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Thermal cracking resistance in massive steel-reinforced concrete structures

Термическая трещиностойкость массивных сталежелезобетонных конструкций

A.V. Bushmanova,
D.K. Kharchenko,
K.S. Semenov,
Yu.G. Barabanshchikov,
V.K. Korovina,
A.V. Dernakova,
Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia

Студент А.В. Бушманова,
студент Д.К. Харченко,
канд. техн. наук, доцент К.В. Семенов,
д-р техн. наук, профессор Ю.Г. Барабанщиков,
студент В.К. Коровина,
студент А.В. Дернакова,
Санкт-Петербургский политехнический университет Петра Великого, Санкт-Петербург, Россия

Key words: steel-reinforced concrete; stressed state; cracking resistance; analytic model; construction period

Ключевые слова: сталежелезобетонные конструкции; термонапряженное состояние; термическая трещиностойкость; расчетная схема; строительный период

Abstract. The work is dedicated to research of the thermal crack resistance in massive steel-reinforced concrete structures in construction period. The article examines the results of the analysis of the thermal stress state, which occurs in massive steel-reinforced concrete column. The steel part of the column is represented by a system of cross UC-beams. The study was conducted with using analytical models, which include the factor of steel profiles availability in comparison with simplified methods. Authors established that calculations of thermal stresses state of massive steel-reinforced concrete structures in construction period should be carried out with using analytical models, which assumed accounting of the availability steel profiles in cross-section of the column. Structure heating and tension stresses are significantly lower in this case. With all characteristics averaged, maximum tension stresses are less than real by 50.9% and thickness of the thermal insulation is less than required 5 times. Was defined, that calculations of thermal crack resistance in construction period of steel-reinforced concrete structures by simplified analytical model (which assume absence of steel profiles in cross-section of the column) lead to significant errors.

Аннотация. Работа посвящена исследованию термической трещиностойкости массивных сталежелезобетонных конструкций в строительный период. В статье рассматриваются результаты анализа термонапряженного состояния массивной сталежелезобетонной колонны, стальная часть которой представлена системой перекрестных двутавров. Исследование проводилось с использованием расчетной схемы, предполагающей учет наличия в поперечном сечении стальных профилей, а также по упрощенным методикам. Авторами установлено, что расчеты термонапряженного состояния массивных сталежелезобетонных конструкций в строительный период следует проводить с использованием расчетных схем, предполагающих учет наличия в поперечном сечении стальных профилей: разогрев конструкции и растягивающие напряжения существенно меньше. Показано, что при осреднении всех характеристик максимальные растягивающие напряжения меньше реальных на 50.9 %, а толщина теплоизоляции меньше реально требуемой в 5 раз. Определено, что упрощенная расчетная схема (предполагающая отсутствие стальных профилей в поперечном сечении) также приводит к существенным погрешностям.

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1. Introduction

Most of massive steel-reinforced concrete structures are made of rigid steel profiles placed inside of reinforced concrete part of the structure [1–3]. Such kinds of structures are usually used for designing massive beam system, columns, and pillars. During the construction period, massive concrete and reinforced concrete structures may suffer from hard cracking [4–10]. In general, the cause of this phenomenon should be called irregular temperature fields at the body of the structure [11–17]. These fields generate significant tensile surface thermal stresses [18–26].

Many researches are devoted to the analysis of possible methods of steel and concrete calculations: definition of the analytical model [27–31]; estimation of different affects, such as concreting conditions, characteristics of materials, application of various technologies [32–36]; etc.

According to the paper [27], material modeling plays a major role in how reinforced concrete beams and frames react to temperature variation. Hence, the nonlinear temperature gradient, which is the realistic profile, is important to implement in the analysis.

In the paper [29], the ultimate strength behavior of the RC beams under different low temperatures is investigated by the methods of experiment, analysis and evaluation. The accuracies of the analytical models and FEM simulations were checked through validations of the predictions by different models against the test results.

In the article [35], a fibre beam element is perceived as a degenerated solid element, and for the last an unified concrete constitutive model is proposed. Beam/column members with a wide range of shear span-to-depth ratios can be simulated with the degenerated solid element considering normal-shear interaction.

