IOP Conference Series: Materials Science and Engineering

Methodology for assessment of the fire-resistant quality of reinforced-concrete floors protected by fire-retardant coatings

To cite this article: A I Kovalov *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **708** 012058

IOP Conf. Series: Materials Science and Engineering **708** (2019) 012058 doi:10.1088/1757-899X/708/1/012058

Methodology for assessment of the fire-resistant quality of reinforced-concrete floors protected by fire-retardant coatings

A I Kovalov[1,3], Y A Otrosh[2], T M Kovalevska[2] and S O Safronov[2]

[1] Cherkasy Institute of Fire Safety named after Chornobyl Heroes of the National University of Civil Defence of Ukraine, 8 Onoprienko St., 18034 Cherkassy, Ukraine
[2] National University of Civil Defence of Ukraine, 94 Chernyshevska St., 61023 Kharkiv, Ukraine

[3] Email: kovalev27051980@gmail.com

Abstract. In the work, the tests have been analysed for fire-resistant quality of hollow-core reinforced-concrete floors with fire-retardant plaster covering. A two-dimensional physical model and computer model have been developed in the ANSYS FLUENT software environment, which includes a system of equations and boundary conditions, taking into account the thermal conductivity in the coating and concrete, as well as complex convection-radiation heat transfer in air voids. A one-dimensional multilayer mathematical model has been developed, equivalent to a two-dimensional model of the thermal state of hollow-core reinforced-concrete floor with fire-retardant plaster covering, with the specific these layers' thicknesses. A methodology has been developed in the article, based on solving the direct and inverse heat conduction problems, with the help of which it is possible to assess the fire-resistant quality of hollow-core reinforced-concrete floors with and without fire-retardant coatings. The developed methodology was applied to determine the thermophysical (heating constant and specific heating capacity per unit volume) and fire-retardant characteristics of the studied plaster covering according to the results of tests for fire-resistant quality of reinforced-concrete floors with this fire-retardant coating. The conclusion was made about the effectiveness of this coating and the boundaries of using the fire-retardant coatings to ensure normalizable values for the limit of the fire-resistant quality of hollow-core reinforced-concrete floors.

1. Introduction

The fire resistance of building structures is an important characteristic that should be considered when engineering buildings and structures. To provide the required limit of such structures fire-resistant quality, they are treated with fire-retardant agents. To determine their fire-resistant quality, the experimental, calculation and calculation-experimental methods are used. In recent times, the calculation-experimental technique has been widely used, which enables based on the results of one or several tests for fire-resistant quality, using mathematical models, to assess the fire resistance of structures and to determine the characteristic of Fire-Retardant Ability (FRA) of coatings. In this work, such a characteristic is defined as the dependence of the minimum thickness of the fire-retardant coating on the thickness of the concrete protective layer, which is necessary to ensure the required fire resistance limit of the floor slab [1–4].

This technique was developed in the works of V.M. Roitman, A.F. Milovanov, Yu.A.Koshmarov, V.L.Strakhov, A.M. Krutov, I.A. Kharchenko, B.G. Demchina, A.I. Yakovlev, P.G. Krukovsky, S.V. Novak, A.V. Dovbysh, B. Bartelemi, L.J. Segerlind, K.N. Huebner, O.C.Zeinkiewicz, K. Kodrin, O.

Pettersson, T. Harmathy, et al. It was used to determine the fire-resistant quality of various types of building structures and their elements, in particular, the fire-retardant coatings ability of metal structures [5], the fire-resistant quality of reinforced-concrete floors with a fire protection system of mineral wool [6], and also when determining the required minimum thickness of fire-retardant partitions for the required limit of fire-resistant quality [7].

2. Unresolved issues

In the above works, the questions have not been described of such a technique application for assessing the fire-resistant quality of hollow-core reinforced-concrete floors, primarily due to the fact that it was difficult to consider the peculiarities of the heat transfer in the cavities of such floors, and also because of the difficulty in developing the physical model and using mathematical model of the thermal state of such floors with account of the heat and mass transfer processes in them. The actuality of this work is conditioned by the disclosure and consideration of these peculiarities, as well as the development of the most appropriate thermal state models of hollow-core reinforced-concrete floors.

