Construction Technologies and Architecture
ISSN: 2674-1237, Vol. 9, pp 59-66
doi:10.4028/p-kev0Ho

Submitted: 2023-03-02
Accepted: 2023-04-09
Online: 2023-08-31

Method of Identification of Mechanical Characteristics of Concrete of Reinforced Concrete Crossbars According to the Results of Fire Tests

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Keywords: reinforced concrete crossbar, fire resistance, standard temperature regime, maximum deflection, interpolation method, concrete strength reduction factor, calculation method.

Abstract. The article substantiates the method of identifying the mechanical characteristics of concrete of reinforced concrete beams based on the results of fire tests. The idea of the work is to improve the calculation approach to assessing the fire resistance of reinforced concrete beams by clarifying the mechanical characteristics of concrete during its heating under the conditions of exposure to the standard fire temperature regime. The proposed method of identifying the mechanical characteristics of concrete is based on the reproduction of temperature distributions in the cross-sections of reinforced concrete beams based on the results of point temperature measurements during fire tests and the application of equilibrium equations compiled using the deformation mathematical model of the stress-strain state.

As a result of the obtained experimental data, the temperature distributions were reproduced using the proposed interpolation method. According to the obtained temperature distributions and the proposed mathematical apparatus, the coefficient of reduction in the concrete strength of reinforced concrete beams during fire tests was identified, the maximum deflection of two sample reinforced concrete beams was determined, and using a deformation model based on the use of equilibrium systems of internal layers in the cross section of reinforced concrete beams, the coefficient of reduction of strength of concrete under the condition of exposure to the standard fire temperature regime was specified. The presented curves of the value of the coefficient of reduction of concrete strength according to the proposed method and according to the recommendations of Eurocode 2 indicate the presence of a deviation between these indicators.

1 Introduction

To ensure fire safety in buildings and structures, there is a need to establish the compliance of reinforced concrete structures with the relevant requirements for their fire resistance. Among such structures, reinforced concrete crossbars are the most suitable [1, 2]. The fire resistance of reinforced concrete crossbars must comply with regulatory and technical standards, where the basic principles of its provision are established [3, 4]. To assess the fire resistance of reinforced concrete structures, there are two main approaches, of which the method of fire tests is considered the most reliable [5, 6]. This method is carried out by heating a sample of the element of the structure under study in a special installation, which includes a furnace and a system for applying the appropriate mechanical load [7, 8]. An important feature of this method is the creation of conditions under which the standard fire temperature regime is ensured in the furnace chamber [9, 10]. The implementation of fire tests is associated with certain technical difficulties, as a result of the inconsistency of the fastening and loading conditions with real conditions, inconsistency of the overall dimensions of the test sample, etc [11, 12]. In addition, the implementation of the method of fire tests requires significant labor and material costs [13].

A reasonable alternative to the experimental approach is the use of a calculated assessment of fire resistance [14, 15]. This approach has recently undergone great development in connection with the intensification of the progress of computer technology [16]. The main advantages of this approach are flexibility, the ability to take into account all types of boundary conditions, materials, geometric dimensions and other parameters of reinforced concrete crossbars, and they are also much less time-consuming and expensive [17].

Most calculation methods for assessing fire resistance are based on the hypotheses of material resistance and work well when taking into account complete information about the behavior of reinforced concrete beams under fire conditions [3, 9]. The inaccuracy of information on the thermomechanical characteristics of materials imposes restrictions on the use of calculation methods and reduces their advantages in comparison with experimental methods [18, 19]. To eliminate these shortcomings, it is effective to use approaches that allow specifying the properties of concrete and reinforced concrete based on the generalization and interpretation of data obtained as a result of fire tests. In view of the above, it can be noted that the importance and relevance of the tasks of studying the mechanical properties of materials of reinforced concrete crossbars based on the generalization and interpretation of the results of fire tests [20, 21].