Structural calculation methods involve usage of structural models made with certain simplifications that greatly facilitate the calculation. Calculation with a wrong structural model cannot be valid qualitative.

For the foregoing reasons, the vital task is to estimate the necessity of steel elements' presence in structure's cross-section model for the construction period. Since the presence or absence of steel elements in calculation of thermal crack resistance may cause a significant distortion of the real thermal stresses diagram while calculation with an incorrectly chosen structural model cannot be valid qualitative, even when using the most accurate methods.

The purpose of article is to estimate the necessity of steel elements' presence in structure's cross-section calculations of thermal crack resistance in massive steel-reinforced concrete structures for the construction period. These calculations are partly carried out by simplified method. It is important to identify possible mistakes in this approach to calculation.

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.

2. Methods and Materials

This paper demonstrates calculation of stressed state with the help of TERM software developed by the Institute of Civil Engineering at the Peter the Great St.Petersburg Polytechnic University [23]. This software calculates nonstationary fields of temperature and thermal stresses in slabs.

In order to estimate the cracking resistance of the concrete column, we would use the deformation criterion suggested by P.I. Vasiliev [26]. According to this criterion, concrete elongation deformations, determined in view of the concrete creep factor and variable deformation modulus, should not exceed the ultimate concrete elongation.

The article examines the results of the analysis of the thermal stress state in construction period, which occurs in massive steel-reinforced concrete column (Figure 1) with dimension in cross-section 1500 x 1500mm. The steel part of the column is represented by a system of cross-UC beams.

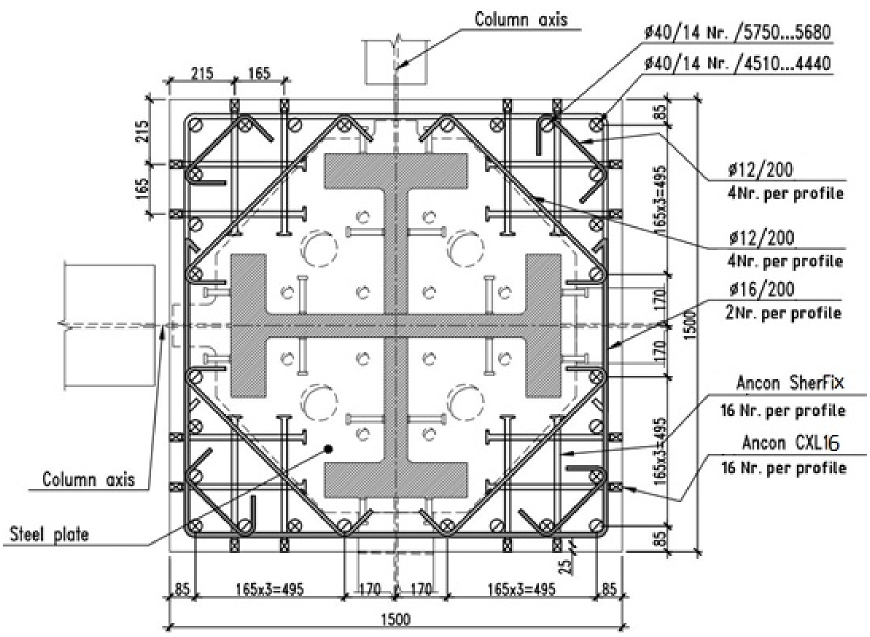

Figure 1. The steel-reinforced concrete column

The research was carried out in three principal analytical models:

- The first analytical model implied a simplified approach, which means it did not take into account the presence of metal profiles in cross-section of the column. The entire cross-section of the column should be considered to consist of concrete. The calculations are made for the cross-section quarter (the symmetry of the section along the horizontal and vertical axes is used).
- The second analytical model implied accurate estimation of the availability of the steel profiles – UC-beams. The calculations are made for the cross-section quarter (Figure 2) (the symmetry of the section along the horizontal and vertical axes is used).

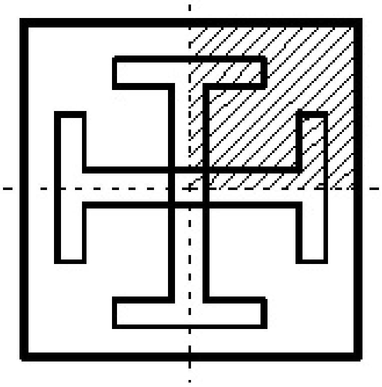

Figure 2. Analytical model

– The third analytical model implied averaging of material characteristics within the limits of the column cross-section and subsequent use of simplified model with homogeneous medium.

