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Methodology for determining true temperature stresses during the construction of massive monolithic reinforced concrete structures

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Abstract. The purpose of the article is to develop and test a simplified method for calculating temperature stresses during the construction of massive monolithic reinforced concrete structures. The essence of the method is to calculate the stress-strain state in standard FEM complexes (ANSYS, Abaqus , etc.) with constant physical and mechanical characteristics of concrete over time, followed by recalculation to true stresses, taking into account the dependence of the elastic modulus of concrete over time. The methodology is based on the hypothesis of equality of temperature deformations for structures with a constant and time-varying modulus of elasticity of concrete. The developed methodology was tested on experimental data for a massive monolithic foundation slab. The calculation at a constant modulus of elasticity of concrete was carried out in the ANSYS software package. Conversion to true stresses was implemented by the authors in the MATLAB environment. A good agreement between the calculated stress values and the experimental values was obtained.
Keywords: massive reinforced concrete structures, foundation slab, finite element method, temperature stresses, early cracking

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1. INTRODUCTION

Currently, the main method for calculating temperature stresses during the construction of massive monolithic reinforced concrete structures is the finite element method (FEM) [1-3]. The solution to this problem, as a rule, is carried out in a non-coupled formulation: the first stage is the calculation of temperature fields, and then, based on data on temperatures in the nodes at calculated times, the temperature stresses are determined [4-6]. A large number of works are devoted to the calculation of temperature fields during the construction of massive monolithic structures using the finite element method, including [7-9], etc. As a rule, ready-made software products are used for calculations, such as ANSYS [7], Abaqus [8], Midas Civil [9], etc. In these complexes, by default, it is impossible to

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take into account the change in the thermophysical characteristics of concrete (thermal conductivity coefficient, specific heat capacity) during the hardening process. Some authors create their own software products to solve this problem [10]. It was shown in [11] that taking into account the time dependence of the thermophysical characteristics of concrete leads to an insignificant change in temperature fields. Thus, existing software packages quite reliably predict the temperature distribution in the volume of a hardening massive structure.

In addition to changes in thermophysical characteristics, during the hardening process of concrete there is a change in its physical and mechanical parameters (elastic modulus, strength) [12-14]. Calculations with constant physical and mechanical characteristics in standard FEM complexes lead to results that differ from the real picture not only quantitatively, but also qualitatively [15]. In the ANSYS and Abaqus software packages , this problem is partially solved by creating custom material models [16-18], however, the possibilities for modifying existing software products are very limited. This article proposes a method for converting temperature stresses obtained in FEM software systems with constant concrete characteristics to true ones, taking into account the dependence of the elastic modulus of concrete on time and hardening temperature.

2. METHODS AND MATERIALS

The methodology is based on the hypothesis that the increments of total concrete deformations are equal for foundation slabs with a constant and time-varying modulus of elasticity of concrete. Since total deformations represent the sum of elastic and temperature deformations, the equality of total deformations also implies the equality of elastic deformations. Let us denote by σ_i stresses at moments of time t_i calculated in a standard software package without taking into account the change in the elastic modulus of concrete over time (at $E(t) = E_0 = const$). The voltage recalculation algorithm is as follows:

1. Stresses increments are calculated at $E(t) = const$ for each step by the time:

$$\Delta\sigma_i = \sigma_{i+1} - \sigma_i . \quad (1)$$

2. The increments of elastic deformations are determined:

$$\Delta\varepsilon_i = \Delta\sigma_i / E_0 . \quad (2)$$

3. The increments of true stresses are calculated:

$$\Delta\sigma_i^{real} = E_i \Delta\varepsilon_i , \quad (3)$$

where E_i is the elastic modulus of concrete at time t_i .

4. At the initial moment of time $\sigma_0^{real} = 0$. At subsequent times, the true stresses are determined by the recurrent formula:

$$\sigma_{i+1}^{real} = \sigma_i^{real} + \Delta\sigma_i^{real} . \quad (4)$$

The proposed method was tested using the results presented in [19]. This work presents the results of a full-scale experiment, as well as numerical modeling in the DIANA FEA software package. A foundation slab is considered with a thickness of 2.1 m, dimensions in plan 26.5 × 41.5 m, located on a soil foundation. The thickness of the subgrade in the finite element analysis was taken equal to 10 m. The heat transfer coefficient on the upper surface of the foundation slab is h = 30 W/(m ^{2} · °C), the initial temperature of the concrete mixture *is* T_0 = 24 °C, the temperature of the soil mass on the lower and side surfaces *is* T_g = 16 °C. The graph of changes in ambient temperature is shown in Fig. 1. Density of concrete ρ_b = 2349 kg/m ^{3}, soil density ρ_g = 2070 kg/m ^{3} , coefficient of thermal conductivity of concrete λ_b = 2.67 W/(m · °C), coefficient of thermal conductivity of soil λ_g = 1.4 W/(m · °C), specific heat capacity of concrete c_b = 1000 J/(kg · °C), specific heat capacity of the soil c_g = 1039 J/(kg · °C).

