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The thermo-stressed state in massive concrete structures

Термонапряженное состояние массивных бетонных конструкций

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Key words: the building period; massive concrete and reinforced concrete structures; cement setting temperature; thermal stressed state; thermal cracking resistance; one-dimensional structural model

Ключевые слова: строительный период; массивные бетонные конструкции; железобетонные конструкции; экзотермия цемента; термонапряженное состояние; одномерная расчетная схема

Abstract. This article examines the justification for using one-dimensional structural models in the analysis of the thermo-stressed state in massive concrete and reinforced concrete structures during the building period. The paper presents calculation results for the thermo-stressed state in massive foundation slabs with different planform dimension ratios. Special attention is paid to presence/absence of thermal insulation on the sides of the slab during the mixture pouring process. Generally, one-dimensional structural model is suitable in cases when ratio h/l < 0.17, h stands for the minimal plane dimension in a construction such as slab. The research indicates the existence of zones near the sides of slabs, where values of the tensile stress exceed the values that were obtained with use of one-dimensional structural model. This excess may account for 9.5 %.

Аннотация. В настоящей работе рассматривается обоснованность использования одномерных расчетных схем при анализе термонапряженного состояния массивных бетонных и железобетонных конструкций зданий и сооружений в строительный период. Приведены результаты расчетного исследования термонапряженного состояния массивной фундаментной плиты с различным соотношением плановых размеров. Особенное внимание уделено наличию/отсутствию теплоизоляции на торцах при укладки бетонной смеси. Определено, что в общем случае одномерная расчетная схема применима при соотношении h/l < 0.17, где h–меньший из плановых размеров конструкции типа плиты. Проведенное исследование показывает наличие зон (в приторцевых участках), в которых растягивающие напряжения несколько превосходят значения, полученные по одномерной задаче. Превышение может составить 9.5 %.

Introduction

Structural calculation methods involve the use of structural models that are made with certain assumptions and simplifications that greatly facilitate the calculation. There is a limit for the use of each structural model after which it becomes invalid. Calculation with an incorrectly chosen structural model cannot be valid, even when using the most accurate methods.

Most of the industrial and civil constructions (especially nuclear power plants [NPP] and high-rise buildings) use large sized reinforced concrete slabs (many times longer than they are thick) for the foundation, for massive walls, and as floor slabs.

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During the building period, non-stationary and non-uniform temperature fields [1-7] appear in the concrete as a result of cement setting and heat exchange with the environment, consequently leading to the formation of thermal stresses [8–16]. Uneven temperature fields are the cause of tensile stresses (and consequently of extension strains) on the surface of the foundation, which are capable of generating dangerous cracking [17–23].

The problem of evaluating the fracture resistance of the concrete and the reinforced concrete blocks during the building period is rather complicated from an engineering point of view [24–30]. Strictly speaking, the foundation (wall, slab) is a 3D object, so the problem should be solved in a 3D formulation. Also, the large dimensions of the massive constructions necessitate the use of a large amount of finite elements in such a design model. The need to consider the influence of temperature on the thermal characteristics and deformability of the concrete (physical nonlinearity of the problem) significantly complicates the calculations. It is also important that the solution of the thermo-elastic problem will be extremely approximate; it is necessary to consider deformations due to concrete creep [31–33].

In the case when the plane dimensions of the slabs considerably exceed their thickness, a one-dimensional structural model can be applied for the central part of the slab with a sufficient degree of accuracy when tension and temperature are functions of a single spatial coordinate – the vertical one [14, 28–31].

The transition to this model is valid for a certain ratio between the thickness of the structure and its plane dimensions. In [10–12] there is an approximate numerical value for this ratio $\frac{h}{l} \leq \frac{1}{3} \ldots \frac{1}{4}$ where l- the smallest dimension of the block; h- thickness of the array of blocks.

