Fire Resistance Evaluation of Reinforced Concrete Structures

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Abstract. **Alternative to fire tests in the near future may become modeling of structures under fire by means of the computer-aided design. With an objective source of data, the quantity of information from the created model is much higher than the results of standard fire tests.**

Based on the range of research a technique for modeling the precast concrete slabs to assess their fire rates with CAD system ANSYS has been developed. The adequacy of the simulation environment is confirmed by comparison with experimental data.

Keywords: **fire resistance, reinforces concrete, structures, modeling, finite element.**

I. Introduction

One of the most important stages of the building and structure design is a set of measures required to ensure the level of security over the estimated period of use, as well as in the emergencies.

For example, the structures should maintain their bearing and protecting capacity for the rated time necessary to ensure the safety of people, to protect assets and to provide liquidation and rescue. Understanding the basics of behavior of reinforced concrete structures under load, thermal effects and the impact of the environment allows performing efficient and safe design under the given criteria.

To date, there are several ways to get the desired results [1-5]. However, their use is tedious, time consuming and costly.

Alternative to existing methods of determining the fire resistance of building structures is their fire behavior modeling by means of computer-aided design. The use of specialized computer codes can significantly increase the profitability of the project works and increase their efficiency. Adequate modeling environment and objective source data can help to create a model of the building structure in the shortest possible time and with minimal cost of funds. The quantity of information will be much higher than at the results of standard fire tests.

II. General Regulations

The aim of work was to study the possibilities of modern software tools to predict the behavior and optimize the design of reinforced concrete used in buildings.

As the design environment for implementing the tasks, software modules of the finite element method (FE) ANSYS were used. Testing of models was implemented in software applications, ANSYS Workbench and ANSYS Mechanical. Choice was motivated by the need for verification of the solutions. It was implemented by two known methods – through a graphical interface and Workbench programming language APDL module Mechanical.

As the main evaluation scheme for theoretical model testing two types of floor plates: P-1 and P-2 [3] were chosen, both types are constructed with class C15/20 concrete (light expanded clay lightweight concrete) reinforced with longitudinal and transverse reinforcement [3]. The impact of 180 minutes heat and uniformly distributed load q were taken into account as external factors. Baseline parameters of plates and load data are presented in Table 1. Conventional load distribution corresponded to uniformly loaded beam on two supports. Heating was uniform over the entire length of the bottom surface (by reinforcement) too. Diagram is shown in Figure 1.

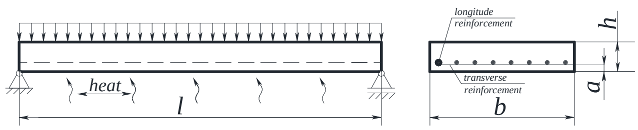


Fig. 1 – Design scheme of plates (P-1, P-2)

TABLE 1

CHARACTERISTICS OF PLATES

Parameters	Plates P-1	Plates P-2
Longitudinal reinforcement: - Number of bars. - Diameter, mm - Spacing between bars, mm	 8 10 133,3	 8 20 133,3
Transverse reinforcement: - Number of bars. - Diameter, mm; - Spacing between bars, mm	 25 6 187,5	
Distance from the bottom edge to center of reinforcement (a), mm	25	30
Plate thickness (h), mm	120	
Width of the plate (b), mm	1200	
Plate length (l), mm	3000	
Distributed load (q), kN/m	10,59	22,95

The analysis was performed on the results of the solution of two types of problems in the following sequence [6,7]:

thermodynamics analysis – the result of the temperature field distribution in terms of plate as a function of time;

strength analysis – the result of the strain and stress distribution in terms of plate as a function of time and temperature. This included the possibility of plastic deformation of materials and concrete failure due to the cracks formation [8,9].

In this formulation the thermodynamics analysis was the primary one, since its results were used in the form of raw data for strength analysis. Mathematical approaches that described the stress-strain state and the temperature field distribution of the model were significantly different, therefore, for each of them different types of FE were used [10].

The experimental curves of the concrete slab heating over the section were used for verification of the model by comparing the thermal analysis results. Experimental data on the temperature field distribution of the selected size of plates are known from the reference [3]. These comparisons are shown in Tables 2, 3 and Figure 2.

