Study of fire-resistance of reinforced concrete slab of a new type

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Abstract. Reinforced concrete structures with complex inner geometry under the effect of high temperatures considering void former materials were examined. The analysis of strain-stress state of new type of architectural and construction system ‘Monofant’ under the effect of high temperature heating in standard fire mode, considering the change of design pattern was carried out. Numerical study of concrete slab with given reinforcement and complex inner geometry was carried out with use of software packages based on finite element method. Temperature fields throughout the depth of cross section of the slab of new type of architectural and construction system ‘Monofant’ upon heating in standard fire mode for time interval 0-240 min. were obtained. The carrying capacity of sections exposed to high temperatures was determined by deformation method. Offered the algorithm that considers the transformation of design patterns depending on temperature values and excessive pressure in thermal insulation cavities taking into account influence of deformation fields on temperature distribution.

1 Introduction

The requirements to constructed structures increase continually in the course of development of modern construction technologies that provides for the use of pre-cast and cast-in-place concrete. These requirements include the following: creation of new architectural forms for construction of different civil buildings, lightening of applied structures and improvement of traditional concreting technologies due to use of new materials. One of the systems that meets modern requirements to reinforced concrete structures is the architectural and construction system ‘Monofant’ [1] (Fig. 1).

The design of the slab is characterized by simple external and complex internal geometry. The main feature of this design is concealing liners of the certain shape made of light and widely used materials, such as polystyrene foam and mineral wool, in slab body.

The efficiency of this structure is also conditioned by section symmetry that determines the ability for random supporting. This results in variableness of bending moment field of cross-section.

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2 Research Significance

Small number of articles dealing with reinforced concrete structures with complex inner geometry under the effect of high temperatures considering void former materials give rise to the need in either field or numerical studies. The purpose of these studies should be not only determining actual temperature field in structural sections in time intervals that are established by normative documents but the study of the transformation of design diagrams (geometrical nonlinearity) due to the effect of high temperatures and development of general approach for managing these factors. Architectural and construction system 'Monofant' was selected as a study object.

Fig. 1. Design features of the slab of structural system 'Monofant'.

3 Proposed algorithm

Since the inner design/anisotropic structure of slab elements consists of different materials, it is characterized by the increase of non-uniform thermal fluxes. Theoretically, such non-uniformity may be the course of reciprocal influence of temperature on the deformation and vice versa. Therefore, it is reasonable to assess this interaction based on the philosophy of dynamic theory of thermoelasticity [2, 3].

This theory is based on V. Novatsky's assumption that the deformation of a solid body relates to the change of the heat that such body contains and, therefore, the change of temperature distribution of envelope building. Time-dependent temperature field causes the change of deformation field and vice versa. Inner energy of the structure depends on deformations and temperature.

It should be noted that the effect of deformation field on temperature distribution in a solid body is significant except for acute (jump-in) change of temperatures [2, 3]. Nonetheless, considering nonhomogeneous internal structure of formed structure and lack of knowledge about the processes that may take place in normal and, especially, abnormal conditions, it is reasonable to waive conventional suppositions and admissions that prove the separation of equations of Voigt- Jeffreys and Lamé.

It is supposed to model 3 design patterns [4] that consider fluctuations of liner - void former (Fig. 2).

Then solution algorithm will include the following operations:

- Task of temperature field T that should meet initial conditions;
- Determination by displacement vector of finite elements method $\{\vec{u}\}^0$;

- Substitution of determined vector $\{\vec{u}\}^0$ and determination of new field T;
- Substitution of temperature field T and determination of the new displacement vector $\{\vec{u}\}^n$;
- Comparison of original vector $\{\vec{u}\}^0$ and new displacement vector $\{\vec{u}\}^n$;

$$|u_k^0| - |u_k^n| \leq \varepsilon \quad (1)$$

$k - 1, 2, \dots, N$,

N is a number of reference points;

ε is required accuracy.

In case of non-fulfilment (1) the procedure stops. Otherwise, $\{u\}^0 = \{u\}^n$ is assigned and the entire procedure repeats once again until fulfilment (1).

Fig. 2. Design patterns that consider fluctuations liner - void former: a) for $T \leq T^*$ (T^* - is fusion temperature); b) for temperatures $T > T^*$ (before crack formation); c) for temperatures $T > T^*$ (after crack formation) 1 is reinforced concrete housing; 2 is liner - void former; 3 is liquid substitution; 4 is gaseous substitution with pressure P; 5 is cracks.