Consider B80 steel-reinforced concrete column the cement consumption of 450 kg/m^3 constructed in summer. Thermal and physical characteristics of the concrete B80 are defined by the concrete thermal conductivity λ =2.67 W/(m·^{0}C) and thermal capacity c = 1.0 kJ/(kg·^{0}C). For modulus of concrete deformation E_{max} = 45000 kg/cm^2, α = –0.37, γ = 0.72 [22]. Thermal and physical characteristics of the steel are defined by the steel thermal conductivity λ =45 W/(m·^{0}C) and thermal capacity c = 0.48 kJ/(kg·^{0}C). The reinforcing steel is assumed to be elastic-perfectly plastic material in both tension and compression with elasticity modulus E = 2×10^5 MPa and Poisson’s ratio equal to 0.2.

The heat dissipation process follows the I.D. Zaporozhets equation [12].

$$Q_T(\tau) = Q_{max}\left\{1 - \left[1 + A_{20}\int_0^t F_Q[T(\tau)d\tau]\right]\right\}^{-\frac{1}{m-1}} \qquad (1)$$

The equation parameters I.D. Zaporozhets gets from experimental evidence on concrete heat dissipation [20] $Q_{max} = 157500$ kJ/m^3, $A_{20} = 1.97 \times 10^{-6}$ c^{-1}.

The following technological specifications of concrete pouring were taken into account: the concrete mix temperature is 15 ^{0}C and air temperature is 15 ^{0}C. Primary there was no thermal insulation on the surface of the column. Then the required thickness of thermal insulation was selected to provide crack resistance.

3. Results and Discussion

3.1. Results of applying the first analytical model

Temperature fields and stress direction fields in cross-section of the column are mentioned below. Moreover, the analysis of possible cracking pattern for the most dangerous moments has been conducted. The maximum of the column tension surface stresses occurs at the first day after concreting. This stresses are equal 23.8 kg/cm^2. Temperature maximum in the cross-section at the first day was 57.1 ^{0}C.