3. Main part

A particular difficulty, when assessing the fire-resistant quality of hollow-core reinforced-concrete floors, is taking into account the geometrical features of the floors, namely the presence of voids, in which convection-radiation heat transfer occurs. In the work, the influence of this heat transfer is studied using modelling and comparison with such an experiment in the form of testing for fire resistance of hollow-core reinforced-concrete floors, first without plaster covering, and then with plaster covering. According to [8, 9], the temperature in the furnace and on the surface unexposed to heating was measured. Each sample was set according to [8], by resting upon a hole of a horizontal furnace from both sides with the possibility of fire exposure to it from the bottom surface and was loaded with loads of concrete blocks. The fire-retarding composition under study with an average thickness of 37 mm was applied to the floor slabs below and on the sides. The tests were conducted under standard temperature conditions for 180 minutes. As a result of fire resistance tests, it has been determined that the limit of fire-resistant quality of such floors was more than 180 minutes, and the average temperature on the floor surface unexposed to heating reached 75°C, and was used in the calculations to determine the thermophysical characteristics and the fire-retardant coating ability [10].

For modelling the thermal state of the floor, the general view of which is shown in Figure 1, a two-dimensional physical model and computer model have been developed in the ANSYS FLUENT software environment. The latter one includes a system of equations and boundary conditions, taking into account the thermal conductivity in the coating and concrete, as well as complex convection-radiation heat transfer in air voids. The mathematical model consisted of well-known equations many times described in the literature and used in the ANSYS FLUENT software [1].

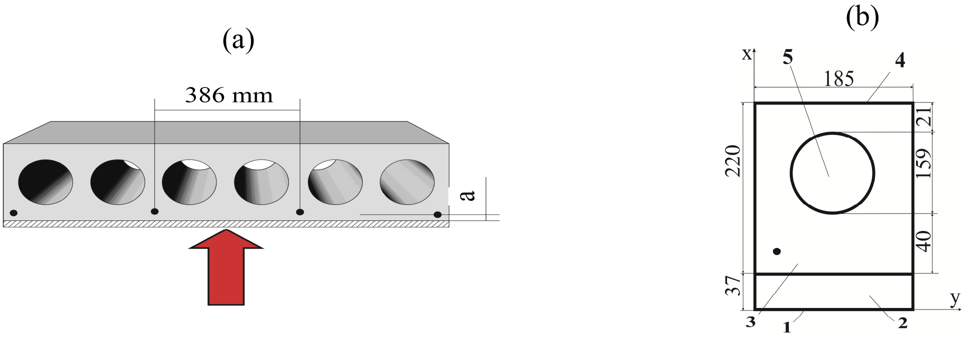

Figure 1. General view of hollow-core reinforced-concrete floor PC 48–12–8t on (a) and scheme of the periodic part (fragment) of the floor slab with coating used in 2D modelling (b): 1 – surface exposed to heating; 2 – fire-retardant coating, 3 – reinforced-concrete floor, 4 – surface unexposed to heating; 5 – void (round cavity) of the floor.

Based on fire resistance tests results and calculations, with the use of a two-dimensional model, an analysis was conducted of the peculiarities of heating the reinforced-concrete floors, which has revealed that its application to determine the thermophysical characteristics and characteristic of the fire-retardant ability of coatings is not possible due to the long calculation time of one direct problem (25 minutes). It may become necessary to perform hundreds of such calculations. The same calculations in the FRIEND software environment take 1–2 minutes. Therefore, an important item of the proposed methodology is the conclusion on the necessity to use one-dimensional models of thermal conductivity for analysing the thermal state of reinforced-concrete floors with coatings in a software environment, for example, by means of the FRIEND software.

For this purpose, a one-dimensional multilayer mathematical model has been developed, equivalent to a two-dimensional model of the thermal state of hollow-core reinforced-concrete floor, with the specific thicknesses of these layers (Figure 2).

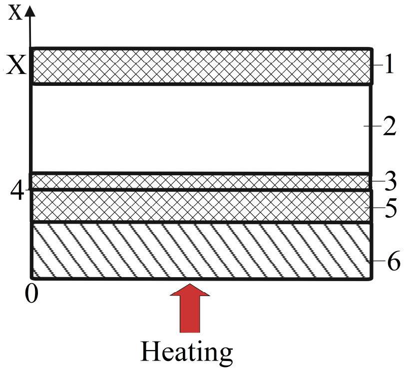

Figure 2. Scheme for reinforced-concrete floor in one-dimensional formulation: 1 – a layer of solid-core concrete between the surface unexposed to heating and a floor layer with voids; 2 – a layer with voids; 3 – a layer of solid-core concrete between the voids and reinforcement; 4 – a reinforcement layer; 5 – a layer of solid-core concrete from reinforcement to the surface exposed to heating; 6 – plaster covering.

