UDC 624.044.3

THERMAL STRESS STATE OF REINFORCED CONCRETE FLOOR SLAB

M.S. Barabash [1,2],
Doctorof Technical Sciences, Associate Professor

M.A. Romashkina [2],
Candidate of Technical Sciences

O.U. Bashynska [1,2]

[1]*National Aviation University*

[2]*Limited liability company "LIRA SAPR"*

Abstract. The article provides research of the stress-strain state of a reinforced concrete floor slab under fire conditions according to refined method. The finite element model of the slab is created. At the first stage of the research, one solved the unsteady heat conduction problem. According to the solution of the problem, it is possible to obtain the temperature fields all over the section of the considered structural element at certain intervals of time. The second stage of the study is strength analysis. Due to the strength evaluation, it is possible to investigate the work of the floor slab at different time points of fire exposure. Several mathematical models are considered. These models correspond to different points in time of fire impact. In each design model of the floor slab, the strength and deformation characteristics of concrete and reinforcement were deepen in accordance with the section temperature. It made three types of fire resistance analysis of the structure: linear analysis, physically-nonlinear analysis, and physically-nonlinear analysis with taking into account the effect of creep. The results of comparison of the kinetic performance of the mathematical models in various problem statements are showed. The technique, which allows to take into account the influence of creep in the numerical simulation of fire effect is proposed.

Keywords: finite elements methods, structures, thermal stress state, numerical experiments, thermal conductivity, comparisons.

1. Introduction. The fire resistance analysis of structures is one of the most important design stages. The building rules expound several variants of fire resistance analysis of structures: simplified, qualified methods of calculation and the calculation with reference to the tabular data.

The calculation with reference to the tabular data is the easiest way when you can determine the thickness of the concrete protective layer, according to the fire resistance class of the structure and geometry of the section.

In the simplified analysis method, it is estimated that concrete at temperatures above 500°C can't be taken into account in the operation of the structure. Therefore, it is necessary to determine the temperature distribution all over the cross-section of every element. According to the temperature fields distribution we have to perform a strength calculation of the reduced cross section. But, the abovementioned analysis types have some limitations. For example, the calculation with reference to the tabular data must only be used for a certain level of loads, eccentricity values and flexibility of elements. A simplified method doesn't give us the opportunity to take into account changes in the strength characteristics of materials caused by increasing temperature. At the same time, the proposed analysis method is universal for any mathematical model and makes it possible to take into account the changes of the properties of concrete and reinforcement during a fire action. While realizing the fire resistance analysis of buildings and structures, for every engineer the most important thing is a choice of building rules and regulatory documents. The choice of these documents depends on the country in which the construction is planned to be built. In any of such documents [1, 2, 3, 4], it is stated that in order to perform a qualified calculation method of the structure for fire resistance, it is necessary first of all to know how the temperature will be distributed all over the cross section of each structural element which is exposed to fire impact. To accomplish the task it is necessary to carry out the heat transfer engineering analysis by the finite element method [1, 2, 3], or by the finite difference method. Based on the temperature distribution data, it is necessary to take into account the change in material properties and to perform a strength analysis. The regulatory documents also state that with this approach it is necessary to take into account creep deformations.

According to the qualified methods of calculation, it is necessary to do a thermal design. On the basis of the thermal design it is necessary to change the mechanical properties of materials.

In order to perform a thermal design, it is necessary to solve the problem of thermal conductivity. The equation for the boundary value problem of nonstationary heat conduction is given in the formula (1):

$$K_{xx}\frac{\partial^2 T}{\partial x^2}+K_{yy}\frac{\partial^2 T}{\partial y^2}+K_{zz}\frac{\partial^2 T}{\partial z^2}+w=\rho c\frac{\partial T}{\partial t}\,, \qquad (1)$$

where $T=T(x,y,z,t)$ – is thermal field in the area of Ω ; K_{xx},K_{yy},K_{zz} – thermal conductivity along the axes x,y,z ; $w=w(x,y,z,t)$ – heat source power inside the body; ρ – density; c specific heat.

It is possible to solve this equation by the finite element method or by the finite difference method. When using the first method, the structure must be modeled by special finite elements with one degree of freedom - temperature, which is a scalar value.

After determining the temperature fields all over the structure, in the considered mathematical model it is necessary to lower the stiffness characteristics of the materials and to make strength calculation. With this approach, to determine the total deformations of the structure it is necessary to take into account the creep deformation. At the same time, the question of creep deformations determining in such a formulation of the question remains open.

Therefore, it can be argued that the study of determining methods for creep deformations, as well as taking them into account when calculating fire resistance and creating methods for numerical modeling of the effect of fire and occurrence of plastic deformations, is a relevant research topic.

A lot of scientists have been studying the effect of creep on the stress-strain state of structures [5, 6, 7, 8]. On the territory of the post-Soviet space, Maslov and his student Harutyunyan [9] were the first researchers of the field. Aleksandrovsky S.V. [10], RabotnovYu.N., Mileyko S.T. were engaged in studying the effect of temperature with regard to creep. Among the foreign scientists the most famous are the works of the Czech scientist Zd. Bazant [11, 12, 13, 14]. In his work, he derived a formula to determine the creep function, which depends on the ambient temperature rise. A lot of modern scientific works are devoted to the problem of influence of concrete rheological properties on stress strain state of a structure [15, 16, 17, 18].

In [19] the problem of numerical modeling of the temperature state situation of reinforced concrete floor slabs is expounded. But the proposed method of calculating the floor slab does not take into account the interaction between the characteristic areas of concrete, because the floor slab is modulated by plates finite elements.In [20] there is a comparison of the methods for fire resistance analysis proposed in regulatory documents. But there is no comparison of calculations of real structures according to various regulatory documents. Therefore, it can be concluded that the process of modeling of floor slabs, taking into account the effects of high temperatures, is not sufficiently explored.