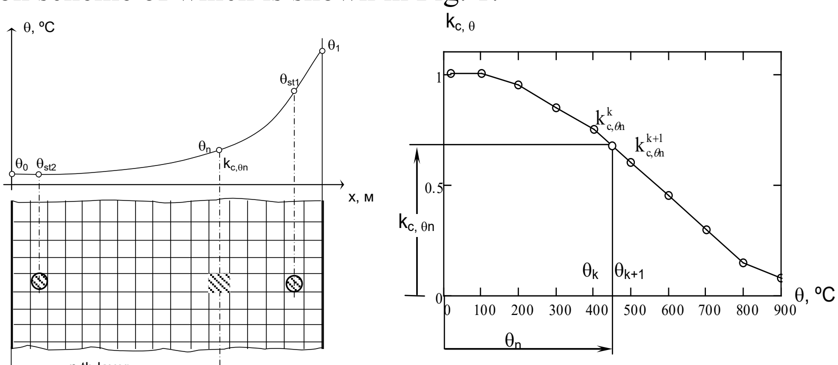
The purpose of the work is to obtain regularities of the decrease in concrete strength of reinforced concrete beams depending on the temperature when they are heated under the conditions of thermal influence of the standard fire temperature regime. To achieve the set goal, the following tasks must be solved:

1. To develop a methodology for conducting fire tests of reinforced concrete crossbars, for the further possibility of identifying the coefficient of reduction of concrete strength directly in the studied structures under the thermal influence of fire.

2. To develop a method for identifying the concrete strength reduction factor of a reinforced concrete crossbar directly in the structure based on the results of research on fire tests in special installations and according to the obtained data of experimental studies on fire tests of reinforced concrete crossbars, to obtain a refined dependence of the coefficient of reduction of concrete strength on the temperature of the standard fire temperature regime, which is the basis for improving the calculation method for assessing the fire resistance of reinforced concrete crossbars based on deformation models.

2 Main Part

To achieve the goal, using the approach proposed in work [22], a method was developed to identify the dependence of the coefficient of reduction of concrete strength of reinforced concrete beams, the implementation scheme of which is shown in Fig. 1.



a *b*

Fig. 1. Calculation of the coefficient of reduction of concrete strength of a reinforced concrete cross-section by temperature in the inner layer: a – diagram of the division into layers of the cross-section of a reinforced concrete crossbar; b – the scheme of linear interpolation of the coefficient of reduction of the concrete strength of the reinforced concrete crossbar according to tabular data.

When implementing this method, it is necessary to perform the sequence of procedures presented below in the form of a diagram in Fig. 2.

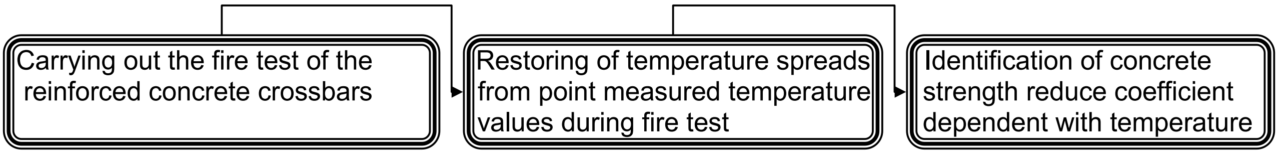


Fig. 2. The scheme of implementation of the method of identification of the dependence of the coefficient of reduction of concrete strength of reinforced concrete beams.

The determination of temperatures at any point of the sections of reinforced concrete cross-sections, based on point measurements of the temperature in their inner layers, during high-temperature tests under the standard fire temperature regime, was carried out by the developed interpolation method, the block diagram of which is shown in Fig. 3.

