Reasons of cracks in floor slab panel

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Abstract. The article considers the problem of the formation of temperature and cracks in a reinforced concrete floor in thin 400 mm, connected by reinforcing outlets with internal reinforced concrete walls and the outer ring wall of the core of a high-rise building. During the hardening of the laid concrete, the formation of through cracks in the overlapping, extending from the walls and located across the corridor formed by the walls, was observed. The paper analyzes the possible causes of cracking. Cracking occurs due to the restriction of free temperature and shrinkage deformation of the floor slab by a rigid connection with the walls. The direction of the cracks indicates that tensile shrink stresses act along the walls. Cracks form during the cooling of the concrete floor, when the directions of the vectors of shrinkage and thermal deformation coincide. The work gives recommendations for the care of concrete floor structures.

1. Introduction

The article discusses the problem of the formation of temperature-shrinkage cracks in a reinforced concrete floor, 400 mm thick, connected by reinforcing outlets with internal reinforced concrete walls and the outer ring wall of the core of a high-rise building. The temperature gradients inside the floors are negligible and do not cause dangerous tensile stresses. Despite this, during the hardening of freshly laid concrete, cracks appear in the ceiling, extending from the walls and located across the corridor formed by the walls. A dangerous moment is the process of cooling the wall after heating, when temperature deformation and shrinkage act together in the same direction. The higher the heating of the plate, the higher the likelihood of cracking [1,2]. This process is most dangerous in the early stages of concrete hardening, when the heat release rate is high and the strength of concrete is negligible.

In massive concrete structures, internal temperature differences are also a danger. At the initial time of hardening (1–7 days), the temperature expansion of the warmed core of the massif is restrained by the colder outer layer, in which tensile stresses arise, leading to the formation of surface cracks. In the later stages of hardening (20-30 days), during the cooling of stress, they change sign - compression occurs on the surface, and tension inside. In this case, cracks form in the inner part of concrete blocks [2-4].

Thus, there are two mechanisms for the formation of temperature cracks. The first is associated with the temperature difference at different points of the concrete mass at a given time, the second is associated with a change in the average temperature of the block in time between the moments when the maximum and minimum temperatures of the concrete are reached during cooling [5-8]. With free (unrestricted) temperature expansion-contraction of the body by the second mechanism of stress, there are no stresses in it [9,10], and no cracks are formed. In constructions, there are always bonds
restricting freedom of deformation. The cracks formed by the first mechanism are not through, they form either in the outer concrete layer (at an early age) and extend only to the depth of tensile stresses, or inside the massif (at a later age). Internal cracks do not surface. Cracks formed by the second mechanism, as a rule, are through [11].

Studies of the thermal stress state of concrete of massive structures were carried out in a rather large volume [12-14], both in our country and abroad. The influence of various factors on the thermal crack resistance of concrete [15,16] was established, the corresponding techniques of the technology of laying [17-19] and concrete care in winter [20,21], spring-summer and summer concreting were developed. The crack resistance of concrete was studied depending on its composition [22-25], type and number of additives, etc. [26-29]. The issue of thermal cracking in thin-walled structures is less studied. Earlier, we studied the crack resistance of a reinforced concrete wall under conditions of thermal deformation constrained by the base. Where the problem of the formation of temperature-shrinkage cracks in thin (200-300 mm thick) and extended reinforced concrete walls erected on a hardened concrete base was considered. When hardening freshly laid concrete of such structures, the formation of through vertical cracks is often observed, starting in the zone of contact with the base and propagating upward, often to the entire height of the wall. Cracking in this case occurs due to the restriction of the thermal deformation of the wall by the base. The danger is mainly the process of cooling the wall when temperature deformation and shrinkage act in the same direction and cause tensile stresses. It was hypothesized earlier that cracking can be avoided either by preheating the concrete base so that the deformation during cooling is joint, or by creating through the transverse slots in the lower part of the wall that localize the wall deformation in separate blocks. In the work, the reliability of these hypotheses was verified, and their failure was shown [30].

The purpose of the work is to study the causes of cracking in the ceilings and develop measures to prevent them.