The one-dimensional model has the following advantages:

1. it is a solution to the wide range of problems that arise in modern practice during the erection of massive concrete structures;
2. the method is comparatively simple ;
3. the implementation of the algorithms is simpler and consequently shortens calculations.

There are the disadvantages of this model as well: ratio $\frac{h}{l} \leq \frac{1}{3} \ldots \frac{1}{4}$ often are not satisfied and heat flow from the side surfaces becomes significant. In such situations, it is necessary to use 2D and 3D structural models.

For the foregoing reasons, finding the precise meaning of ratio $\frac{h}{l}$ is the vital task. Since calculation with an incorrectly chosen structural model cannot be valid, even when using the most accurate methods.

The purposes of this article are an elaboration of the numerical ratio $\frac{h}{l}$, which allows a change to one-dimensional structural model for the calculation of thermal-stressed state of concrete massifs (such as slabs, ceiling panels or walls) during the construction period, and an assessment of observational errors in case of the changing 2D and 3D models to the one-dimensional structural model.

Thermo-stressed state is meticulously surveyed on the ends (2D model) of foundation slabs (walls, ceiling panels), considering the heat sink from the side surfaces. As initial data (thermophysical and stress-related characteristics of concrete, cement heat radiation) the results or research, obtained in laboratory “Polytech-SKiM-Test” in CUBS department by Professor Y.G. Barabanschikov were accepted.

Statement of the problem

To define thermal stresses in a construction a concrete slab was analyzed. This slab does not have restraints in deformations and it is laid as one block and has height in a range of [0.5…2.5] m.

The process of concreting takes place in summer period.

In a slab’s cross-section the problem is two-dimensional, since stresses and temperatures are functions of the two spatial coordinates – vertical and horizontal.

It is required to analyze the thermal stressed state of foundation slab considering that the heat flow is two-dimensional, to assess influence of the heat flow from the ends with different ratio $\frac{h}{l}$, to elaborate the ratio $\frac{h}{l}$ wherein a structural model can be considered as one-dimensional.

This paper demonstrates calculation of the foundation slab's thermal stressed state with the help of TERM software [14] developed by the Institute of Civil Engineering at the St. Petersburg State Polytechnic University. This software calculates nonstationary fields of temperature and thermal stresses in slabs. In order to estimate the cracking resistance of the foundation slab, we would use the deformation criterion suggested by P.I. Vasiliev [24–28]. An essential feature of the TERM software is the consideration of temperature influence on thermophysical and stress-related concrete characteristics, which is vital for problems of the construction period.

The results of analysis of the thermal stressed state of foundation slab allow us to elaborate the $\frac{h}{l}$ ratio, which permits change to one-dimensional structural model. The assessment of the possible measurement errors is provided. The dangerous zones in the ends of the slab are surveyed.

Initial data.

1. Technological conditions of concrete mixture pouring:
a. ambient temperature (temperature of ambient air): 15^0C;
b. concrete mix temperature: 15^0C;

2. Conditions of heat transfer on the surface: third type boundary conditions. Heat transfer according to the Newton's law:

$$\frac{\partial \mathrm{T}}{\partial \mathrm{n}} = \frac{\beta}{\lambda}\left(\mathrm{T_{cp}} - \mathrm{T_{cp}}\right) \tag{1}$$

3. Geometry and plan dimensions: slab thickness equals to 1; 1.5; 2 m;

4. Thermal and physical characteristics of the concrete: thermal conductivity= 2.67 W/m·^{0}C, thermal capacity c= 1.0 kJ/kg·^{0}C;

5. Stress-related characteristics:
a. According to N.A. Malinin, the instantaneous elastic deformation modulus of concrete follows the equation [13]:

$$E(t) = E_{max}\left(1 - e^{\alpha t^{\gamma}}\right), \tag{2}$$

where E_{max}= 38000 MPa is the limit value of the concrete deformation [24]. Functional dependency parameters are $\propto = -0.37$, $\gamma = 0.32$, and t stands for the current time;

b. The heat dissipation process follows the I.D. Zaporozhets equation [2]:

$$\mathrm{Q}(\tau) = \mathrm{Q}_{\max}\left[1 - (1 + A_T\tau)^{-\frac{1}{m-1}}\right] \tag{3}$$