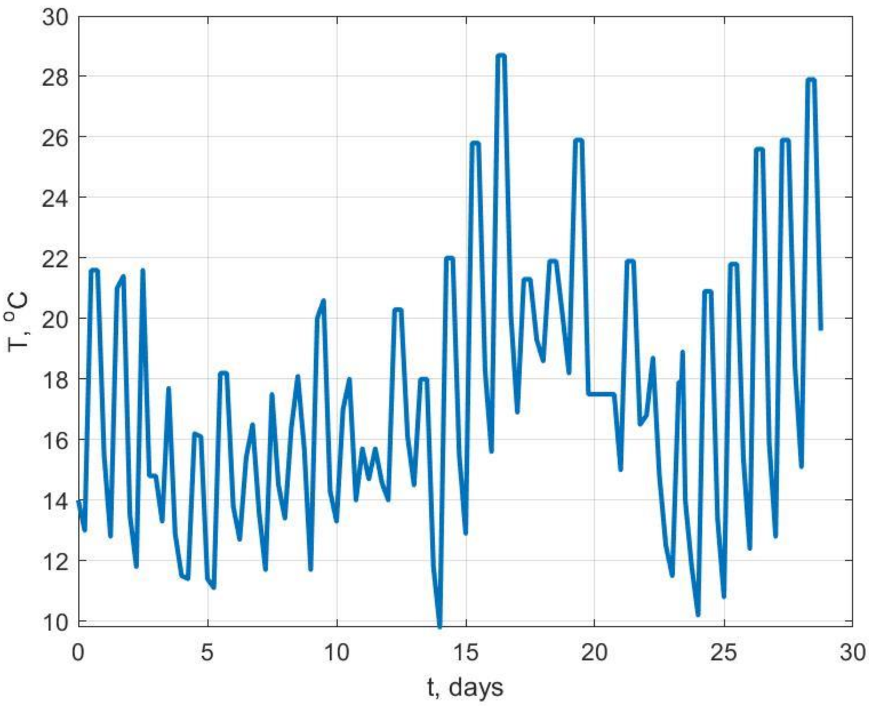

Fig. 1. Change in ambient temperature over time.

The coefficient of linear thermal expansion of concrete in [19] was taken equal to 1.2·10 $^{-5}$ 1/ °C, the coefficient of linear thermal expansion of soil was taken 1·10 $^{-5}$ 1/ °C. Poisson's ratios of concrete and soil were assumed to be the same and equal to 0.2. Modulus of elasticity of the soil E_g = 30 MPa. The dependence of the elastic modulus of concrete on time in [19] was determined by the expression:

$$E(t) = E(t_{eq}) = \alpha_1 e^{-\left(\frac{\tau_1}{t_{eq}}\right)^{\beta_1}} + \alpha_2 e^{-\left(\frac{\tau_2}{t_{eq}}\right)^{\beta_2}}, \quad (5)$$

Where α_1 = 15 GPa, α_2 = 20 GPa, τ_1 = 2 days, τ_2 = 4 days, $\beta_1 = \beta_2 = 1.5$, t_{eq} is the equivalent age of concrete, determined by the integral:

$$t_{eq} = \int_0^t e^{-\frac{E_a}{R}\left(\frac{1}{T(\tau)} - \frac{1}{T_{ref}}\right)} d\tau, \quad (6)$$

where $T(\tau)$ is the temperature of the concrete at the moment τ in Kelvin, T_{ref} = 293 K, $R = 8.314$ J/(mol ·K) is the universal gas constant, $E_a = 38500$ J/mol is the activation energy.

Temperature stresses were calculated in the ANSYS software package with a constant modulus of elasticity of concrete $E_0 = 10^4$ MPa over time, followed by conversion to true stresses using formulas (1)-(4), as well as the dependence of the modulus of elasticity of concrete on time (5).