The thermophysical characteristics of concrete layers 1, 3 and 5 were specified from [11], and the thermophysical characteristics of layer 2 with voids were set by solving the Inverse Heat Conduction Problems (IHCP). The specific thicknesses of layers 1, 3 and 5 for concrete were calculated, and the concrete layer with voids 2 was chosen to be equal to the diameter of the voids with the available concrete volume.

The mathematical model (1–5) for one-dimensional model of the thermal state of the floor consisted of equations describing the thermal conductivity in a six-layer floor slab (Figure 2), the second layer of which takes into account the natural convection and radiation heat transfer in the cavities by means of the effective thermal conductivity determined by solving the inverse heat conduction problems.

$$c_v(x,t)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda(x, T)\frac{\partial T}{\partial x}\right), \tag{1}$$

$$\lambda_p \frac{\partial T(x_2, t)}{\partial x} + \alpha^*(T_s(t) - T(x, t)) = 0, \tag{2}$$

$$\alpha^* = \alpha_c + \frac{C_0\varepsilon}{T_s(t) - T(x_2, t)}\left\{\left[\frac{T_s(t)}{100}\right]^4 - \left[\frac{T(x_2, t)}{100}\right]^4\right\}, \tag{3}$$

$$\lambda_c \frac{\partial T(x,t)}{\partial x} = \alpha^{**}\left[T(X,t) - T_{C_2}\right], \tag{4}$$

$$\alpha^{**} = \alpha_{C_2} + \frac{C_0 \varepsilon}{T(X,t) - T_{C_2}(t)} \left\{ \left[\frac{T(x,T)}{100} \right]^4 - \left[\frac{T_{C_2}(t)}{100} \right]^4 \right\}, \; \alpha_{C_2} = A \left[T(X,t) - T_{C_2}(t) \right]^{0.33}. \quad (5)$$

where C_{heat} – specific heating capacity per unit volume, λ – heating constant, T – temperature, t – time, x – coordinate, α_{c1} – heat-exchange coefficient from hot gases to the surface exposed to heating with a fire-retardant coating (FRC) or concrete, α_{c2} – heat-exchange coefficient from a floor surface unexposed to heating into air, C_0 – blackbody coefficient (C_0 = 5.67), ε – coefficient of radiation of the surface exposed to heating with a fire-retardant coating (FRC) or concrete; T_{c1} – temperature of the hot gases in the furnace during the test; T_0 – initial floor temperature before testing. The heat-exchange coefficient from hot gases in the furnace to the surface exposed to heating of the sample α_{c1} is accepted as equal to 25 W/(m^2·K), the emissivity factor of the surface exposed to heating is ε = 0.7. The heat-exchange coefficient between a floor surface unexposed to heating and ambient air α^{**} (4)–(5) also takes into account the convection α_{c2} and radiation heat transfer from a horizontal surface (A=1.16) into the environment. Multiple layers of the model under consideration is taken into account by the dependences C_v and λ from the coordinate.

As a result, a methodology has been developed for determining the characteristics of the fire-retardant coatings ability of reinforced-concrete floors using the calculation-experimental technique according to the tests results for fire-resistant quality, which consists of:

1. Selecting a one-dimensional mathematical model of the thermal state of the floor slab by breakdown the floor slab into 6 layers.
2. Using the extreme technique of solving IHCP in order to calculate the necessary model parameters according to the results of testing the floors for fire-resistant quality.
3. Setting the thermophysical characteristics of concrete for the layers 1, 3, 5 to model heating the floor from [7].
4. Determining the heating constant of layer 2 of a slab with voids by solving IHCP and using the data of tests for the fire-resistant quality of reinforced-concrete floors without coating.
5. Determining the thermophysical characteristics of the studied fire-retardant coating by solving IHCP.
6. Determining the dependence of the coating thickness on the thickness of the concrete protective layer for various limits of fire-resistant quality according to the criteria that the reinforcement reaches a critical temperature (500°C), or the loss of thermal insulating capacity by numerous calculations of the direct heat conduction problems.

The developed methodology was applied to determine the thermophysical and fire-retardant characteristics of the studied plaster covering according to the results of tests for fire-resistant quality of reinforced-concrete floors with this fire-retardant coating [10]. According to the above points 1, 2, an equivalent heating constant of layer 2 with voids has been determined, equal to 3.18 W/m·K, at which the closest proximity of the calculated and experimental temperatures on the surface unexposed to heating for the sample with the highest temperatures without fire-retardant coating was observed. Moreover, the value of the mean-square deviation criterion was 3.2°C (6).

$$\phi = \sqrt{\sum_{i=1}^{n} \left[T_{M,i}(P) - T_{E,i} \right]^2}, \quad (6)$$

where n – the number of experimental temperature values of the reinforced-concrete floor over time.