To obtain specific initial data, the tests of concrete for heat generation, compressive strength, and linear thermal expansion were performed.

To achieve this goal, the following tasks were set:
1. To analyze the possible causes of thermal cracking.
2. To calculate the thermally stressed state of the floor, caused by the non-uniformity of the temperature field in thickness.
3. Identify the main danger of cracking.
4. Develop the necessary measures to counter cracking.

2. Materials and methods
As an experimental design, an overlap of concrete of class B40 was selected on cement CEM I 42.5H with a flow rate of 350 kg/m³.

2.1 The heat dissipation of concrete
The computer program for calculating the thermal stress state uses the heat release equation of ID Zaporozhets (1), according to which the value of heat generation of concrete at each time of hardening is calculated:

\[ Q = Q_1 \left( 1 - (1 + A_t t)^{\frac{1}{m-1}} \right) \]  

\[ (1) \]

\( A_t \) is the coefficient of the rate of heat release, characterizing the rate of heat release at a given constant temperature \( t \);
\( m \) is the order of the hydration reaction. For portland cement, the reaction order is from 2 to 2.3.

The values of the parameters of the equation \( Q_{max} \), \( A_t \) and \( m \) are determined by experimental data. The theoretical curve according to equation (1) should maximally correspond to the experimental
curve. However, as can be seen from Fig. 1, the coincidence of the curves is observed only after 3 days of hardening. This is since equation (1) does not reflect the inhibitory effect of additives on hardening in the initial period. This discrepancy gives a certain margin of concrete crack resistance in the calculations of the thermal stress state.

The heat dissipation of concrete was experimentally determined according to EN 196-9: 2010 by the semi-adiabatic (thermos) method at an initial concrete temperature of 20 °C and the calculation led to isothermal hardening at a temperature of 20 °C. Three twin samples of this concrete were tested. The readings of temperature sensors were recorded with a multi-channel meter-recorder “Terem-4” every 30 minutes. The specific heat release of cement in B40 concrete with a cement flow rate of 350 kg/m³ is characterized by the following parameters of the ID Zaporozhets equation: $Q_{\text{max}} = 410 \text{ MJ/m}^3$; $A_{20} = 1.2 \text{ days}^{-1}$; $m = 2.2$, which are used in the calculations below.

![Figure 1. Heat dissipation of concrete: 1 - experimental curve; 2 - theoretical curve according to the equation of I.D. Zaporozhets.](image)

2.2 **Coefficient of linear thermal expansion**

According to the results of our tests, concretes of various compositions aged 1 to 7 days have a coefficient of linear thermal expansion (KLTR) from $0.96 \cdot 10^{-5}$ to $1.3 \cdot 10^{-5}$ 1/°C. In the calculations, it is advisable to take the greatest value as the least favorable.

2.3 **Ultimate tensile strength of concrete**

The ultimate tensile strength of concrete can be roughly calculated using the following formula:

$$\varepsilon_{\text{lim}} = \frac{R_{bt}}{E_{bt}}$$

(2)

$R_{bt}$ – is the tensile strength; $E_{bt}$ – is the tensile elastic modulus.

Based on the control tests of the concrete floor, the average values of cubic strength at the age of 7 days were obtained from 47.0 MPa to 54.4 MPa. We take an average of 50.7 MPa. The tensile strength can be taken as 0.1 from $R_7$, i.e. $R_{bt} = 5.1$MPa.

The elastic modulus for seven-day concrete at $R_7=50.7$ MPa is taken according to SP 41.13330.2012 equal to 35,000 MPa, then $\varepsilon_{\text{lim}}=5.1/35000 = 0.000147$ or 0.147 mm/m.
2.4 Crack characteristics
The layout of cracks in the overlap is shown in Fig. 2. The cracks are oriented mainly across the walls of the corridor. The width of the crack opening is in the range from 0.08 to 0.3 mm, and the depth is more than 100 mm.

![Figure 2. The layout of cracks in the overlap.](image)

According to the measurement results and an approximate calculation, the total width of all cracks on the length of the overlap between the walls is 3.7 mm (the average value of the opening width for a sample of 0.16 mm multiplied by the number of cracks or 0.185 mm per 1 m of the length of the overlap.