The parameters of heat dissipation process were defined experimentally. The results of research which was conducted by professor Barabanschiov Y.G. were used as initial data for heat dissipation process: the maximum heat dissipation $\mathrm{Q_{max}}$=1.66×10^5 kJ/м^3; heat dissipation's rate of increase coefficient at 20°C A_{20} = 1×10^5 s^{-1}; 1/(m-1) = 0.833.

For accurate results, sizes of a finite element (in this problem 8-knot isoparametric finite elements are used) were not changed during the calculations. The structural model is represented at Figure 1.

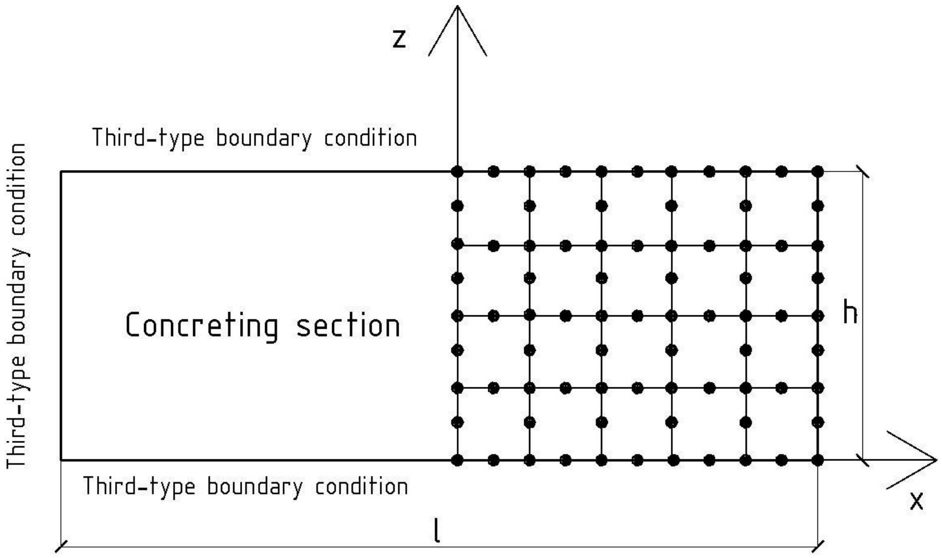

Figure 1. The structural model

Analysis of the thermo-stressed state

First experiment.

The following situation was modeled: for the structural model (Figure 1), the heat transfer from the ends is prohibited by artificial input of infinitesimal reduced heat transfer coefficient βred. The point of time where the maximum of exothermic heat of the plate takes place is explored (first and second day). There is an extension on the surface in this moment, while in the center – compression. Tensile stresses on the surface of the slab are dangerous and may cause crack formation.

As an example, we analyze the thermal stress of the slab, cross section of which is equal to the size 1.5 x 11 m. The temperature fields and thermal stress fields will look (on the 2nd day after laying the mixture) as shown in Figures 2–3.