4 Numerical study

4.1 The structure of numerical study

Square slab with border size of 4 m made of heavy concrete class C25/30 was chosen as an object of numerical study. Operating temperature in each areas: bottom - 1Ø14A400C and top - 1Ø8A400C. Depth of cross section of the slab is 300 mm. Arris pitch is 1 m and arris width is 150 mm. The thickness of outer and inner trimming is 150 mm. Total vertical load, including dead weight, is 10 kN/m². The procedure of numerical study includes the following stages:

1. Determination of temperature field in floor slab caused by high temperatures during bottom-up heating in standard fire mode;
2. Analysis in finite-element setting of slab flat sections in different time intervals with creation of vertical loads, applied temperature and excessive pressure due to melting of polystyrene foam provided that such event takes place in considered moment of time to determine transformation moment of design pattern;
3. Determination of effective bending thickness of floor slab and determination of resulting forces caused by the temperature in set moment of time and vertical load;
4. Determination of carrying capacity of the cross section of the slab that is subject to load by deformation method DSTU 2.6-156:2010 [5] considering requirements of EN 1992-1-2 [6] and comparison with resulting forces.

FEM-based software packages were used for creation of numerical study models. The configuration and sizes of the elements in these models are established on the grounds of test

tasks by checking the convergence of finite elements method and evaluation of the accuracy of obtained results.

4.2 Temperature fields

Temperature fields on cross section of floor slab upon one-sided heating in standard fire mode were obtained by means of Ansys software package [7] at volumetric FE model for heating time from 0 min. to 240 min. Floor slabs of dwelling and administrative buildings are required to be fire-resistant R60. Therefore, temperature fields for the period of time of not less than 60 min. (Fig. 3) were used for further analysis.

Fig. 3. Temperature distribution along the depth of cross section of floor slab in 60 min. upon heating in the standard fire mode.

4.3 Excessive pressure upon heating

To prevent the effects of excessive pressure at the insulation bottom upon heating, we have created 12 plane models, FE hull of zero gauss's curvature, by means of Lira-SAPR software package [8]. Each model reflected the cross section of floor slab in definite period of time (6-50 min., in increment of 5 min.). The temperature was set as a load in each FE model according to previously received temperature fields. Moreover, full vertical load was applied to all models at those moments of time when insulation temperature reached melting values [2]. Excessive pressure caused by insulation melting was applied. Calculation results have shown that excessive pressure in slab cavity was so high that the tensile strength for a concrete C25/30 reached threshold values after 30 min. ($f_{ctm}=2.6$ MPa) (figure 4).

4.4 Effective thickness of floor slab

To obtain final forces from joint effect of vertical loads and temperature, we also considered FE model of the slab made of hulls of zero Gaussian curvature. Effective thickness of the slab was determined by the formula (2). Effective thickness was 27.4 cm before the effect of excessive pressure caused by insulation melting and it was 21.5 after damage of the integrity of bottom trimming.

$$\frac{b_{eff}\Delta}{12} = I_x \Rightarrow \Delta = \sqrt[3]{\frac{12I_x}{b_{eff}}} \quad (2)$$

where
 b_{eff} is an effective thickness of profile section;
 I_x is preliminary calculated second area moment
 Δ is an effective thickness of the slab.

Fig. 4. Feature of deformation of cross section of floor slab after 30 min. of standard fire.

Fig. 5. Bending moment (kNm) – curvature diagram.

4.5 Carrying capacity of the section based on deformation method

The carrying capacity of sections exposed to high temperatures was determined by deformation method described in [5]. The temperature effect was traced by the method of isothermal curve 500°C [6]. As a result, we have obtained bending moment-curvature

diagram (figure 5) for effective thickness. Numerical experiment of considered floor slab of architectural and construction system 'Monofant' has shown the correspondence to fire resistance R60. The deformation of design section does not have significant effect. The reduction of carrying capacity is 17% in comparison with non-heated slab.

5 Conclusions

- We offer the algorithm that considers the transformation of design patterns depending on temperature values and excessive pressure in thermal insulation cavities.
- We have obtained fields throughout the depth of cross section of the slab of new type of architectural and construction system 'Monofant' upon heating in standard fire mode for time interval 0-240 min.
- We have carried out the analysis of strain-stress state of new type of architectural and construction system 'Monofant' under the effect of high temperature heating in standard fire mode, considering the change of design pattern. It was disclosed that this slab corresponds to fire resistance rating R60.

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