Concreting of the structure was carried out in the following sequence: annular wall of the core, internal walls - overlapping - with an interval of one week. In the lower room under the ceiling, air was warmed up to 40 ºС. On top of the plate was covered with a film and thermal insulation (polyethylene foam 10 mm thick).

Cracks formed in three corridors located parallel to each other and separated by internal walls.

3. Result and discussion

3.1 Checking the possibility of cracking as a result of temperature changes across the thickness of the floor slab
The option less favorable from the point of view of crack formation was calculated than the one that took place. The temperature of the concrete mixture and air was taken at 15 ºС, the bottom floor was covered with formwork (plywood 20 mm thick). The thermal insulation of the slab from above (a layer of polyethylene foam) was not considered, it was believed that concrete was closed only with a plastic film that did not resist heat transfer. Below, the air had a temperature of 40 ºС for the first two days, then the heating was turned off. The temperature values in the middle and on the surface of the floor slab depending on the hardening time are shown in Fig. 3 and the corresponding values of thermal stresses in Fig. 4.

As can be seen from fig. 4 tensile thermal stresses have a maximum value not exceeding 0.5 MPa for 1-day hardening, which is absolutely not dangerous for concrete.
Figure 3. Figure with short caption (caption centred).

Figure 4. The values of thermal stresses in the middle and on the surface of the floor slab depending on the hardening time.

The calculation of the thermally stressed state in a two-dimensional formulation of the problem confirmed the absence of cracking due to uneven heating of the floor, which has freedom of temperature deformations.

Calculation of the thermally stressed state of the floor slab model with free support on the annular wall. The fragment of abutment of the ceiling to the annular wall was calculated in the absence of a rigid connection at the opposite end (Fig. 5).

An annular wall with a thickness of 2.5 m and an overlap of 0.4 m are concreted with an interval of 14 days. The temperature of the concrete mixture is 15 °C, air - 12 °C. The bottom surface of the floor slab is covered with formwork (plywood 20 mm). The top surface is open. The care regimen involves heating under an awning, removing formwork and awning for 3 days, covering with 10 mm
thick polyethylene foam and removing insulation for 10 days. From below, heating is carried out to 40 °C for the first 2 days.

In fig. 5, the color diagrams of the overlap fragment show the fields of temperature, stress along the X and Y axes, and the crack location zone (in red) for the curing time of 16 days. The zone marked in red, which appeared only on the 16th day, is too small and lies within the calculation error. Therefore, we can assume that crack resistance is provided.

Figure 5. The results of the calculation of the thermally stressed state of the floor slab with the free support of one end on the annular wall.

In case of rigid fixing of the plate on two opposite sides, crack resistance is ensured only when air is heated under the ceiling. In the absence of heating, crack formation develops very intensively over the entire length of the overlap.

3.2 Calculation of the thermally stressed state of the floor slab with a rigid fixing of the floor from two opposite sides

In this calculation, the same concreting conditions are assumed as in the previous case, but the overlap is rigidly fixed on two sides of Fig. 6. In fig. 6 anchorage points are highlighted in a circle.

Figure 6. The design scheme.

In this case, the pattern of cracking changes dramatically. The time moments become critical immediately after the bottom heating is turned off 2 days after the concrete was laid in the ceiling or on the 16th and 17th days from the moment the concrete was placed in the annular wall. In fig. Fig. 7
shows diagrams of cracking zones during heating of air under the ceiling, in Fig. 8 heating - when heating is off.

**Figure 7.** Diagrams of cracking zones when heating air under the ceiling for 2 days (16 and 17 days from the moment of laying concrete in the annular wall).

**Figure 8.** Diagrams of cracking zones after turning off the air heating under the ceiling after 2 days (18 and the next day from the moment of laying concrete in the annular wall).