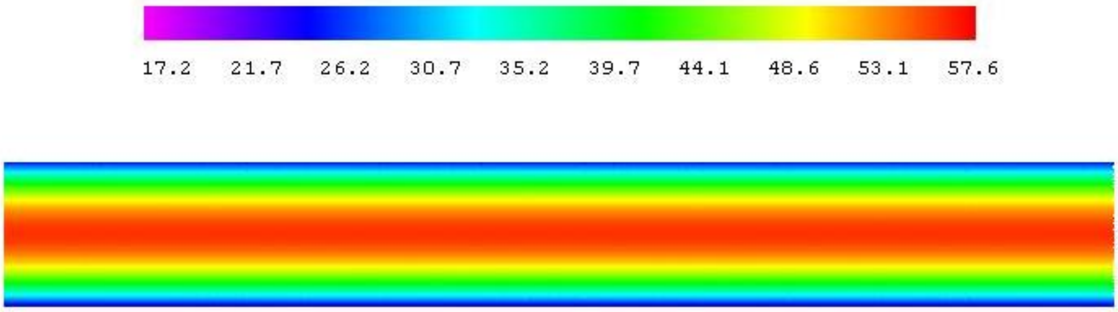

Figure 2. The temperature field on second day after pouring the concrete mixture (0C)

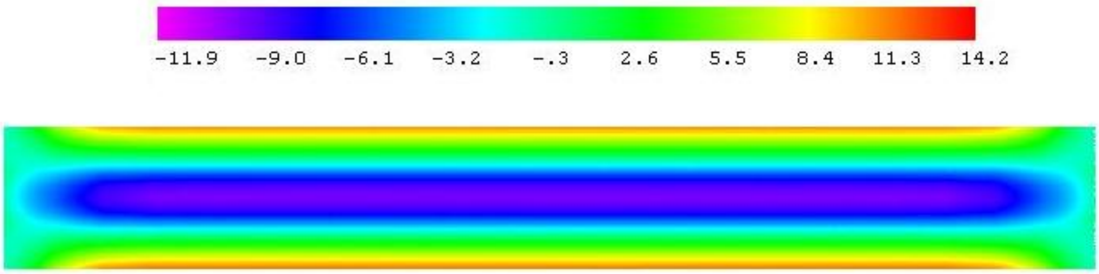

Figure 3. The stress field on second day after pouring the concrete mixture (kg/cm2)

Analysis of temperature fields (Figure 3) shows that temperature field is one-dimensional: the temperature's value varies along the Z-axis (height boards) only. The problem connected with stresses is still two-dimensional.

The diagrams of thermal stress (the X-axis) on the surface of the slab, as shown in Figure 4, decrease monotonically from the center to the sides of the slab. The values of the X-axis on the chart – the number of cross-section of the slab, considering that number 1 is a central cross-section.