TABLE 2

THE TEMPERATURE DISTRIBUTION OVER THE CROSS SECTION OF P-2 PLATE

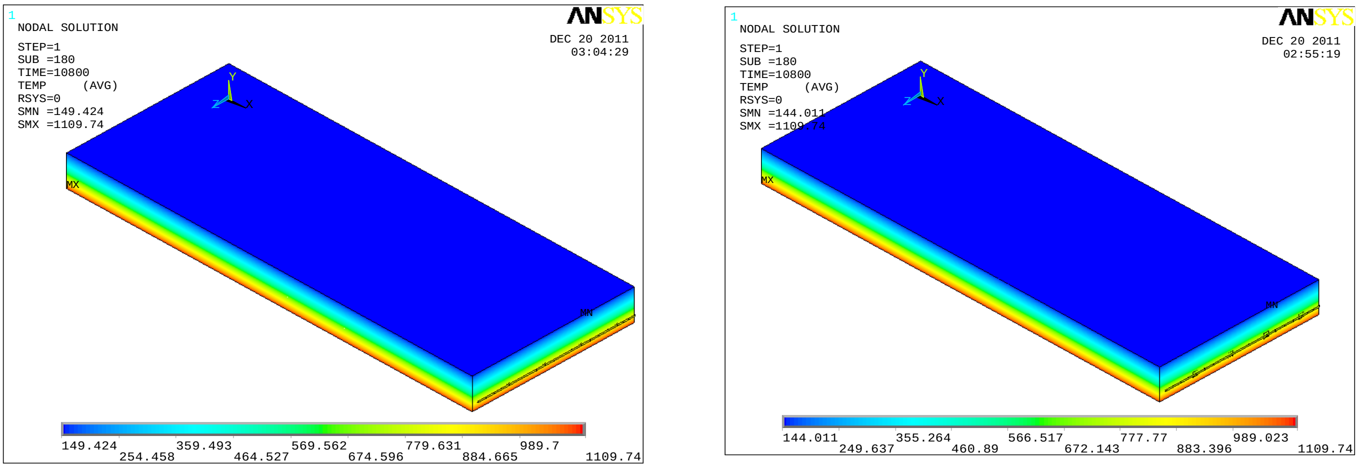
Position of the layer	Source	Temperature layers at time t, min								
		20	40	60	80	100	120	140	160	180
Heating surface	experiment (in camera)	781	885	945	990	1025	1049	1072	1092	1110
	calculation	781	885	945	990	1024	1050	1070	1090	1109
Reinforcement	experiment	250	400	500	570	630	660	700	730	770
	calculation	192	310	420	540	630	652	715	740	782
Cooled surface	experiment	20	45	60	70	80	85	100	120	140
	calculation	20	40	48	52	67	88	109	127	144