As in [19], a quarter of the structure was considered; the finite element mesh is shown in Fig. 2. The soil mass extended beyond the foundation on each side by 4 m. The foundation slab together with the soil mass was divided into 20-node finite elements in the form of SOLID 186 parallelepipeds. To analyze the sensitivity of the mesh, the calculation was performed in three variants: when the slab was divided by thickness into 3, 7 and 14 finite elements (Fig. 2). The time interval under study ranged from 0 to 690 hours, the number of time steps was taken to be 400. The time interval was divided uniformly.

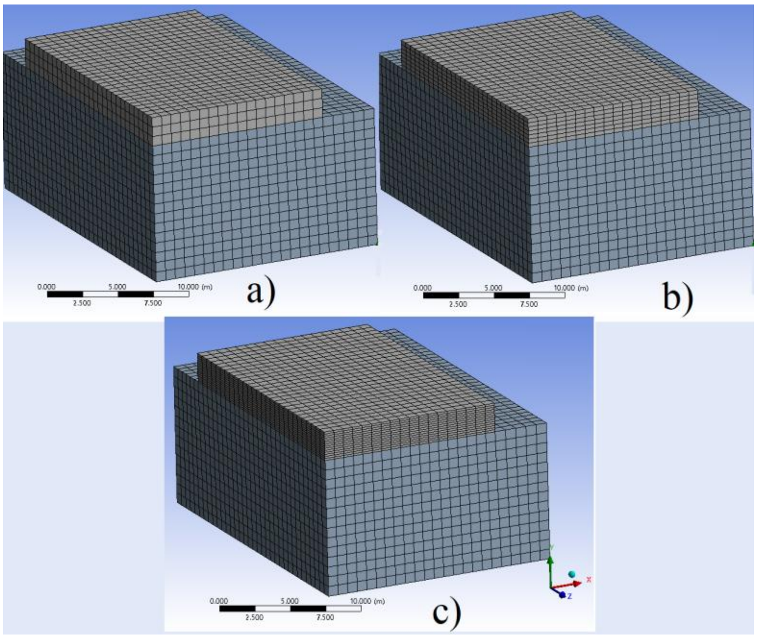

Fig. 2. Accepted finite element mesh: a) division of the slab by thickness into 3 FEs, b) division of the slab by thickness into 7 FEs, c) division of the slab by thickness into 14 FEs.

Since in [19] there was not enough data on the heat release of concrete to accurately reproduce the results of calculating the temperature field, the parameters of the heat release function were selected for maximum agreement with the results of a full-scale experiment. The heat release function was taken in the form [20]:

$$Q(t) = Q_{28} \cdot \exp\left[k \cdot \left(1 - \left(\frac{28}{t}\right)^x\right)\right], \tag{7}$$

where t is the time in days, Q_{28} is the amount of heat released during the first 28 days of hardening, MJ/m ^{3}, the coefficients k and x determine the kinetics of concrete hardening.

The problem of finding a heat release curve was posed as a nonlinear optimization problem. An objective function was written in MATLAB, the input parameters of which were the quantities Q_{28} k, x. The objective function calculated the temperature field using the finite element method in a one-dimensional formulation according to the method given in [21], and returned the sum of the squared deviations of the experimental temperature values from the calculated values for two points in the center of the foundation slab: in the middle of the thickness and on the lower surface. The minimum of the objective function was found using the interior point method [22, 23] implemented in the Optimization Toolbox package.

3. RESULTS AND DISCUSSION

The values $Q_{28} = 51.7$ MJ/m ^{3}, $k = 1.62 \cdot 10^{-5}$, $x = 3.76$ were obtained as a result of searching the parameters of heat release function. Next, using these parameters, the temperature field was calculated in a three-dimensional formulation using the ANSYS software package . Figure 3 shows the experimental curves of temperature changes over time in the middle of the slab thickness and at the lower surface, as well as the calculation results. The match is quite good.