According to the point 5 of the methodology, the temperature-dependent heating constant (Figure 3) and specific heating capacity per unit volume (C_v=1.01·10^6 J/(m^3·K)) have been determined for fire-retardant coating under study.

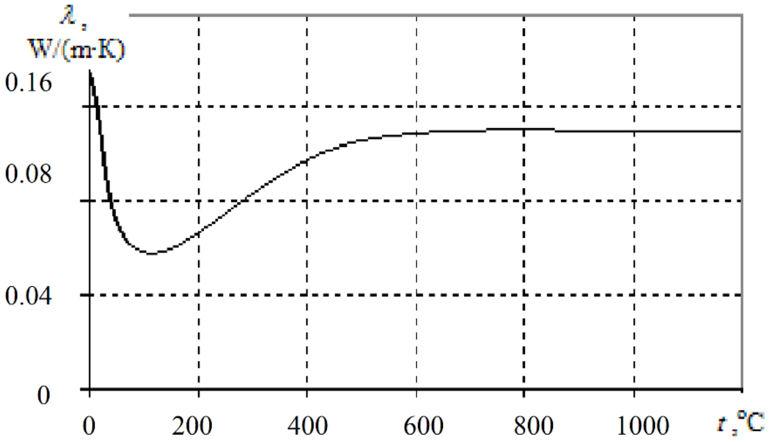

Figure 3. Dependence of the effective thermal conductivity coefficient of the studied plaster covering on the temperature determined by solving IHCP according to the data of tests for the fire-resistant quality.

As it can be seen from Figure 3, in the temperature range from 0°C to 100°C, the value of thermal conductivity of the studied plaster covering decreases and passes through the minimum extreme values of 0.06 W/m·K (at 100°C), which is explained by intense physical-chemical evaporation processes at the initial stage of heating, and then it increases in the temperature range from 100°C to 600°C, which is explained by burning-out the coating layer. In this case, the criterion of the mean-square deviation was 1.7°C (6).

According to the study results of the two floor slabs for which the tests for fire-resistant quality were performed, and according to point 6 of the methodology, a characteristic of fire-retardant ability has been obtained for various limits of fire-resistant quality of the floor, based on the criterion that the reinforcement reaches a critical temperature of 500°C at a specified level of loading (570 kg/m^2) in the course of testing (Figure 4).

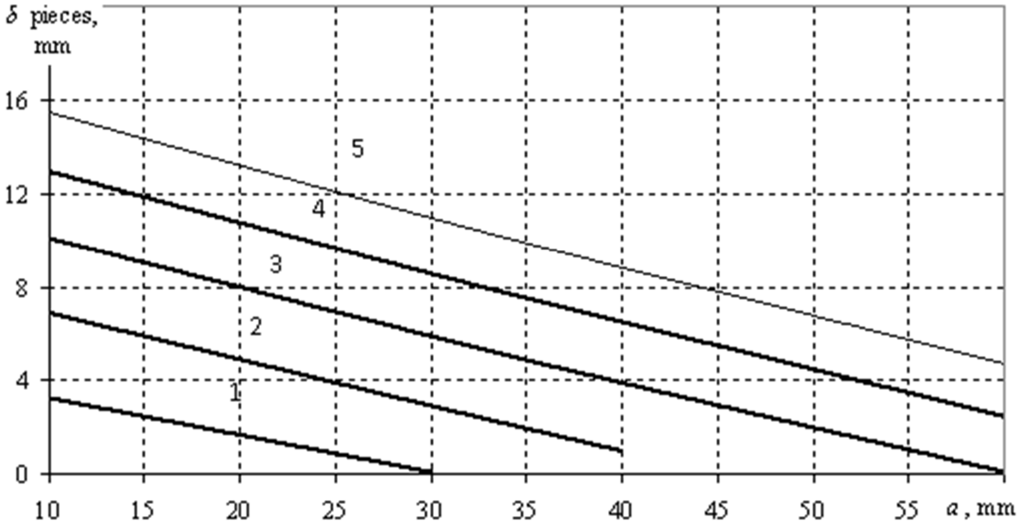

Figure 4. Characteristic of the fire-retardant ability of the studied plaster covering based on the criterion that the reinforcement reaches a critical temperature of (500°C) for limits of fire-resistant quality: 1 – 60 min; 2 – 90 min; 3 – 120 min; 4 – 150 min; 5 – 180 min.

