression, low-cyclic loads, alternating eccentricity, reliability.

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Масюк Г.Х., Алексієвець В.І., Алексієвець І.І., Масюк В.Г. **Розрахункова надійність позацентрово стиснутих залізобетонних колон за дії мало циклових навантажень із знакозмінними ексцентриситетами** //Опір матеріалів і теорія споруд: наук.-тех. збірник. – К.:КНУБА, 2020. – Вип. 104. – С. 289-298.

Стаття присвячена визначенню розрахункової надійності позацентрово стиснутих залізобетонних елементів за дії мало циклових навантажень із знакозмінними ексцентриситетами. На основі теоретичних досліджень, використовуючи експериментальні дані, виконаний числовий приклад визначення розрахункової надійності вище зазначених елементів. Величина ексцентриситету, рівень і характер навантажень суттєво впливають на зміну фізико-механічних властивостей матеріалів, так як ці параметри вважаються випадковими величинами від яких і залежить надійність, конструктивна безпека і довговічність позацентрово стиснутих елементів. При визначенні оцінки надійності колон використано існуючу методику розрахунку надійності будівельних конструкцій за дії однократних статичних навантажень з дотриманням чинних норм. Визначення зміни фізико-механічних властивостей бетону при визначенні коефіцієнта умов роботи, обґрунтовано статистично. Враховано ці зміни у роботі позацентрово стиснутих елементів за дії мало циклових знакозмінних навантажень.
Табл. 0. Іл. 0. Бібліогр. 30 назв.

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Masiuk H.Kh., Aleksiievets V.I., Aleksiievets I.I., Masiuk V.H. **Calculated reliability of eccentrically compressed concrete columns under the action of low cycle loading with alternating eccentricities** // Strength of Materials and Theory of Structures: Scientific-and-technical collected articles – Kyiv: KNUBA, 2020. – Issue 104. – P. 289-298.

The paper gives definition of design reliability of eccentric compressed reinforced concrete columns under the action of low-cyclic loads with alternating eccentricities. Based on theoretical researches and using the experimental data the numerical example of defining the design reliability of aforesaid elements was made. The value of eccentricity, level and loading conditions influence essentially on reversal of physical and mechanical properties of materials, since these parameters are considered as random variables from which reliability, constructive reliability and long-term durability of eccentric compressed elements are depended. During estimating the column reliability, it was used the existed method of reliability calculation of building constructions under the action of single-stage steady loads in accordance with existing norms. It was justified statistically the definition of the reversal of physical and mechanical properties of

concrete during determining the coefficient of operating conditions. These reversals were taking into account during operating the eccentric compressed elements under action of low-cyclic alternating loads.
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