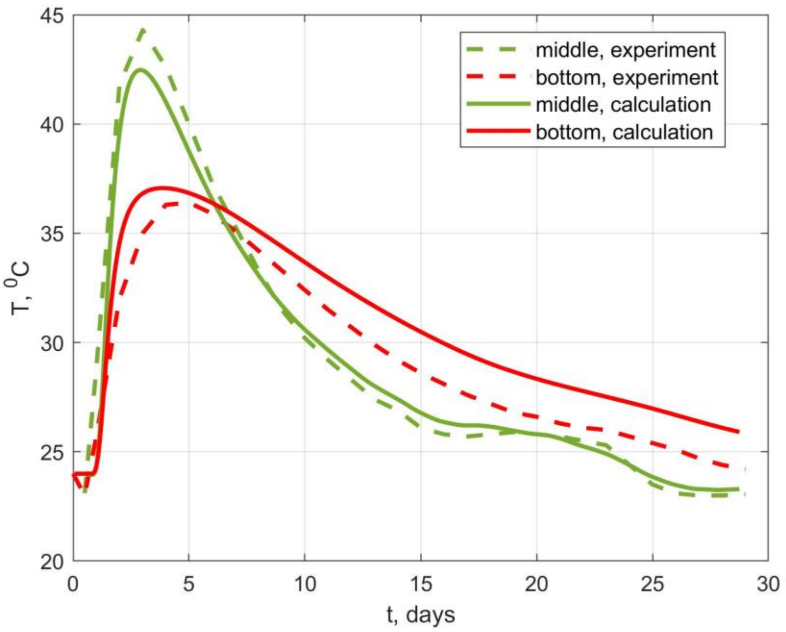

Fig. 3. Comparison of experimental and calculated curves of temperature change over time.

Fig. 4 shows graphs of changes in normal stresses σ_x in the center of the foundation slab in the middle of the thickness, calculated in ANSYS with a constant modulus of elasticity of concrete over time $E(t) = E_0 = 10^4$ MPa $= const$ for a different number of finite elements along the thickness of the slab *n*. From Fig. 4 it can be seen that with *n* = 7 and *n* = 14 there is no noticeable difference in the results; dividing into 7 finite elements by thickness is quite sufficient to obtain reliable results. Also Fig. 4 shows that the deformation process at $E(t) = const$ is completely reversible: the stresses at the beginning and at the end of the process are close to zero.

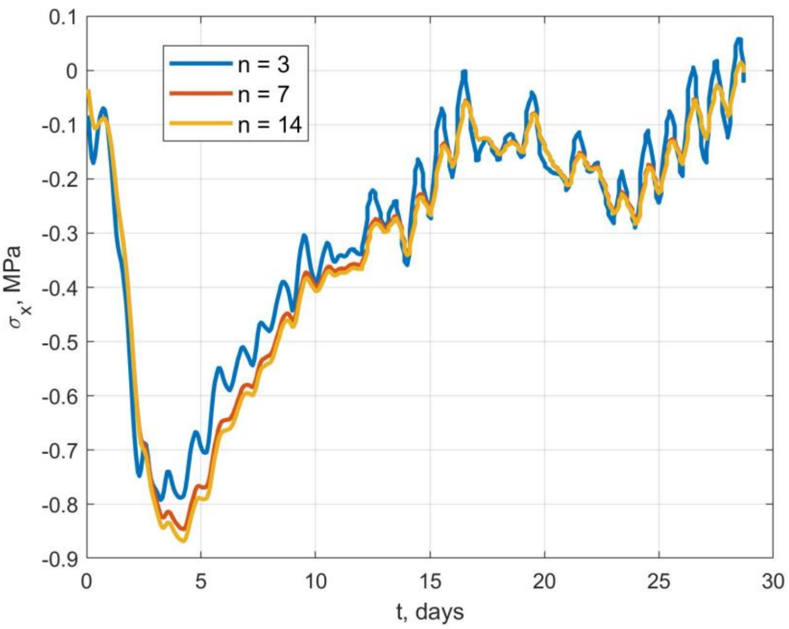

Fig. 4. Change in time of stresses σ_x in the center of the foundation slab in the middle of the thickness at $E(t) = E_0 = const$.

Fig. 5 shows the dependence of the modulus of elasticity of concrete on time in the center of the foundation slab in the middle of the thickness, obtained based on the results of calculating the temperature field, as well as formulas (5)- (6).