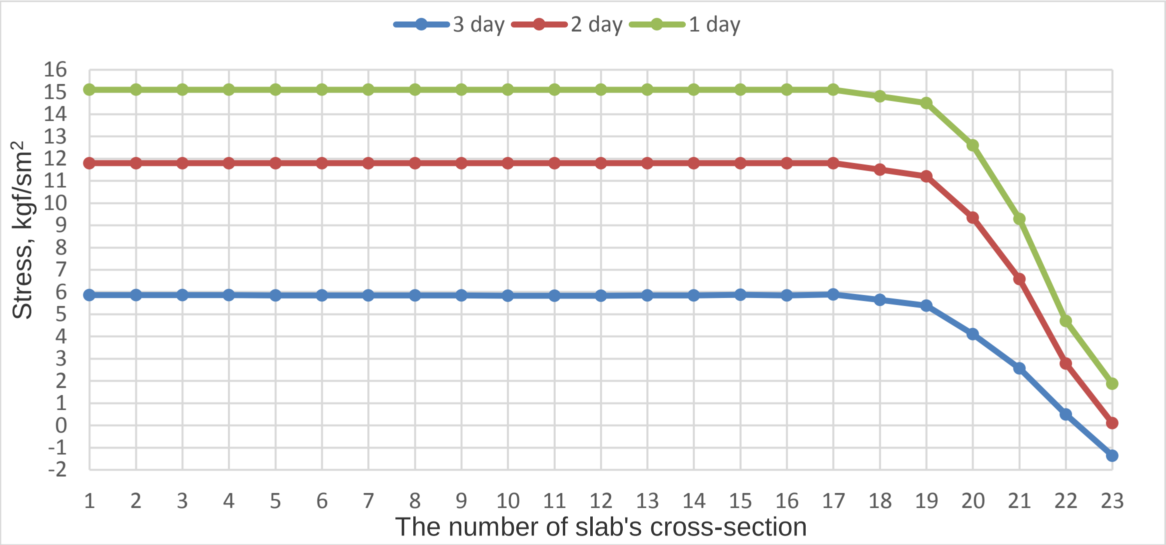

Figure 4. The diagrams of thermal stresses of the surface of the slab

At the same time it is possible to identify two areas inside the cross section (Figure 5) end region A (the amount of such areas - the number of the ends, which equals to 2) and the central region B over the area along the X coordinate are: zone B – 8.370 m, zone A – 2.630 m, or in relative units (relative to the length of the slab), respectively, 76.1 % and 23.9 %.

In the zone B stresses vary are relative only to the Z coordinate and it is suitable to apply the one-dimensional structural model. Obviously, in the zone A we can't obtain a sufficiently accurate solution without using 2D structural model.

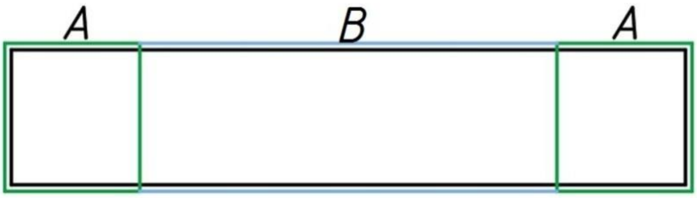

Figure 5. Zones of the slab

Second experiment.

In case of heat flow from the sides of the slab (that is what happens during the real building process), the diagrams of tensile stresses of the surface of the slab are different.

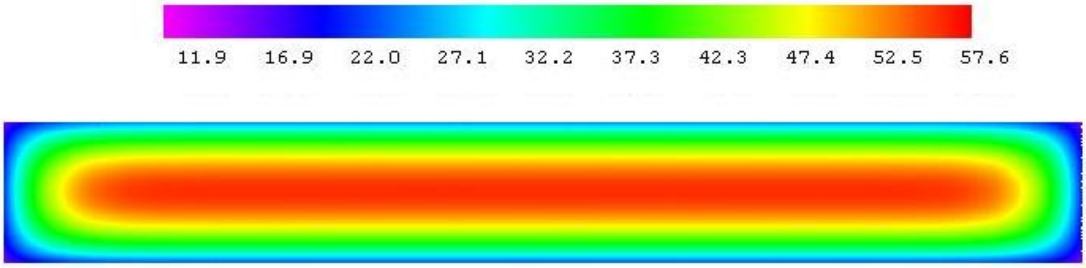

Figure 6. The temperature field on second day after pouring the concrete mixture (0C)

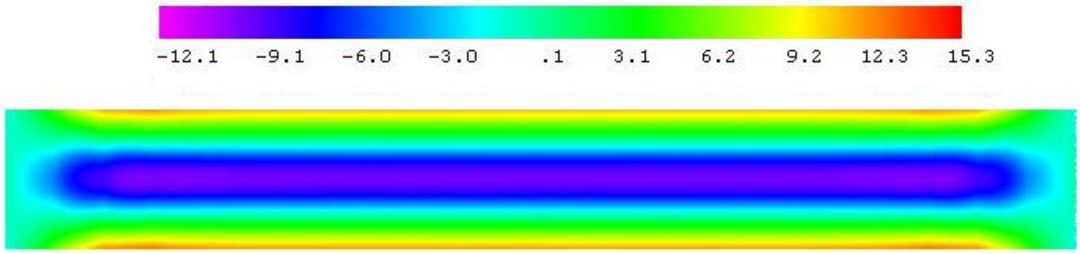

Figure 7. The stress field on second day after pouring the concrete mixture (kg/cm2)

The temperature field is non-uniform (2D problem). The diagrams of thermal stresses (X-axis) of the surface of the slab, according to the figure 7 decrease monotonously (they have maximum) – from the center of the slab to it's sides. As it shown on the Figure 9, in the cross-section of the slab there are 3 zones A, B, C. C – a new zone (mostly because zone B became shorter). C – is a zone of enhanced tensile stresses on the surface of the slab.