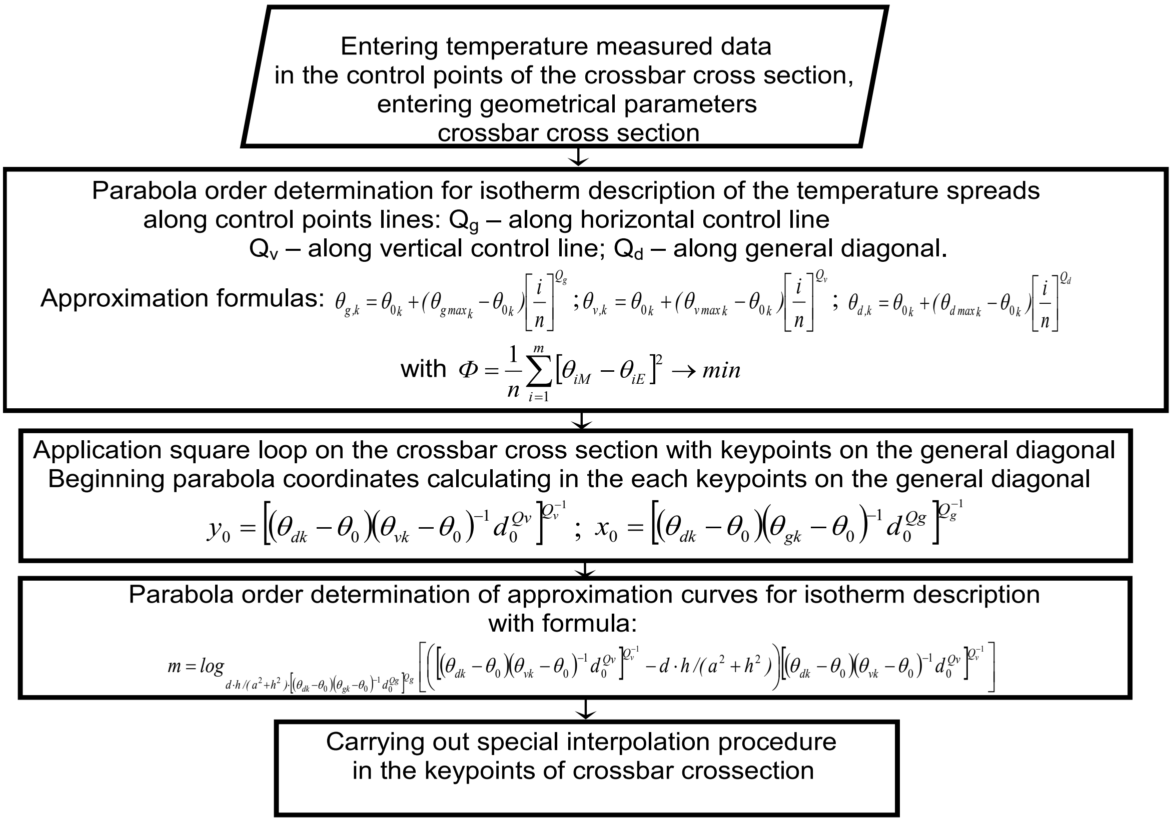


Fig. 3. Block diagram of the algorithm for determining the temperature at nodal points of the cross-section by interpolating the temperatures according to the temperature indicators at the control points of the cross-section.

In order to identify the concrete strength reduction factor of the tested reinforced concrete crossbars during fire tests, the maximum deflection of the sample reinforced concrete crossbars was measured.

The approach described in [22] was used to identify the concrete strength reduction factor of a reinforced concrete beam. Determination of the stress-strain state in the cross-section of a reinforced concrete beam under heating conditions is described using a deformation model based on the use of equilibrium systems of internal layers in the cross-section. The system of equilibrium equations has the following form:

$$[\mathbf{F}]\{\mathbf{k}\} + \{\mathbf{S}\} = M_{Ed}, \quad (1)$$

where $\{k\}=(k_{c1}\ k_{c2}\ \dots\ k_{cm})^T$ – the vector of values of the coefficients of reduction of the concrete strength of the reinforced concrete crossbar corresponding to the table values of temperatures $\{\Theta_m\}=(0\ 100\ 200\ \dots\ \theta_m)^T$, which are unknown of the recorded System of linear algebraic equations (SLAE); M_{Ed} – acting moment in a reinforced concrete beam.