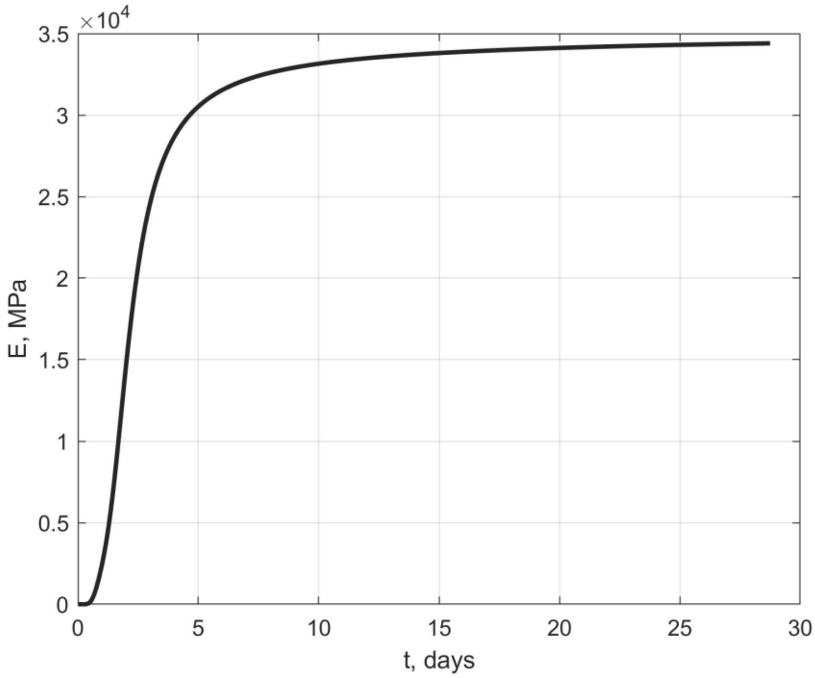

Fig. 5. Dependence of the modulus of elasticity of concrete on time in the center of the foundation slab in the middle of the thickness.

In Fig. 6, the red line shows the experimental stresses values at the same point. The orange line shows the calculation results given in [19]. The blue line shows the stress values calculated using the method proposed in this article by correcting the stresses shown in Fig. 4, according to formulas (1)-(5). Also, the green dashed line in this graph shows the calculation results using the simplified method given in [11], in a one-dimensional formulation.

From Fig. 6 it can be seen that the results given in [19], in comparison with the author's methodology and the methodology [11], are in worst agreement with experimental data: from the moment of 10 days, tensile stresses in concrete turn out to be greatly overestimated. The results obtained using the author's method and the method given in [11] are quite close to each other, especially from the time point of 15 days, which indicates the possibility of calculating foundation slabs in a simplified one-dimensional formulation.

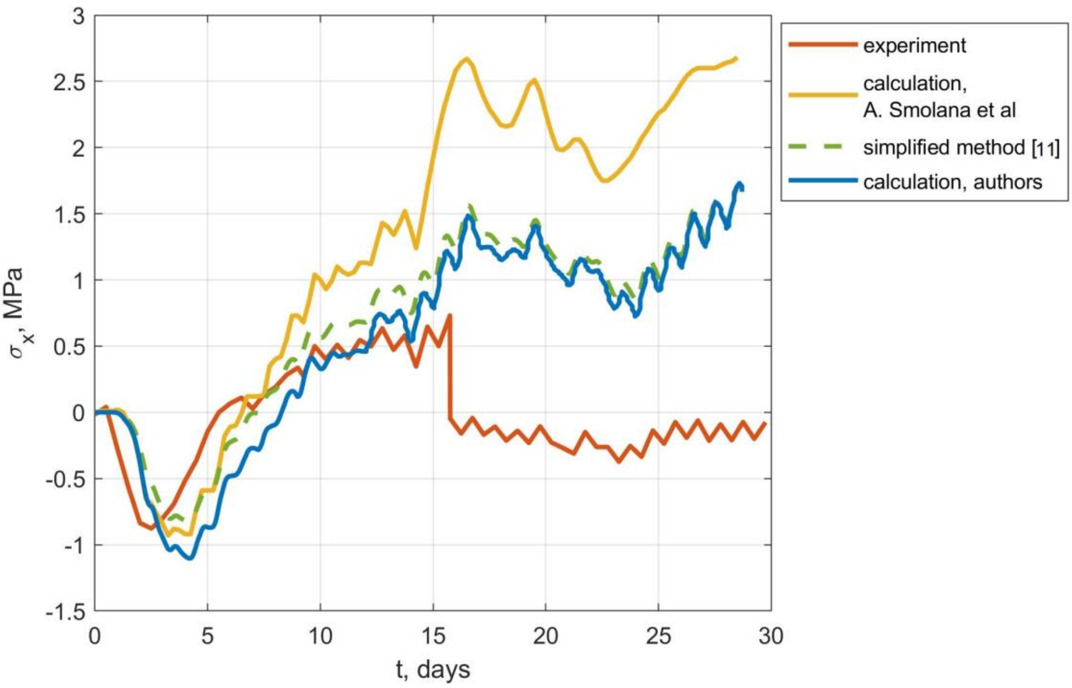

Fig. 6. Change in time of stresses in the center of the foundation slab in the middle of the thickness.