The length of zones along the X-axis equals to: zone B – 6.935 m, zone C – 2.152 m, zone A – 1.913 m. In relative units (relative to the length of the slab), respectively, 63 %, 19.6 % and 17.4 %.

Thermal stresses in zone C exceed stresses in zone B for first 3 days (when there are tensile stresses on the surface) from 7.63 % to 14.85 %

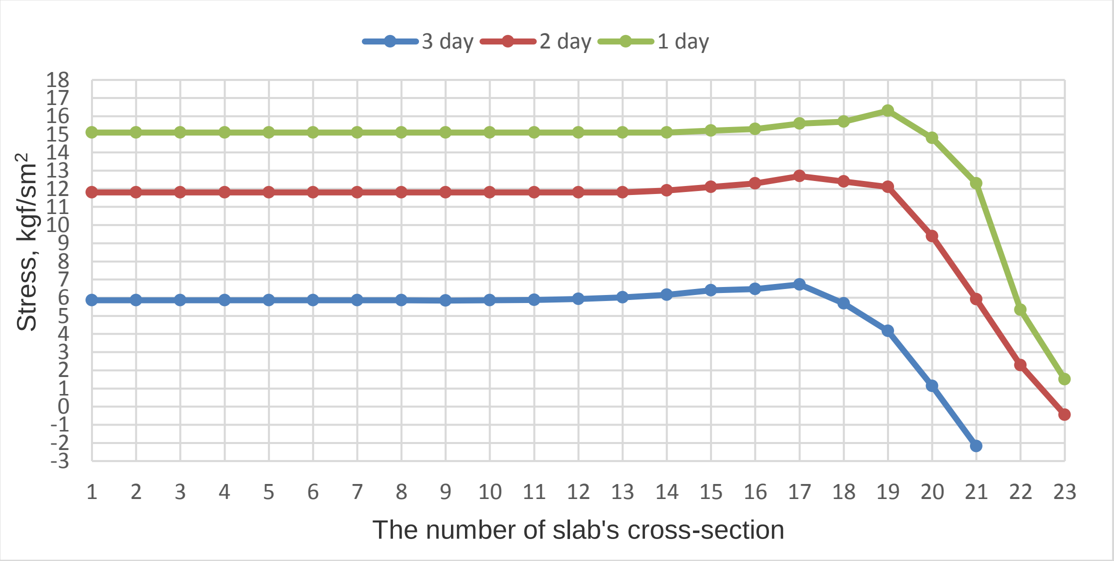

Figure 8. The diagrams of thermal stresses of the surface of the slab

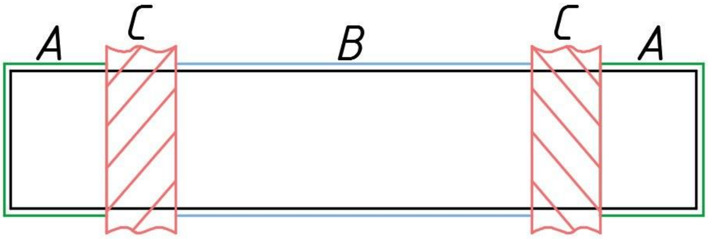

Figure 9. Zones of the slab

It is known that thicknesses of slabs which are used in industrial and civil constructions (especially in NPP and high-rise buildings) have range of 0.5-0.3 m. First and second numerical experiments were conducted for thicknesses 0.5-0.3 m and ratio $\frac{h}{l}$ was changing. There were 100 numerical experiments conducted.