The question of the influence of concrete rheological properties on structure deformation is not sufficiently studied. Of course, there are some articles, in which the effect of temperature on concrete properties is considered. Such as [21, 22] or the previous works of the authors of the current article [23, 24], but in the literature there is no research oncalculation of real structures with taking into account the effect of high temperatures and development of short-term thermal creep.

Since the main method to determine the stress-strain state of structures is the finite element method, so many works are devoted specifically to improving this method [25, 26, 27, 28]. One of the most famous scientist in the field of finite elements is Zienkiewicz O.C. [25, 26]. But there are practically no works that consider the effect of the rheological properties of concrete into stress strain situation of the structure taking into account the fire effect calculated by finite elements method.

The goal of the research is the studying the strength and deformation characteristics of reinforced concrete floor slabs under fire exposure.

To achieve this goal it has solved the following tasks:

- the problem of heat conductivity by the method of finite elements. By solving the problem, it revealed the temperature change all over the cross section of the structural element in time;
- linear and nonlinear strength problems, which consider changes of the strength and deformation properties of materials according to the temperature increasing.

2. Methods. In this article, the authors propose the fire resistance analysis methodology for reinforced concrete floor slabs, taking into account the influence of temperature creep. According to the proposed methodology, afloor slab should be divided into characteristic areas all over the whole structure. At the first step, it is necessary to perform the calculation of thermal conductivity and determine the temperature distribution all over the entire plate. After the thermal calculation, it is necessary to reduce the rigidity of the corresponding layers of the plate. The next step is the calculation of the creep coefficient depending on the temperature change of each layer of the plate. After that it is necessary to make a strength calculation considering the physical non-linearity of the structure.

To implement the proposed methodology, the finite elements of thermal conductivity were implemented on SPLIRA SAPR. The theory of the definition of some thermal finite elements is below.

If we introduce the boundary conditions to solve the quasi-harmonic equation (1), then this equation will be of the form of:

$$K_{xx}\frac{\partial^2 T}{\partial x^2}l_x + K_{yy}\frac{\partial^2 T}{\partial y^2}l_y + K_{zz}\frac{\partial^2 T}{\partial z^2}l_z + q + h\left(T_s - T_b\right) = 0\ , \tag{2}$$

where l_x, l_y, l_z are directional cosines to the external normal boundary, q – heat flow, $h(T_s - T_b)$ – convection heat losses (h – convection coefficient).

To solve the equation (2), the examined body is divided into finite elements, in which the degrees of freedom are temperatures at the nodes. At the same time, the temperature inside each element is approximated by linear polynomials.

Let’s regard an example of some approximating polynomials of finite elements of thermal conductivity:

- three-nodal plane finite element:

$$T(x,y) = \alpha_1 + \alpha_2 x + \alpha_3 y\ ; \tag{3.1}$$

- four-nodal isoparametric plane finite element:

$$T(x,y) = \alpha_1 + \alpha_2 x + \alpha_3 y + \alpha_4 xy\ ; \tag{3.2}$$

- solid tetrahedral finite element:

$$T(x,y) = \alpha_1 + \alpha_2 x + \alpha_3 y + \alpha_4 z\ . \tag{3.3}$$

Since the linear polynomials are used to approximate the temperature function of a discrete model, the finite elements of thermal conductivity are also called simplex elements [26].

Substituting the values of nodal temperatures and coordinates of nodes into the corresponding polynomials we can obtain expressions for the coefficients $\alpha_1, \alpha_2, \alpha_3, \alpha_4$. If we return these coefficients into the equations 3.1 - 3.3, we can get the expression:

$$\left[T(x,y,z)\right] = \left[N(x,y,z)\right]_e \left\{T\right\}_e , \tag{4}$$

where $\left[N(x,y,z)\right]_e$ – is a function form matrix.

Let’s consider the matrix of thermal conductivity coefficients

$$\mathrm{K} = \begin{bmatrix} \mathrm{K}_{xx} & 0 & 0 \\ 0 & \mathrm{K}_{yy} & 0 \\ 0 & 0 & \mathrm{K}_{zz} \end{bmatrix}, \tag{5}$$

and the column matrix of temperature gradients, which is analogous to the stress matrix in the strength problem

$$\operatorname{grad} T = \begin{bmatrix} \dfrac{\partial T}{\partial x} \\ \dfrac{\partial T}{\partial y} \\ \dfrac{\partial T}{\partial z} \end{bmatrix} = DT\ . \tag{6}$$

Then the contribution of each individual finite element to the solution of the problem of non-stationary heat conduction can be written as a matrix differential equation:

$$\{Q\}_e = [C]_e \frac{\partial}{\partial t}\{T\}_e + [K]_e \{T\}_e - \{Q\}_e^q - \{Q\}_e^g - \{Q\}_e^h, \tag{7}$$

where $[K]_e$ – element conduction matrix (equivalent to stiffness matrix),

$$[K]_e = \int [B]^T [D][B] dV + \int h[N]^T [N] \mathrm{d}S, \tag{8}$$

$[C]_e$ – specific heat matrix (equivalent to damping matrix),

$$[C]_e = \int \rho c [N]^T [N] \mathrm{d}V, \tag{9}$$

$\{Q\}_e^q, \{Q\}_e^g, \{Q\}_e^h$ - node heat transfer vector.

The study is based on the existing methods of the theory of elasticity, plasticity, short-term and long-term creep, generally accepted methods of static linear analysis and physically nonlinear analysis of reinforced concrete structures. The basis of the study was also the main hypotheses and rules adopted in structural mechanics and the mechanics of a deformable solid body.