Calculation of the spatial model of overlap with rigid fastening of the slab along the entire length of the internal walls. As was shown earlier by calculating a wall fragment for its interaction with the base and analyzing the causes of the formation and development of cracks in it in the ANSYS finite element modeling complex (version 15.0) in a spatial setting, the formation of cracks occurs as a result of the incompatibility of thermal deformations of the wall and the base [b]. A similar situation occurs in the case of floor slabs, leaning on the walls.
The following is a calculation of the model of the floor slab and its interface with the walls. For the calculation, the most dangerous section of the floor was selected, which has the largest size on the long side – about 70 m.

The design diagram of the simulated slab and walls is shown in Fig. 9.

In the calculation model, loads from the dead weight of the structure and the temperature effect as a result of the heat of concrete were set.

![Figure 9. The design scheme (model) of the slab and walls.](image-url)

The criteria for crack formation are:
1) the limiting values of the main tensile stresses, which constitute, according to the II group of limiting states, \( R_{bt,ser} = 1.95 \text{ MPa} \);
2) the limiting values of the main relative linear strains, which according to SP 63.13330.2012 are \( \varepsilon_{bt0} = 0.0001 \), and in accordance with SP 41.13330.2012 for a 3-day concrete age, \( \varepsilon_{bt0} = 0.00005 \).

The model in a deformed state after cooling is shown in Figure 10.

![Figure 10. Model in a deformed state (fragment).](image-url)

The trajectories of the main tensile stresses on the lower and upper plane of the plate (Fig. 11) have the same direction and the same numerical values of the stresses, which also differ slightly in coordinate in plan, which explains the practically through nature of cracks with a uniform opening width.

The trajectory of the main tensile stresses is oriented along the plate and becomes oblique in the vicinity of the mating walls with the annular wall. This circumstance correlates with the picture of crack formation in the floor slab.

The numerical values of the isofields of the main tensile stresses and the main relative linear strains (Fig. 12-13) show that the largest values of the main tensile stresses lie in the range of 4.5-5 MPa at the limiting value of \( R_{bt,ser} = 1.95 \text{ MPa} \), and the largest values The main relative linear strains are 0.00025-0.00030 with the accepted limit values \( \varepsilon_{bt0} = 0.0001 \) and 0.00005.

A comparison of the obtained indicators with standard values indicates the possibility of formation and development of cracks in the plate from a given temperature effect.
As a search for possible solutions to the problem of thermal cracking, we studied the thermally stressed state of the slab during preliminary heating of the upper part of the walls before concreting, assuming that the deformations during cooling will be joint.

For greater clarity, the heating of concrete walls with subsequent cooling in the calculation model was set as the only effect.

The calculation results showed that when the walls cool down, their deformations in the longitudinal direction are restrained by the annular walls, and deformations develop mainly in the vertical direction (wall growth in height due to the absence of restrictions).

Thus, wall heating is not an effective measure.
4. Conclusion
1. In the work, the possible causes of the formation of thermal cracks were analyzed by calculation:
   - uneven deformations caused by the temperature drop across the plate thickness, considering the
     heating of the air in the lower room.
   - the presence of rigid bonds that limit thermal deformation and leading to tensile stresses.
2. Calculation of the thermal stress state of the overlap caused by the non-uniformity of the
   temperature field in thickness showed that temperature gradients do not cause dangerous tensile
   stresses due to the small thickness of the plate.
3. The main danger of cracking is the tightness of the longitudinal (along the inner walls)
   temperature deformation of the plate during cooling. The elongation of the slab during self-heating of
   concrete, restrained by the walls, causes compressive stresses and does not lead to cracking.
4. A necessary measure to counteract cracking is to limit the self-heating of the floor and slow it
   down. To reduce the temperature maximum, it is necessary, first of all, to lower the temperature of the
   concrete mixture before laying, and to cover the concrete with thermal insulation, but only after a
   certain time after reaching the temperature peak. The purpose of thermal insulation application is to
   slow down the cooling rate of concrete in order to delay the onset of low temperature and give
   concrete time to gain the necessary strength and crack resistance.

Acknowledgments
This research work was supported by the Academic Excellence Project 5-100 proposed by Peter the
Great St. Petersburg Polytechnic University.

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