It should be noted that at time $t = 16$ days, a jump to almost zero is observed in the experimental curve, which can be explained either by sensor failure or the formation of a crack.

The deviation of the calculation results using the author's method from the experimental results can be explained, firstly, by the fact that despite the selection of the parameters of the heat release function, it was not possible to achieve absolute agreement between the calculated temperatures and the experimental ones. Secondly, the results shown in Fig. 6, were obtained with a coefficient of linear thermal expansion of concrete of $\alpha = 12 \cdot 10^{-6}$ 1/ °C. For different concrete compositions, the coefficient of linear thermal expansion varies from 5.4 to $14.4 \cdot 10^{-6}$ 1/ °C [24]. The value most often used in calculations is 10^{-5} 1/ °C. Also debatable is the question of what is considered the starting point when determining stresses, from what point can concrete be considered a solid body.

Fig. 7 shows a graph of the change in stress over time in the center of the foundation slab, obtained as a result of calculation using the author’s method at $\alpha = 10^{-5}$ 1/ °C. An experimental curve is superimposed on it with the reference point shifted by 1 hour to the right. In this case, the agreement between the results is much better than in Fig. 6.

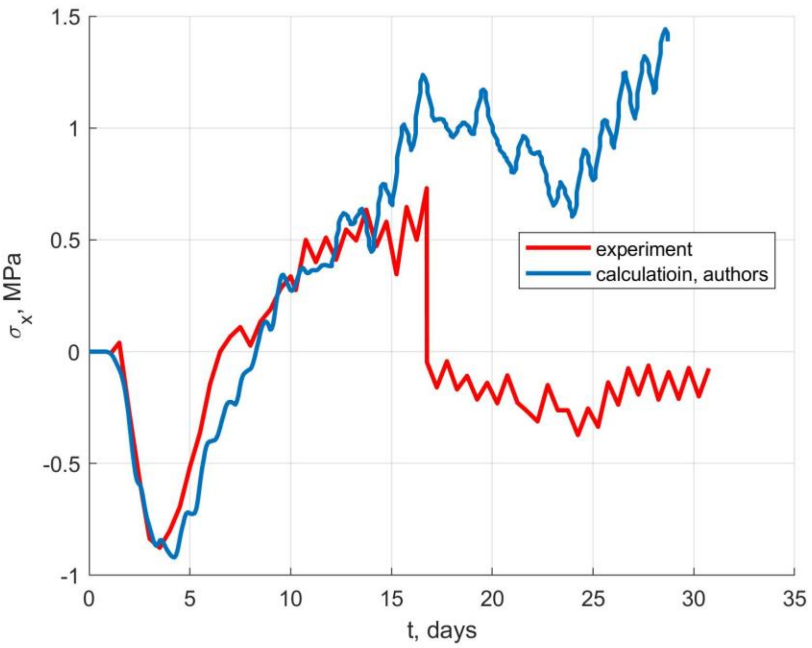

Fig. 7. Comparison of experimental results with calculation results using the author’s method.

Other factors that could influence the calculation result in some degree include the discrepancy between the actual curve of the elastic modulus of concrete versus time and the curve presented in Fig. 5, the presence of shrinkage and creep of concrete. Our further research will be devoted to the analysis of these factors.

4. CONCLUSIONS

1. A simple methodology is proposed for converting temperature stresses during the construction of massive monolithic structures, calculated in standard software systems with a constant modulus of elasticity of concrete, into true stresses, taking into account the dependence of the modulus of elasticity of concrete on time.
2. The developed methodology was tested on experimental data for a massive monolithic foundation slab located on a soil foundation, as well as a comparison with the calculation results of other authors. It is shown that the developed method, in comparison with the results of other authors, provides better agreement with experimental data.
3. It has been established that the resulting temperature stress curve is significantly influenced by the value of the coefficient of linear thermal expansion, as well as the point in time from which concrete can be considered a solid body and stresses can be measured.

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