The analysis of mathematical models was made on the basis of the software package “LIRA-SAPR”, on which the problem of heat conductivity and strength was solved.The heat transfer problem was modeled using finite elements of thermal conductivity. Heat transfer between the floor slab and air space was modeled by special finite elements of convection. The strength problem was implemented by using physically linear and nonlinear finite elements (depending on the formulation of the problem).

3. Results and discussion. To verify the results of theoretical studies, the test problem is solved. The dimensions of the test plate were: length - 16.5 m, width - 8 m, height of the plate (above the columns) - 600 mm, height of the plate in the span - 300 mm. Armature in the span (lower) - Ø16 and Ø20, reinforcement above the supports (upper) - Ø32.

Concrete is modeled by the solid isoparametric finite elements. The armature is modeled by finite elements of bar with number 210. The whole mathematical model includes 20390 finite elements.

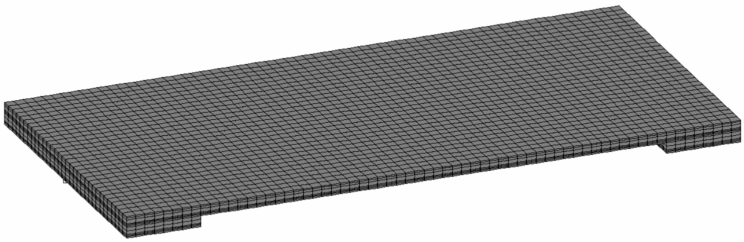
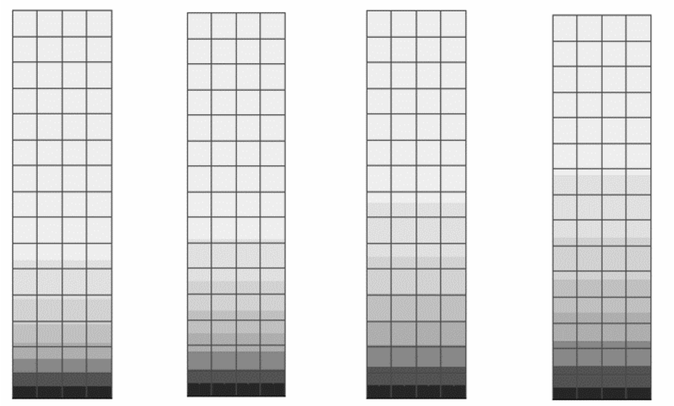


Fig. 1. The plate finite element model

The boundary conditions of symmetry are set on the boundary nodes. At the points of connection of the column to the floor slab, an analogue of the work of the columns was finite element with number 56, with stiffness corresponding to the work of the columns in the span. In height, the plate is divided into 6 and 12 layers, in the span and on the supports, respectively.

To release heat transfer analysis and to determine the temperature fields, the cross section analysis of the floor slab is accomplished. Since the change of temperature all over the height of the cross section occurs uniformly, this makes it possible to consider the temperature distribution just along the part of the cross section of the same height.

To accomplish the heat transfer analysis the following heat-conducting properties of concrete were adopted: specific weight - 2300 N/m^3, thermal conductivity - 1.2 J/(m·s·°C), specific heat - 710 J/(kg·°C). The convection coefficient according to paragraph 3.2.1 of [3] was assumed to be 25 W/(m^2·s). The temperature load was set according to the standard temperature of the fire. The ambient temperature at the initial moment of time is assumed to be 20 °C. The results of the thermal analysis are shown in Figure 2.



60 minutes
Tmax = 613°C

120 minutes
Tmax =784°C

180 minutes
Tmax = 900°C

240 minutes
Tmax = 989°C

Fig. 2. The temperature field distribution all over the cross section of the floor slab in the span (h = 300mm) at different timepoints

Obtained the distribution of temperature fields it set the reduced stiffness and strength characteristics to the corresponding layers of the floor slab. At Figure 3 it is shown an example how to determine the reduction factor for concrete compressive strength depending of the layer temperature. The reduction factors are taken from [3]. An example is shown for a section with temperature fields at 120 minutes of fire exposure.

At Figure 4 it shown an example of comparison of changes in the characteristics of the material depending of the temperature.

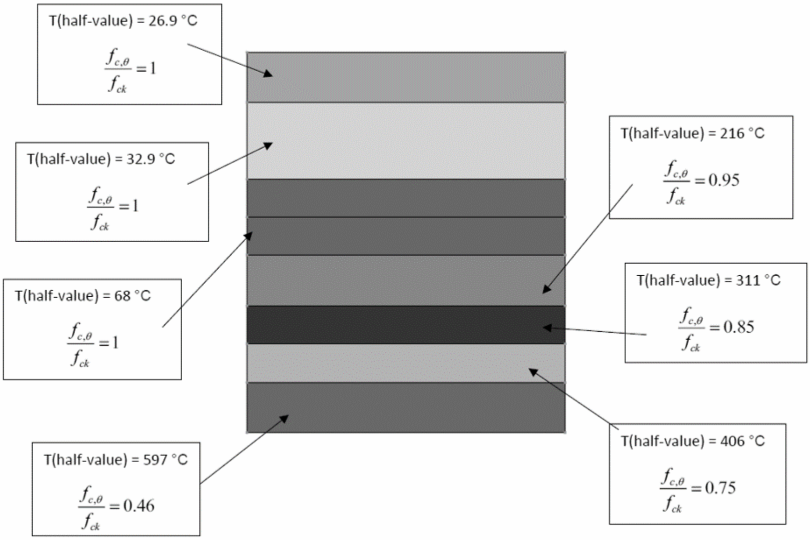
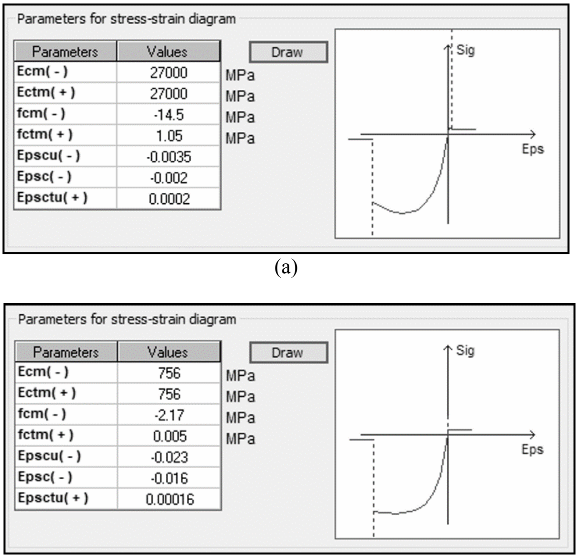