Here [F] – matrix of SLAE coefficients, which has the following form:

$$[\mathbf{F}]=\begin{pmatrix} Z_{11} & \dots & Z_{1j} & \dots & Z_{1m} \\ \vdots & & \vdots & & \vdots \\ Z_{i1} & & Z_{ij} & & Z_{im} \\ \vdots & & \vdots & & \vdots \\ Z_{m1} & \dots & Z_{mj} & \dots & Z_{mm} \end{pmatrix}, \tag{2}$$

where the parameters of the matrix of coefficients are calculated by expressions:

$$Z_{i1}=\sum_n [1-0.01(\theta_{ni}-\theta_1)]F_n(\varepsilon,\theta_{ni})A_c y_n\ ,\ Z_{im}=\sum_n 0.01(\theta_{ni}-\theta_{m-1})F_n(\varepsilon,\theta_{ni})A_c y_n$$

$$Z_{ij}=\sum_n [1-0.01(\theta_{ni}-\theta_j)]F_n(\varepsilon,\theta_{ni})A_c y_n+\sum_n 0.01(\theta_{ni}-\theta_{j-1})F_n(\varepsilon,\theta_{ni})A_c y_n\ . \tag{3}$$

Magnitude $m=[\theta_{max}\cdot 0.01]$ – is the number of equations and variables in SLAE (1), which is calculated based on the maximum heating temperature of a reinforced concrete beam during fire tests.

When writing equations for specific test moments, the value of the maximum deflection is set evenly between the first test moment and the time when the correspondence of the deformation and stress plot to the linear relationship is maintained.

In SLAE (1) {S} – is the vector of forces in the reinforcing bars, which is calculated using the following formula:

$$\{S\}=(S_1\ \dots\ S_i\ \dots\ S_m)^T, \tag{4}$$

where $S_i=\Sigma_p F_{st,p}(\varepsilon,\ \theta_{st,p})$. Force in the p-th reinforcing bar in i moment of time are calculated according to the expressions recommended by the guidelines on the estimated fire resistance of reinforced concrete structures [17].

Deformations of concrete and reinforcing steel are determined by expressions [22]:

$$\varepsilon_{ci}=\varepsilon_0+y_{ci}\chi_t\ ,\ \varepsilon_{si}=\varepsilon_0+y_{si}\chi_t\ , \tag{5}$$

where ε_0 – relative deformation of the upper cross-section point of the reinforced concrete crossbar in the transverse direction;

χ_t – the curvature of a reinforced concrete beam at a certain point in time.

The relative deformation of the upper point and the curvature of the section of the reinforced concrete cross-section are calculated using the hypothesis of flat sections according to the formulas:

$$\varepsilon_0=\frac{h^2\chi_t}{2h-z_0}\ ,\ \ \chi_t=\frac{48w_t}{5L^2}\ , \tag{6}$$

where L – span length of reinforced concrete crossbar;

w_t – the maximum deflection of a reinforced concrete beam at a certain point in time;

z_0 – the axial distance from the outermost reinforcing bar to the lower edge of the reinforced concrete cross section.

To implement the method of identification of the dependence of the coefficient of reduction of concrete strength on temperature, a test of a reinforced concrete crossbar was carried out, the structural scheme of which is shown in Fig. 4.

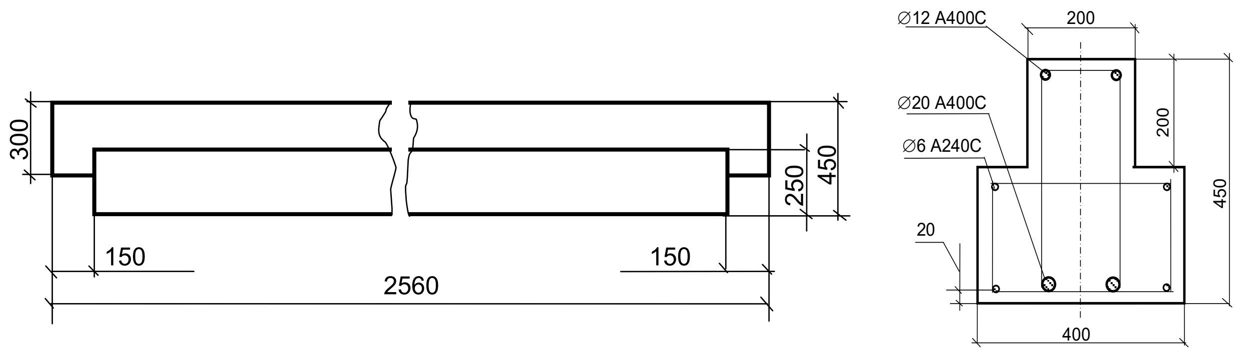


Fig. 4. Block diagram of the algorithm for determining the temperature at the nodal points of the cross-section by interpolating the temperatures according to the temperature indicators at the control points of the cross-section.