TABLE 3

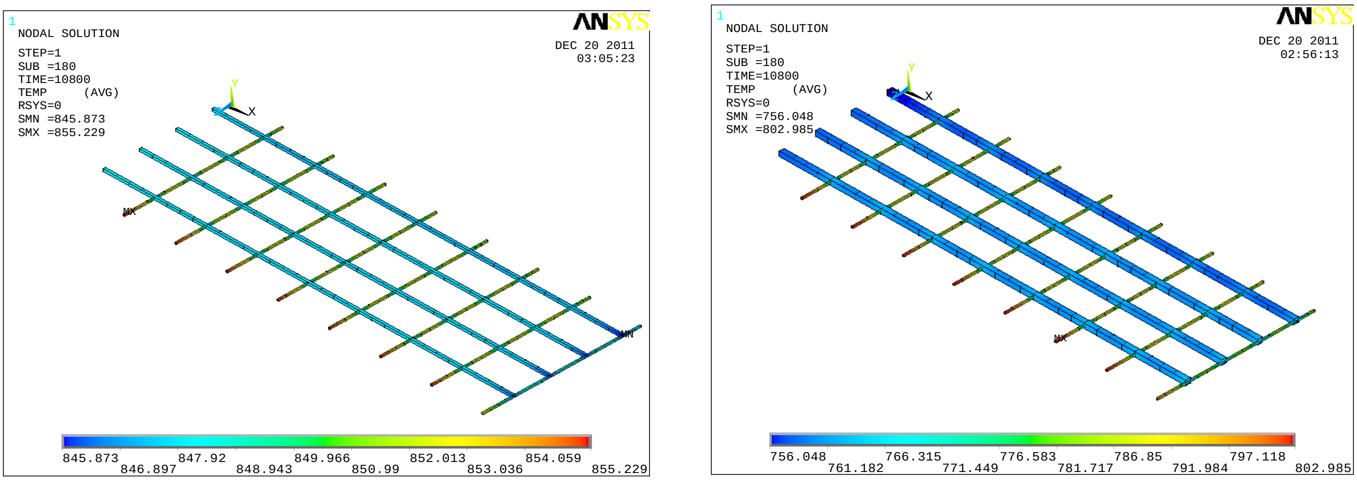
THE TEMPERATURE DISTRIBUTION OVER THE CROSS SECTION OF P-1 PLATE

Position of the layer	Source	Temperature layers at time t, min								
		20	40	60	80	100	120	140	160	180
Heating surface	experiment (in camera)	781	885	945	990	1025	1049	1072	1092	1110
	calculation	781	885	945	988	1025	1049	1073	1092	1110
Reinforcement	experiment	250	400	500	570	630	660	700	730	770
	calculation	230	400	525	610	680	710	760	800	845
Cooled surface	experiment	20	45	60	70	80	85	100	120	140
	calculation	20,1	42	51	60	71	93	114	133	149

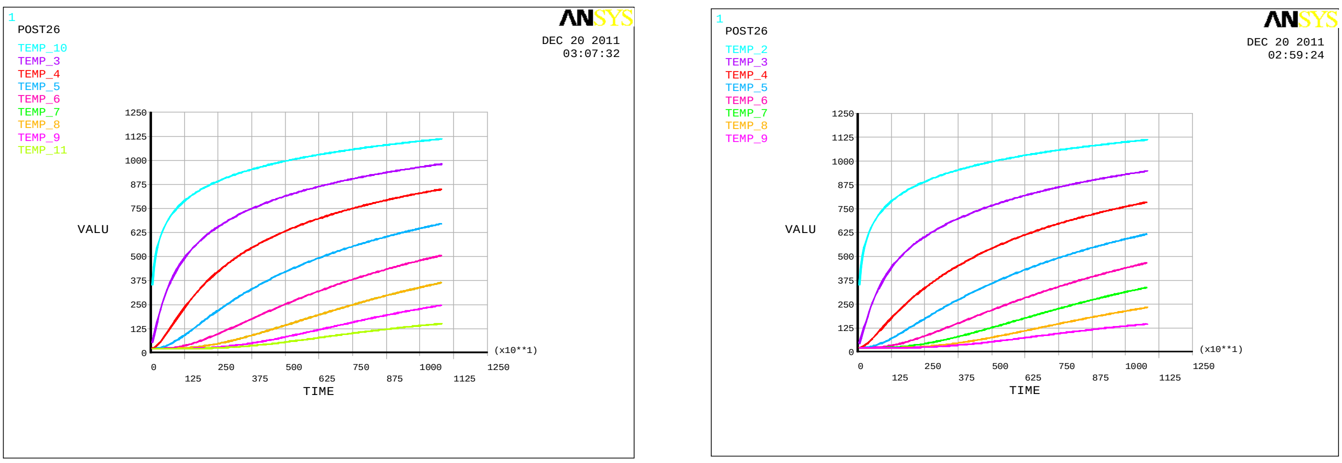
P-1 plate P-2 plate



a) The temperature distribution in the volume of plates



b) the temperature distribution in the amount of reinforcement



c) The temperature versus time in the layers of plates

Fig. 2 - The distribution of temperature in the cell plates P-1 and P-2

As follows from the calculation, the accuracy of temperature fields data obtained using the finite element method is quite high. There is some error, especially for plate P-1 in the temperature of the reinforcement. This desynchronization can be caused by an error of the experimental data. According to the source [3], the experimental temperature in the reinforcement was determined by measuring the layer of concrete on the longitudinal reinforcement center depth.

The differences in the temperature of the cooled surface are small and may not have a significant effect on the level of physical and mechanical properties of concrete.

The obtained results demonstrate high accuracy of the finite element analysis.

In view of the requirements for the convergence of the analysis the concrete cracking and crushing in compression were not performed. In connection with mentioned the evaluation was carried out on the fire endurance level equivalent stresses in the reinforcement and magnitude of ultimate strains in materials.

Stress state of the plate is determined by the components of a number of indicators:

- the equivalent von Mises stress;
- longitudinal normal stress (axis X);
- stress profile height plate.