Fig. 3. Decrease of the concrete properties



Parameters for stress-strain diagram

Parameters	Values	
Ecm(-)	27000	MPa
Ectm(+)	27000	MPa
fcm(-)	-14.5	MPa
fctm(+)	1.05	MPa
Epscu(-)	-0.0035	
Epsc(-)	-0.002	
Epsctu(+)	0.0002	

(a)

Parameters for stress-strain diagram

Parameters	Values	
Ecm(-)	756	MPa
Ectm(+)	756	MPa
fcm(-)	-2.17	MPa
fctm(+)	0.005	MPa
Epscu(-)	-0.023	
Epsc(-)	-0.016	
Epsctu(+)	0.00016	

(b)

Fig. 4. Comparison of concrete deformation parameters at temperature: (a) - 20°C; (b) - 800°C

When calculating the structures for fire resistance, it is necessary to take into account creep deformations. Therefore, in this study, it accomplished a comparison of the stress strain state of the structure with a physically non-linear calculation taking into account the influence of creep (which depends on temperature) and without creep.

To determine the total deformations of the structure, the creep function was calculated using the formula:

$$\Phi(T,t,t') = \sum_{t=t'}^{\tau} \varphi_T(t)\cdot H(t')\cdot n\cdot(f^{(n-1)}(t))\cdot\Delta t\,. \qquad (10)$$

Where φ_T – temperature function; $H(t')$ – parameter that displays the change in the physical characteristics of concrete depending on the concrete age at the load application moment; t' – load application moment; t – moment of determination of structural deformations.The formula is based on the works of the Czech scientist Bazant Z.P. and described in detail in the works [23, 24].

After thermal analysis and definition of decrease concrete properties, it is possible to make astrength calculation of the floor slab at different timepoints: at 60, 120, 180 and 240 minutes of fire action. At Figure 5, it shown the deformed scheme of the slab in the 240th minute of fire exposure.

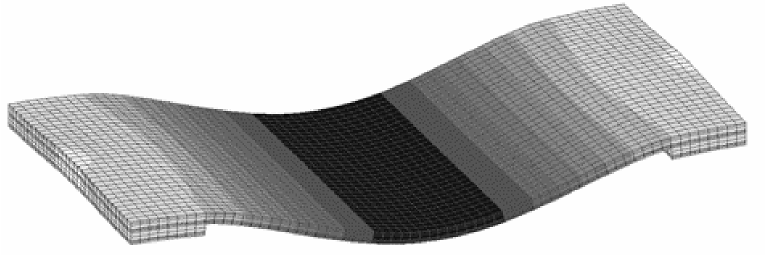


Fig. 5. Deformed floor slab model

With a static linear calculation, the maximum displacement of the structure along axis Z was 19.4 mm. Comparison of vertical displacements of the structure with a physically non-linear calculation is given in Table 1.

Table 1

Maximum displacement along axis Z

Analysis task type	Time (minutes)			
	60	120	180	240
Physically non-linearity	16	22	28	28.9
Physically non-linearity and creep	24.1	71.4	86.6	98.8

It is possible to see from the table that the values obtained by taking into account the physically non-linear operation of the structure and the lowered characteristics of the concrete, depending on the temperature increase,are completely different from the linear static calculation. In addition, the calculation with regard to creep gives us even greater increase in the vertical displacements of the structure.

Various reference documents describe different methods for determining creep deformations. Figure 6 shows a comparison of the deflections of a structure using different methods for determining creep deformations: the methods described in the Company's cod [2], Eurocode [3] and the author's method.

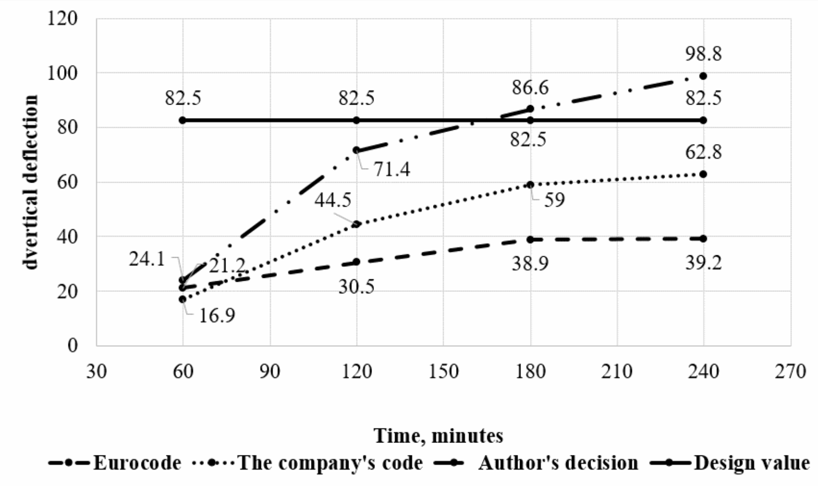


Fig. 6. Comparison of the model vertical displacement calculated with different creep models