Fig. 5 shows the scheme of temperature measurement in the inner layers of the beam.

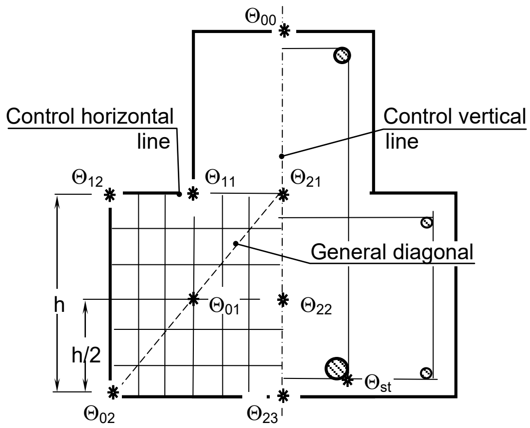


Fig. 5. Diagram of thermocouple location in the cross-section of a reinforced concrete crossbar-sample for testing.

During the fire tests of samples of reinforced concrete crossbars, the temperature was measured at control points of the section located according to the diagram shown in Fig. 5 [23]. To reproduce the temperature fields in the section the algorithm shown in Fig. 3 was used every minute. After carrying out the relevant calculations, the temperature distributions were obtained, which are presented in Fig. 6.

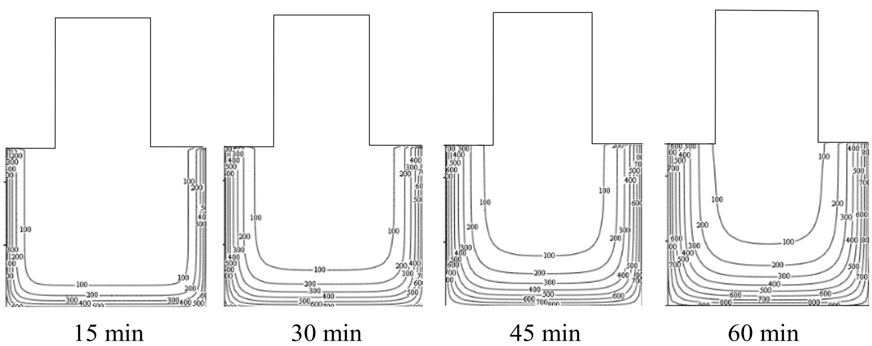


Fig. 6. Temperature distributions in the reinforced concrete beam, determined as a result of the calculation (°C).

To implement the method of identifying the coefficient of strength reduction during fire tests, a curve of dependence of the maximum deflection on the test time was constructed, which is presented in Fig. 7.

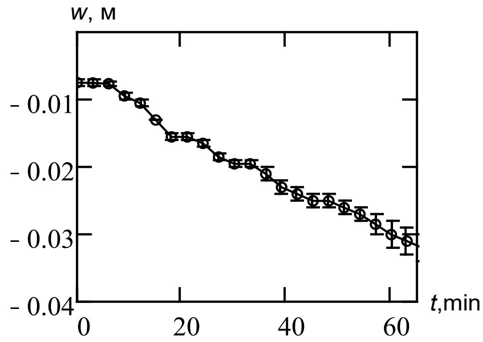


Fig. 7. The dependence of the value of the average maximum deflection of reinforced concrete beans with deviations.