As it can be seen from Figure 4, a coating thickness of 13 mm with a thickness of the concrete protective layer of 20 mm is sufficient to provide the required limit of fire resistance for such a floor for a period of 180 minutes, but not 37 mm, as it was stated in the tests for fire-resistant quality.

4. Conclusions

A methodology has been developed which enables with the required accuracy to determine the thickness of the fire-retardant coating for providing the required fire resistance limit of hollow-core reinforced-concrete floors.

The developed methodology can be used to determine the characteristic of the fire-retardant ability of coatings of reinforced-concrete floors that work under load, and also to determine the characteristic of the fire-retardant ability of coatings of monolithic reinforced-concrete structures, for example, fire barrier slab floors.

A promising development of the proposed methodology is the additional use of mathematical models of the stress-strain state of floors using the criterion of ultimate state, based on the load-bearing capacity loss when reaching the maximum value of the deflection or rate of increase in the floor deformation [12–16].

The authors convey sincere gratitude for the help and advice during working on this article to Viktor Rivchachenko, Vice Director of Promat Ukraine LLC.

References

[1] Kovalov A, Otrosh Y, Ostroverkh O, Hrushovinchuk O and Savchenko O 2018 Fire resistance evaluation of reinforced concrete floors with fire-retardant coating by calculation and experimental method *E3S Web of Conferences* **60** 00003

[2] Dubinin D, Korytchenko K, Lisnyak A, Hrytsyna I and Trigub V 2018 Improving the installation for fire extinguishing with inelydispersed water *Eastern European Journal of Enterprise Technologies* **2**(10–92) 38–43

[3] Vasiliev M, Movchan I and Koval O 2014 Diminishing of ecological risk via optimization of fire-extinguishing system projects in timber-yards *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* **5** 106–113

[4] Tiutiunyk V, Ivanets H, Tolkunov I and Stetsyuk E 2018 System approach for readiness assessment units of civil defense to actions at emergency situations *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* **1** 99–105

[5] Vasilchenko A, Otrosh Y, Adamenko N, Doronin E and Kovalov A 2018 Feature of fire resistance calculation of steel structures with intumescent coating *MATEC Web of Conferences* **230** 02036

[6] Otrosh Y, Kovalov A, Semkiv O, Rudeshko I, Diven V 2018 Methodology remaining lifetime determination of the building structures *MATEC Web of Conferences* **230** 02023

[7] Kovalov A, Otrosh Y, Vedula S, Danilin O and Kovalevska T 2019 Parameters of fire-retardant coatings of steel constructions under the influence of climatic factors *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* **3** 46–53

[8] Cheng Xuansheng, Du Y-F and Li H 2007 Thermal buckling of reinforced concrete rectangular plate with simply supported boundary conditions *Gongcheng Lixue/Engineering Mechanics* **24** 1–6

[9] Engin M Reis, Luis A Mata, Ufuk Dilek 2009 An analytical model for estimating load-test deflections in fire-damaged precast, prestressed concrete members *PCI Journal* **54** 129–142

[10] Lakhani Hitesh, Kamath Praveen, Bhargava, Pradeep, Sharma, Umesh Kumar and Reddy G Rami 2013 Thermal Analysis of Reinforced Concrete Structural Elements *Journal of Structural Fire Engineering* **4** 227–244

[11] EN 1992–1–2: 2004 Eurocode 2: Design of concrete structures. Part 1–2: General rules. *Structural fire design* Brussels: The European Union Per Regulation

[12] Lakhani Hitesh, Kamath, Praveen, Bhargava, Pradeep, Singh Tarvinder and Reddy G Rami 2013

Simulation of Fire Resistance of Reinforced Concrete Structural Members (Extended Abstract) *Journal of Structural Engineering* **40** 7–11

[13] Andrey Ustinov, Olga Zybina, Anastasia Tomakhova and Sergey Pavlov 2018 The enhancement of operating properties of intumescent fire-protective compositions *MATEC Web of Conferences* **245** 11008

[14] De Silva D, Bilotta A and Nigro E 2019 Experimental investigation on steel elements protected with intumescent coating *Construction and Building Materials* **205** 232–244

[15] Bourbigot S and Duquesne S 2007 Fire retardant polymers: recent developments and opportunities *J. Mater. Chem* **22**(17) 2283–2300

[16] Biswas B and Kandola B 2011 The effect of chemically reactive type flame retardant additives on flammability of PES toughened epoxy resin and carbon fiber-reinforced composites *Polymers for Advanced Technologies* **7(22)** 1192–1204