According to the calculations performed with reference to the regulatory documents, this design model must withstand a fire load during 240 minutes. But according to the calculation performed with the author's methodology, it is clear that the stability of the structure is not ensured. And at the 160th minute of fire impact, the deflections exceed the maximum permissible values. The degree of fire resistance of the structure is R240, but according to the calculation performed with the author’s methodology, it can be seen that the degree of fire resistance of the structure is not ensured.

At Figure 7, it shown a comparison of thequantity of destroyed finite elements of the floor slab over time. According to [3], the floor slab with thickness of 300 mm must withstand the fire impact during 240 minutes, upon condition that all design requirements are observed. But, at Figure 7 it shown that the structure lost its integrity.

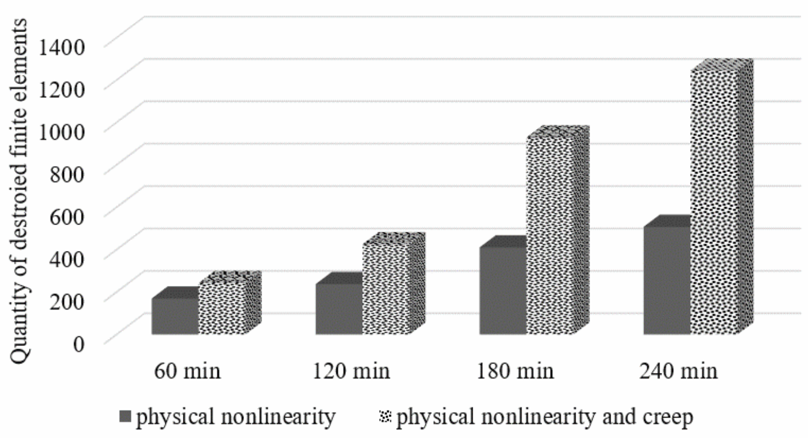


Fig. 7. Destroyed elements of the floor slab at various intervals

In compliance to Figure 7, in consequence of fire action the lower part of the concrete is completely destroyed already at the 180th minute of the fire expose and it lost its integrity. Therefore, it can be argued that in such situation, the lower reinforcement will heat up to the temperature above its hypothetical limit value (600 °C) and also lose its rigidity. While the upper half of the floor slab is still able to carry the load and may avoid destruction.

Such consequences occurred in the building of the shopping center called «Auchan» of the entertainment center Sky-Mall (Kiev, Ukraine) in the fall of 2017 as a result of fire action. The pictures of the real object, which corresponds to the mathematical model of the evaluated floor slab, are presented at Figure 8.

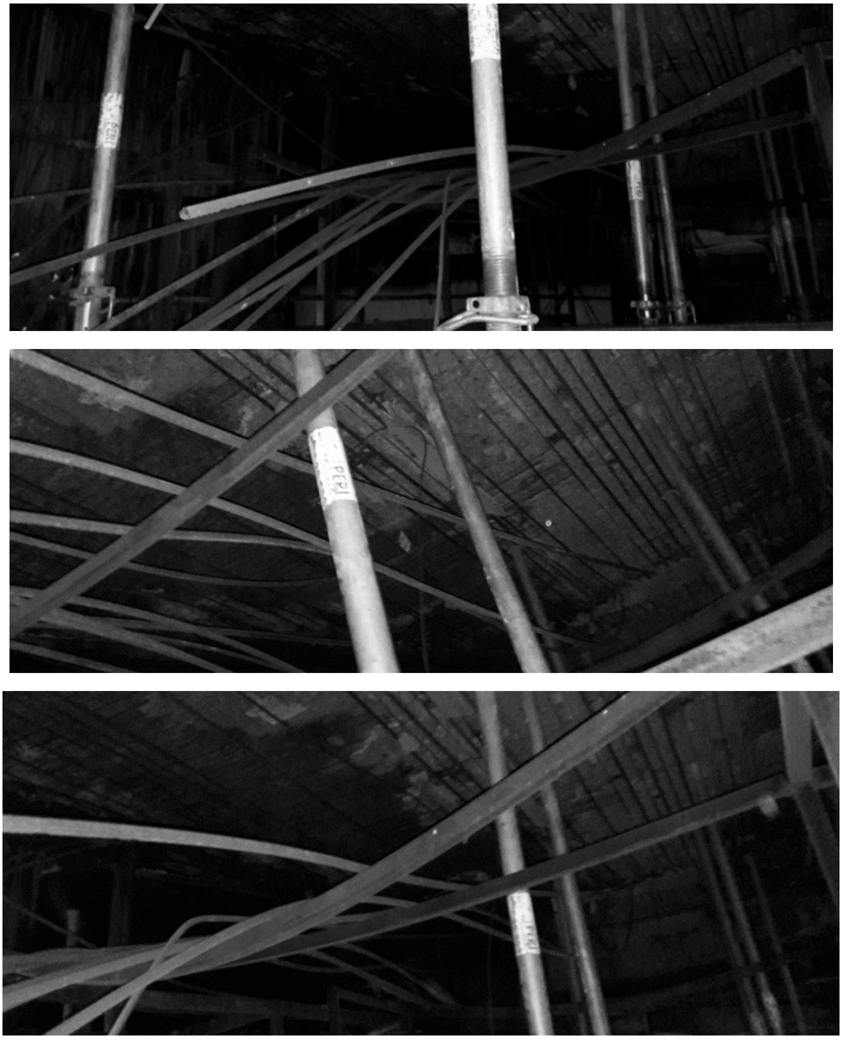


Fig. 8. Consequences of fire expose in «Auchan» store at «Sky Mall» shopping and entertainment center

The pictures are taken as a part of the implementation of scientific and technical works of the state enterprise called Scientific Institute of Building Constructions. The theme of the scientific and technical works is "Performing an examination of the supporting structures of the Auchan hypermarket building at the address: Kiev, Vatutina Ave., 2 and make a reportabout their technical condition with recommendations for ensuring their subsequent reliable operation", (contract number is 5615 dated January 16, 2018).