Using the results of temperature measurements and the maximum deflection of a reinforced concrete beam, obtained during fire tests, and mathematical models expressed by formulas (1)–(6), the coefficient of reduction of concrete strength as a function of temperature was identified, shown in Fig. 8. Fig. 8 also presents the dependence curves of the value of the coefficient of reduction of concrete strength according to the proposed method and according to the recommendations of Eurocode 2 [24, 25].

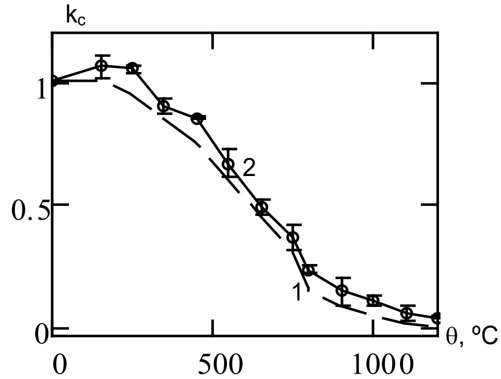


Fig. 8. Dependencies of the concrete strength reduction factor: 1 – standard dependence, 2 – averaged dependence for samples № 1 and № 2 with deviations.

Thus, a refined dependence of the coefficient of reduction of concrete strength for reinforced concrete beams was obtained, which will allow to significantly increase the accuracy of the calculation method of fire resistance assessment for structural elements of this type.

3 Conclusions

As a result of the conducted research, an important scientific result was obtained, which consists in clarifying the dependence of the coefficient of reduction in the concrete strength of reinforced concrete beams depending on the temperature, which is the scientific basis for improving the calculation method for assessing the fire resistance of reinforced concrete beams based on deformation models. At the same time, the following conclusions can be drawn.

1. A methodology was developed and fire tests of a reinforced concrete beam were conducted using it, the measurement data of which allow implementing the proposed method of identifying the coefficient of concrete strength reduction.

2. As a result of the conducted research, a method for identifying the coefficient of reduction in concrete strength of a reinforced concrete beam based on its fire tests is proposed.

3. According to the data obtained during the fire tests, a refined dependence of the concrete strength reduction coefficient was obtained, which is the basis for improving the calculation method for assessing the fire resistance of reinforced concrete beams based on deformation models.

References

[1] A. Kovalov, Yu. Otrosh, S. Vedula, O. Danilin, T. Kovalevska, Parameters of fire-retardant coatings of steel constructions under the influence of climatic factors, Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 3 (2019) 46–53.

[2] A. Vasilchenko, Yu. Otrosh, N. Adamenko, E. Doronin, A. Kovalov, Feature of fire resistance calculation of steel structures with intumescent coating, MATEC Web of Conferences, 230 (2018) 02036.

[3] V.K.R. Kodur, Guidelines for Fire Resistance Design of High-Strength Concrete Columns, J. of Fire Protection Engineering, 15:2 (2005) 93–106.

[4] A. Kovalov, Yu. Otrosh, M. Surianinov, T. Kovalevska, Experimental and computer researches of ferroconcrete floor slabs at high-temperature influences, Materials Science Forum, 968 MSF (2019) 361–367.

[5] Long T. Phan, Therese P. McAllister, John L. Gross, Morgan J. Hurley, Best Practice Guidelines for Structural Fire Resistance Design of Concrete and Steel Buildings, NIST Technical Note 1681 (2010) 217 p.

[6] V. Sadkovyi, V. Andronov, O. Semkiv, A. Kovalov, E. Rybka, Yu. Otrosh et. al.; Sadkovyi, V., Rybka, E., Otrosh, Yu. (Eds.), Fire resistance of reinforced concrete and steel structures, Kharkiv: PC TECHNOLOGY CENTER, (2021) 180.

[7] A. Kovalov, Yu. Otrosh, E. Rybka, T. Kovalevska, V. Togobytska, I. Rolin, Treatment of Determination method for strength characteristics of reinforcing steel by using thread cutting method after temperature influence, 1006 MSF (2020) 179–184.

[8] M. Surianinov, V. Andronov, Yu. Otrosh, T. Makovkina, S. Vasiukov, Concrete and fiber concrete impact strength, Materials Science Forum, 1006 MSF (2020) 101–106.