Strain state of the plate is determined by the following factors:

- full deformation (mechanical and thermal);
- plastic deformation;
- temperature deformation.

For each indicator, output is displayed on the following criteria:

- deformations of the von Mises;
- longitudinal strain (along the axis X);
- strain profile height plate.

The analysis of the stress-strain state in comparison with experimental data as a function of temperature is presented in Tables 4 and 5.

Certain differences in design stresses are caused by deflection sensitivity of the model to the values of linear expansion coefficients with a significant temperature gradient through the thickness of the slab. In the reference [1-3] for a concrete class C15/20 (light expanded clay lightweight concrete) given coefficient of linear thermal expansion (TCLE) materials differs significantly.

Temperature component in the deflection of the beam reaches 70-80% of the maximum, therefore, even minor fluctuations TCLE able to exercise significant influence on the overall strain state of the structure.

TABLE 4

EXPERIMENTAL AND THEORETICAL CHARACTERISTICS OF THE STRESS-STRAIN STATE OF PLATE P-1 EXPOSED TO HEATING AND LOAD

Parameter	Data source	Heating time, min								
		20	40	60	80	100	120	140	160	180
The equivalent stress in the reinforcement, MPa	experiment	226,1	231,2	189,3	173,0	196,6	–	–	–	–
	calculation	212	200	195	182	175	–	–	–	–
Compressive stress in concrete	experiment	8,48	9,22	9,60	9,93	10,31	–	–	–	–
	calculation	10	12,5	12,8	13,1	13,5	–	–	–	–
Strains of the concrete,%	experiment	0,08	0,10	0,11	0,14	0,20	–	–	–	–
	calculation	0,089	0,12	0,125	0,15	0,23	–	–	–	–
Strains of the reinforcement,%	experiment	0,30	0,50	0,60	0,81	1,32	–	–	–	–
	calculation	0,30	0,54	0,65	0,87	1,38	–	–	–	–
The maximum deflection, mm	experiment	43	61	68	89	137	–	–	–	–
	calculation	39	64	72	104	160	–	–	–	–

TABLE 5

EXPERIMENTAL AND THEORETICAL CHARACTERISTICS OF THE STRESS-STRAIN STATE OF PLATE P-2 EXPOSED TO HEATING AND LOAD

Parameter	Data source	Heating time, min								
		20	40	60	80	100	120	140	160	180
The equivalent stress in the reinforcement, MPa	experiment	132	139	134	127	125	119	115	113	117
	calculation	125	130	132	120	120	115	113	110	110
Strains of the concrete,%	experiment	0,07	0,14	0,16	0,18	0,20	0,22	0,25	0,28	0,31
	calculation	0,08	0,16	0,17	0,20	0,21	0,25	0,30	0,32	0,34
Strains of the reinforcement,%	experiment	0,06	0,25	0,39	0,50	0,58	0,69	0,80	0,97	1,20
	calculation	0,08	0,32	0,42	0,52	0,60	0,76	0,87	1,05	1,3
The maximum deflection, mm	experiment	14	40	56	68	80	93	107	124	160
	calculation	28	52	68	78	89	104	115	142	186

Overall, the obtained results are quite close to the experimental data, particularly in regard to the bearing deformation reinforcement. Due to advances in concrete yield strength at high temperatures, the bearing capacity of the reinforcement is the main factor for fire resistance of reinforced concrete slabs.

According to the thermo-mechanical deformation diagrams of reinforcing steel, early stages of deformation strength are 1,25% [10-12]. When reaching this value at temperature influence is ductile failure of the material, fixtures loses load capacity.

According to experimental data presented in Tables 4 and 5, the ductile failure reinforcement occurs at temperatures of 100 °C for plate P-1 and P 160-170 °C - for plate P-2, which agreed with the calculated results.

III. Conclusion

The results of the research can be used in calculations of fire resistance of reinforced concrete frame building designs for computer-aided design.

The main results obtained in this paper:

1. The analysis of the ANSYS computing environment components was developed. Their ability to record the temperature and force effects that arise in the construction of a fire was reviewed;
2. The experimental data of reinforced concrete slabs in-fire behavior were studied, including heat exposure of standard and real fire;
3. A computational model of reinforced concrete slabs in-fire behavior was developed in order to assess the their fire rates;
4. The method for fire resistance assessment of reinforced concrete slabs was developed, allowing the use of it in computer-aided design.

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