4. Conclusions. Thus, the article presents the methodology of analysis of reinforced concrete structures under the effects of high temperatures. The methodology permits to take into account the influence of temperature distribution all over the cross section on thedecrease of the strength and strain material properties of any structural unit.It represents the analysis of the material physical nonlinearity weigh and the creep weigh with the stress strain state of the structure.

The proposedmethodology most accurately represents the work of the structure under fire expose, and makes it possible to make the adequate fire resistance analysis of a structure and ensure their durability and reliability.It solved the test problem with performed analyze of the work of a reinforced concrete floor slab, taking into account the fire impact.

Taking into account the influence of creep it makes possible to determine the total deformations of the structure, and to perform the qualified method which let us to calculate any buildings or structures.

REFERENCES

1. Eurocode 2. Proyektuvannya zalizobetonnikh konstruktsiy. Chastina 1-2. Zagalni polozhennya. Rozrakhunok konstruktsiy na vognestiykist: DSTU-N EN 1992-1-2:2012 [Design of reinforced concrete structures. Part 1-2. General. Fireresistancecalculationofstructures] (EN 1992-1-2:2004, IDT).
2. STO 36554501-006-2006 Pravila po obespecheniyu ognestoykosti I ognesokhrannosti zhelezobetonnykh konstruktsiy [Rules to ensure fire resistance and fire protection of reinforced concrete structures], Moskva: 2006.
3. EN 1992-1-2 (20014): Eurocode 2: Design of concrete structures – Part 1-2: General rules – Structural fire design [Authority: the European Union Per regulation 305/2011, directive 98/34/EC, Directive 2044/18/EC].
4. Guide for Modeling and Calculating Shrinkage and Creep in Hardened Concrete: ACI 209.2R-08. – U.S.A., American Concrete Institute, 2008. 48 p. (Guide for modeling and calculating).
5. *Barabash M.S.* Kompyuternoye modelirovaniye protsessov zhiznennogo tsikla obyektov stroitelstva: Monografiya [Computer simulation of the life cycle processes of construction objects: Monograph]. K.: Izd-vo «Stal», 2014. 301 p.
6. *Gorodetskiy A.S., Barabash M.S.* Uchet nelineynoy raboty zhelezobetona v PK LIRA-SAPR. Metod «Inzhenernaya nelineynost» [Accounting of non-linear work of reinforced concrete in SP LIRA-SAPR. Method "Engineering nonlinearity"]. // International Journal for Computational Civil and Structural Engineering. 2016. №. 12 (2). Pp. 92-98.
7. *Savin O.B., Sobol V.M.* Zmishanyi variatsiinyi funktsional v zadachakh povzuchosti ta poshkodzhuvanosti sterzhniv pry zghyni [Mixed variational functional in the problems of creep and damage of rods at bending]// Strength of Materials and Theory of Structures, 2018. №100. Pp. 115-123.
8. *Iakovenko I., Kolchunov V.I.* (2017). The development of fracture mechanics hypotheses applicable to the calculation of reinforced concrete structures for the second group of limit states. Journal of Applied Engineering Science, vol. 15(2017)3, article 455, pp. 366–375.
9. *Arutyunyan N.Kh.* Nekotoryye voprosy teorii polzuchesti [Some questions of the theory of creep]. M.: Gostekhteorizdat, 1952. 323 p.
10. *Aleksandrovskiy S.V.* Raschet betonnykh I zhelezobetonnykh konstruktsiy na temperaturnyye I vlazhnostnyye vozdeystviya (s uchetom polzuchesti) [Calculation of concrete and reinforced

concrete structures with temperature and humidity effects (including creep)]. M.: Stroyizdat, 1966. 443 p.