[9] S.L. Fomyn, O.A. Stelmakh, Dzhafar Shaker Shakhyn Fire resistance of centrally compressed reinforced concrete elements, Fire Safety: Organizational and technical support, Kharkiv: KhIPB MVD Ukraine, (1996) 78–81.

[10] Building structures. Test method for fire resistance. General requirements. Fire safety. (ISO 834: 1975) DSTU B B.1.1-4-98*. [Effective from 1998-10-28.] Kyiv: Ukrarkhbudinform, (2005) 20 p. (The National Standard of Ukraine).

[11] A. Buchanan, Structural Design for Fire Safety, New York: John Wiley & Sons, (2001).

[12] S. Gurung, O. Salem, Effects of Load Level on the Structural Fire Behaviour of GFRP-Reinforced Concrete Beams with Straight-End bar Lap Splices, Lecture Notes in Civil Engineering, 267 (2023) 85–92.

[13] S. Pozdieiev, O. Nuianzin, S. Sidnei, S. Shchipets, Computational study of bearing walls fire resistance tests efficiency using different combustion furnaces configurations, MATEC Web of Conferences, 116 (2017) 02027.

[14] Y. Otrosh, Y. Rybka, O. Danilin, M. Zhuravskyi, Assessment of the technical state and the possibility of its control for the further safe operation ofbuilding structures of mining facilities, E3S Web of Conferences, 123 (2019) 01012.

[15] O. Nuianzin, O. Tyshchenko, S. Zhartovskyi, P. Zaika, A. Peregin, The research of carrying capacity of reinforced concrete walls under uneven warming, IOP Conference Series: Materials Science and Engineering, 708 1 (2019) 012063.

[16] Yu. Otrosh, M. Surianinov, O. Holodnov, O. Starova, Experimental and computer researches of ferroconcrete beams at high-temperature influences, Materials Science Forum, 968 (2019) 355–360.

[17] S. Pozdieiev, O. Nekora, V. Slovynsky, The research of bearing capacity of reinforced concrete beam with use combined experimental-computational method, MATEC Web of Conferences, 116 02024. DOI: 10.1051/matecconf/201711602024.

[18] Pilipenko A., Pancheva H., Reznichenko A., Myrgorod O., Miroshnichenko N., Sincheskul A. The study of inhibiting structural material corrosion in water recycling systems by sodium hydroxide. *Eastern-European Journal of Enterprise Technologies.* 2017. Vol. 2, No. 1–85. P. 21–28.

[19] B. Pospelov, V. Andronov, E. Rybka, O. Krainiukov, K. Karpets, O. Pirohov, I. Semenyshyna, R. Kapitan, A. Promska, O. Horbov, Development of the correlation method for operative detection of recurrent states, Eastern-European Journal of Enterprise, 6/4 (102) (2019) 39–46.

[20] O. Nekora, V. Slovynsky, S. Pozdieiev, The research of bearing capacity of reinforced concrete beam with use combined experimental-computational method, MATEC Web of Conferences, 116 (2017) 02024.

[21] A. Vasilchenko, E. Doronin, O. Chernenko, I. Ponomarenko, Estimation of fire resistance of bending reinforced concrete elements based on concrete with disperse fibers, IOP Conference Series: Materials Science and Engineering, 708 1 (2019) 012075.

[22] S.D. Shchipets, Improvement of the method of testing the fire resistance of reinforced concrete and stone load-bearing walls: Ph.D. thesis in technical sciences, (2015)160 p.

[23] S. Lamont, B. Lane, A. Usmani, D. Drysdale, Assessment of the Fire Resistance Test with Respect to Beams in Real Structures, Engrg. J. AISC, 40:2 (2003) 63–75.

[24] EC2, Design of Concrete Structures–Part 1.2, General Rules–Structural Fire Design, ENV 1992-1-2, CEN, (2002).

[25] Fire safety of construction objects. General requirements of State Construction norms B.1.1-7-2016 [Effective from 2017-06-01] The Ministry of Regional Development and Construction, (2017) 35 p. (The National Standard of Ukraine).