For convenience the results of the experiments are represented in the table, part of which is listed below. The first and second columns are description of initial data for the experiment: the sizes of the cross-section and calculated ratio $\frac{\mathrm{h}}{\mathrm{l}}$. The third column is the number of days after the beginning of the experiment, when the mixture was poured. The fourth column is the length of zone B in percentage from the whole length. The fifth column the length of zone A, %. The sixth column is the maximal excess of thermal stress values in zone C above the values in zone B.

Table 1. The results of the numerical experiment

Slab's cross-section sizes h x l, м	$\frac{h}{l}$	Days	The length of zone B, %	The length of zone A, %	The maximal excess in zone C, %
1x3	0.33	1	19.2	46.2	8.7
		2	15.4	46.2	
1x4	0.25	1	38.2	44.7	9.4
		2	29.4	44.7	
1x5	0.2	1	50.0	38.1	7.0
		2	33.3	38.1	
1x6	0.17	1	56.0	32.0	7.0
		2	44.0	32.0	
1.5x4.5	0.33	1	26.3	42.1	7.2
		2	21.1	42.1	
1.5x6	0.25	1	36.0	36.0	8.5
		2	32.0	36.0	
1.5x7.5	0.2	1	51.6	25.8	7.9
		2	41.9	25.8	
1.5x9	0.17	1	56.8	21.6	8.5
		2	51.4	21.6	
2x6	0.33	1	28.0	36.0	9.3
		2	18.0	36.0	
2x8	0.25	1	42.4	30.3	9.2
		2	33.3	30.3	
2x10	0.2	1	53.7	21.9	9.2
		2	43.9	21.9	
2x12	0.17	1	59.2	19.4	9.2
		2	51.0	19.4	

Discussion

There is a limit for each structural model when it becomes impossible to use. The application of this research is that more accurate value of $\frac{\mathrm{h}}{\mathrm{l}}$ ratio was found and this ratio allows the use of one-dimensional structural models for calculations of massive concrete and reinforced concrete structures during the building period. In this research of the thermo-stressed state in massive foundation slabs with different planform dimension ratios the elaborated ratio $\frac{\mathrm{h}}{\mathrm{l}}$ was found allowing the use of one-dimensional structural model for the central part of the slab with a sufficient degree of accuracy when tension and temperature are functions of a single spatial coordinate – the vertical one: $T(z,\tau) = f(z)$; $\sigma(z,\tau) = f(z)$.

The transition to this model is valid for ratio $\frac{\mathrm{h}}{\mathrm{l}} < 0.17$. This value does not equal to the value that was used by other authors in articles [10–12, 14, 28–31]. They used the ratio in the range of $\frac{h}{l} \leq \frac{1}{3} \dots \frac{1}{4}$.

The elaborated ratio $\frac{\mathrm{h}}{\mathrm{l}}$ decreases the number of observational errors in calculations. It also diminishes the calculation time and intensity. This ratio can be used to solve the wide range of problems that arise in modern practice during the erection of massive concrete structures.

Conclusions

The results of the conducted experiments allow us to make following conclusions:

1. Generally, one-dimensional structural model is suitable in cases when ratio $\frac{h}{l} < 0.17$, h stands for the minimal plane dimension in a construction such as slab;

2. The calculation results of thermo-stressed state with use of one-dimensional structural model should be used carefully in assessment of crack resistance of building blocks. This research indicates the existence of zones near the sides of slabs, where values of the tensile stress exceed the values that were obtained with use of one-dimensional structural model. This excess may account for 9.5 %;

3. In a real practice, ratio $\frac{h}{l}$ should be found individually, since intensity and amount of the heat dissipation significantly depend on exothermic characteristics of applicable cement and the amount of cement in the concrete mixture. Listed calculation results are based on constant concrete composition. The amount of cement and it’s characteristics are averaged. There is also an influence on $\frac{h}{l}$ from β_{red} of the sides of the slabs and there are different unaccounted factors.

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