11. *Bažant, Z.P., Jirásek M.* Basic properties of concrete creep, shrinkage, and drying // Solid Mechanics and its Applications. 2018. №. 225. Pp. 29-62.
12. *Bažant Z.P., Jirásek M.* Numerical analysis of creep problems // Solid Mechanics and its Applications, №. 225. 2018. Pp. 141-175.
13. *Bazant Z.P., Cusatis G., Cedolin L.* Temperature effect on Concrete Creep Modeled by Microprestress-Solidification Theory // Journal of engineering mechanics. 2004. Pp. 691-699.
14. *Rahimi-Aghdam, S., Rasoolinejad, M., Bažant, Z.P.* Moisture Diffusion in Unsaturated Self-Desiccating Concrete with Humidity-Dependent Permeability and Nonlinear Sorption Isotherm // Journal of Engineering Mechanics. №. 145 (5). 2019.
15. *Rasoolinejad, M., Rahimi-Aghdam, S., &Bazant, Z.P.* Correction to: Statistical filtering of useful concrete creep data from imperfect laboratory tests. Materials and Structures/Materiaux et Constructions . 2018. №. 51 (6).
16. *Hubler M., Wendner R., Bažant Z.* Statistical justification of model B4 for drying and autogenous shrinkage of concrete and comparisons to other models // Mater Structures. 2015. №. 48(4). Pp. 797–814.
17. *Wendner R., Hubler M., Bažant Z.* Optimization method, choice of form and uncertainty quantification of model B4 using laboratory and multi-decade bridge databases // Mater Structures. 2015. №. 48(4). Pp. 771–796.
18. *Wendner R., Hubler M., Bažant Z.* Statistical justification of model B4 for multi-decade concrete creep using laboratory and bridge databases and comparisons to other models. MaterStructures. 2015. №. 48(4) . Pp. 815–833
19. *Krukovskiy P.G., Kovalev A.I., Chernenko K.A.* Modelirovaniye teplovogo sostoyaniya I ognestoykosti mnogopustotnogo zhelezobetonnogo perekrytiya [Simulation of thermal state and fire resistance of hollow-core reinforced concrete floor] // Zbirniknaukovikh prats LDU BZhD. 2012. №. 21. Pp. 85-94.
20. *Fomin S.L.* Raschet ognestoykosti zhelezobetonnykh plit perekrytiya po utochnennym I uproshchennym metodam [Fire resistance calculation of reinforced concrete slabs according to refined and simplified methods] // Zbirniknaukovikh prats UkrDUZT. 2016. №. 161. Pp. 145–157.
21. *Pyskunov S.O., Shkryl O.O.* Vyznachennia trishchynostiikosti zakhysnoi obolonky yadernoho reaktoru pry termosylovomu navantazhenni [Determination of the crack resistance of the protective shell of a nuclear reactor with a thermosetting load]// Strength of Materials and Theory of Structures, 2018. №101. Pp. 60–66.
22. *Pyskunov S.O., Shkryl O.O.* Vyznachennia trishchynostiikosti zakhysnoi obolonky yadernoho reaktoru pry termosylovomu navantazhenni [Influence of temperature regimes on the stress-strain state of structures] // Strength of Materials and Theory of Structures, 2018. №101. C. 103–110.
23. *Bashinskaya O.Yu., Pikul A.V., Barabash M.S.* Resheniye zadachi termopolzuchesti betona metodom konechnykh elementov [Solution of the problem of concrete thermocreepiness by the finite element method] // sb. nauchn. trudov «Stroitelstvo. Materialovedeniye. Mashinostroyeniye», 2017. №. 99. Pp. 22-29.
24. *BashinskayaO.Yu., Barabash M.S., Pikul A.V.* Chislennoye modelirovaniye tsiklicheskogo temperaturnogo rezhima ekspluatatsii v PK «Lira-SAPR» [Numerical simulation of cyclic temperature model operation on the SP "Lira-SAPR"] // Visnik Odeskoï derzhavnoi akademii budivnitstva ta arkhitekturi, 2017. №. 67. Pp. 13-19.
25. *Diez P., Rodenas J.J., Zienkiewicz O.C.* Equilibrated Patch Recovery error estimates: simple and accurate upper bounds of the error // International Journal for Numerical Methods in Engineering. 2007. №. 69 (10). Pp. 2075–2098.
26. *Samuelsson A., Zienkiewicz O.C.* History of the stiffness method // International Journal for Numerical Methods in Engineering. 2006. №. 67. Pp. 149–157.
27. *Ibrahimbegovic A., Melnyk S.* Embedded discontinuity finite element method for modeling of localized failure in heterogeneous materials with structured mesh: an alternative to extended finite element method // Computational Mechanics. 2007. №. 40 (1). Pp. 149–155.
28. *Bazhenov V.A., Gulyar A.I., Maiboroda E.E., Piskunov S.O.* Semianalytic Finite-Element Method in Continuum Creep Fracture Mechanics Problems for Complex-Shaped Spatial Bodies and Related Systems. Part 1. Resolving Relationships of the Semianalytic Finite-Element Method and Algorithms for Solving the Continuum Creep Fracture Problems // Strength of Materials. 2002. №. 34 (5). Pp. 425–433.

Стаття надійшла 27.09.2019

Барабаш М.С., Ромашкіна М.А., Башинська О.Ю.

ТЕРМОНАПРУЖЕНИЙ СТАН ЗАЛІЗОБЕТОННОЇ ПЛИТИ ПЕРЕКРИТТЯ

Проведено дослідження напружено-деформованого стану залізобетонної плити перекриття в умовах пожежі за уточненим методом. Створеноскінченно-елементну модель плити перекриття. На першому етапі дослідження вирішено нестаціонарну задачу теплопровідності. Відповідно до рішення задачі, отримано температурні поля по всьому перерізу розглянутого конструктивного елемента через певні проміжки часу. Другий етап дослідження –розрахунок на міцність. Завдяки оцінці міцності можна дослідити роботу плити перекриття в різні моменти часу вогневого впливу. Розглянуто кілька математичних моделей. Ці моделі відповідають різним моментам вогневого впливу. У кожній розрахунковій моделі плити перекриття було зміненоміцнісні і деформаційні характеристики бетону та арматури відповідно до температури перерізу. Виконано три типи аналізу вогнестійкості конструкції: лінійний аналіз, фізично-нелінійний аналіз і фізично-нелінійний аналіз з урахуванням ефекту повзучості. Показано результати порівняння кінематичних характеристик математичних моделей в різних постановках задач. Запропоновано методику, яка дозволяє врахувати вплив повзучості при чисельному моделюванні ефекту вогневого впливу.

Ключові слова: метод скінченних елементів, конструкція, термонапружений стан, чисельний експеримент, теплопровідність, порівняння.

Барабаш М.С., Ромашкина М.А., Башинская О.Ю.

ТЕРМОНАПРЯЖЕННОЕ СОСТОЯНИЕ ЖЕЛЕЗОБЕТОННОЙ ПЛИТЫ ПЕРЕКРЫТИЯ

Проведено исследование напряженно-деформированного состояния железобетонной плиты перекрытия в условиях пожара по уточнённому методу. Создано конечно-элементную модель плиты перекрытия. На первом этапе исследования решена нестационарнуя задача теплопроводности. Согласно решению задачи, получены температурные поля по всему сечению рассматриваемого конструктивного элемента через определенные промежутки времени. Второй этап исследования – расчёт на прочность. Благодаря оценке прочности можно исследовать работу плиты перекрытия в различные моменты времени огневого воздействия. Рассмотрены несколько математических моделей, в соответствии с различными моментами огневого воздействия. В каждой расчетной модели плиты перекрытия были изменены прочностные и деформационные характеристики бетона и арматуры в соответствии с температурой сечения. Выполнено три типа анализа огнестойкости конструкции: линейный, физически нелинейный и физически нелинейный анализ с учетом эффекта ползучести. Показаны результаты сравнения кинематических характеристик математических моделей в различных постановках задач. Предложена методика, которая позволяет учесть влияние ползучести при численном моделировании эффекта огневого воздействия.

Ключевые слова: метод конечныхэлементов, конструкция, термонапряженное состояние, численный эксперимент, теплопроводность, сравнение.

УДК 624.044.3

Барабаш М.С., Ромашкіна М.А., Башинська О.Ю. **Термонапружений стан залізобетонної плити перекриття** // Опір матеріалів і теорія споруд: наук.-техн. збірник. – К.: КНУБА, 2019. – Вип. 103 . – С. 43-56.

Представлено розрахунок залізобетонної плити перекриття на вогневий вплив із урахуванням впливу термоползучесті бетону. Розрахунок виконано в два етапи. На першому етапі вирішується задача нестаціонарної теплопровідності для визначення температурного поля по перерізу плити. На другому етапі виконано розрахунок на міцність з урахуванням жорсткісних і деформаційних характеристик бетону та арматури, а також із урахуванням впливу повзучості.

Табл. 1. Іл. 8. Бібліогр. 28 назв.

UDC 624.044.3
Barabash M., Romashkina M., Bashynska O. **Thermal stress state of reinforced concrete floor slab //** Strength of Materials and Theory of Structures: Scientific-and-technical collected articles – Kyiv: KNUBA, 2019. – Issue 103 . – P. 43-56.

The fire influence analysis of reinforced concrete slabs with taking into account the impact of concrete thermal creep is presented. The calculation is made in two stages. At the first stage, it is solved the thermal conductivity analysis to determine the temperature fields all over the plate cross-sections. At the second stage, it is solved the structural analysis, taking into account the strength and strain properties of concrete and reinforcement, as well as the effect of creep.

Tables 1. Fig. 8. Ref. 28.

УДК 624.044.3
Барабаш М.С., Ромашкина М.А., Башинская О.Ю. **Термонапряженное состояние железобетонной плиты перекрытия** // Сопротивление материалов и теория сооружений: науч.-техн. сборник. – К.: КНУСА, 2019. - Вып. 103 . - С. 43-56.

Представлен расчет железобетонной плиты перекрытия на огневое воздействие с учётом влияния термоползучести бетона. Расчет произведен в два этапа. На первом этапе решается задача нестационарной теплопроводности для определения температурных полей сечения плиты. На втором этапе происходит прочностной расчет с учетом понижения жесткостных и деформационных характеристик бетона и арматуры, и учетом влияния ползучести.

Табл. 1. Ил. 8. Библиогр. 28 назв.

Автор (науковий ступінь, вчене звання, посада): *доктор технічних наук, доцент, старший науковий співробітник, професор кафедри комп'ютерних технологій будівництва Навчально-наукового інституту аеропортів НАУ БАРАБАШ Марія Сергіївна.*

Адреса робоча: *03058, Україна, м. Київ, просп. Космонавта Комарова 1, Національний авіаційний університет, Навчально-науковий інститут аеропортів. БАРАБАШ Марії Сергіївні*

Робочий тел.: *+38(044) 406-74-24.*

Мобільний тел.: *+38(095) 286-39-90.*

E-mail: bmari@ukr.net

ORCID ID: https://orcid.org/0000-0003-2157-521X

Автор (науковий ступінь, вчене звання, посада): *кандидат технічних наук, інженер-проектувальник ТОВ «ЛІРА-САПР» РОМАШКІНА Марина Андріївна.*

Адреса робоча: *03058, Україна, м. Київ, пров. Киянівський 7а, ТОВ «ЛІРА-САПР». РОМАШКІНА Марина Андріївна*

Робочий тел.: *+38(044) 406-74-24.*

Мобільний тел.: *+38(095)* 931-52-50.

E-mail: romashkina.liraland@gmail.com

ORCID ID: https://orcid.org/0000-0002-7158-4037

Автор (науковий ступінь, вчене звання, посада): *асистент кафедри комп'ютерних технологій будівництва Навчально-наукового інституту аеропортів НАУ БАШИНСЬКА Ольга Юріївна.*

Адреса робоча: *03058, Україна, м. Київ, просп. Космонавта Комарова 1, Національний авіаційний університет, Навчально-науковий інститут аеропортів. БАШИНСЬКА Ольга Юріївна*

Робочий тел.: *+38(044) 406-74-24.*

Мобільний тел.: *+38(063) 108-22-01.*

E-mail: olchik01@ukr.net

ORCID ID: http://orcid.org/0000-0002-4161-782X