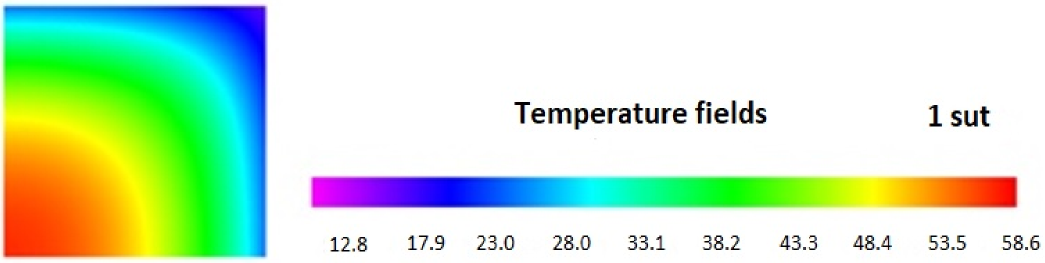

Figure 3. Thermal fields in section of the column at the first day

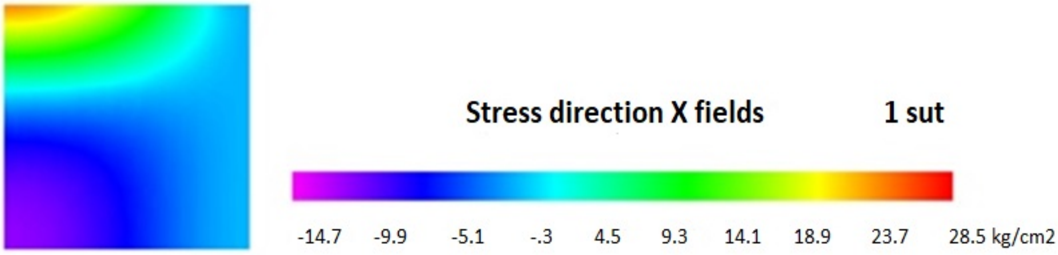

Figure 4. Stress direction fields in section of the column at the first day

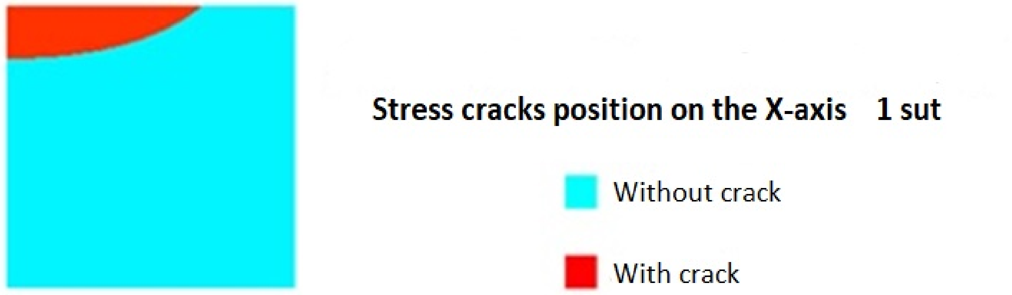

Figure 5. Stress cracks position at the first day

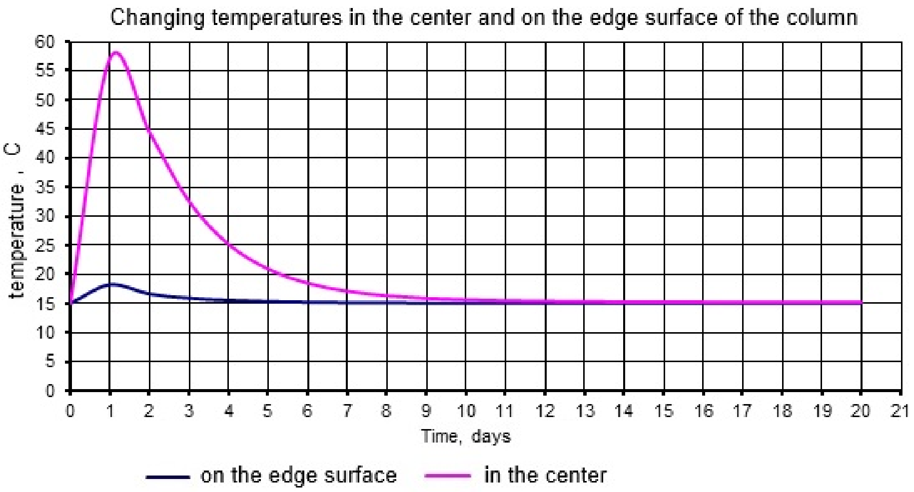

Figure 6. Graphs of changing temperatures in section of the column

To provide full crack resistance of the column during construction period a covering of surfaces with special thermal insulation requires β_{red} = 3.24 W/m^{2}·^{0}C (β_{red} match to the thermal insulation thickness 8 mm, using thermal insulation with λ = 0.03 W/m·^{0}C).

3.2. Results of applying the second analytical model

The maximum of the column tension surface stresses occurs at the first day after concreting. This stresses are equal σ = 17.2 kg/cm^{2}. Temperature maximum in the cross-section at the first day was 40.2 ^{0}C.

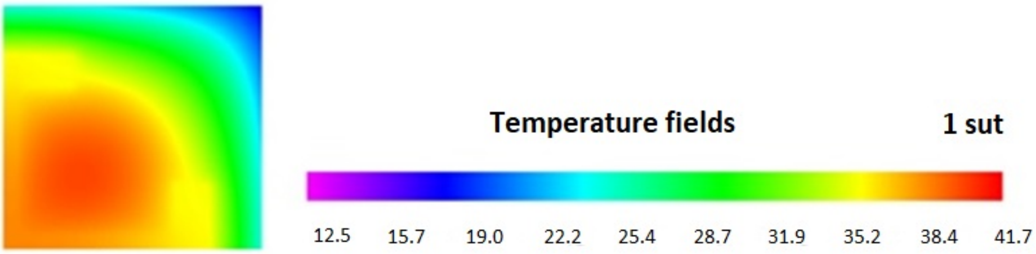

Figure 7. Thermal fields in section of the column at the first day

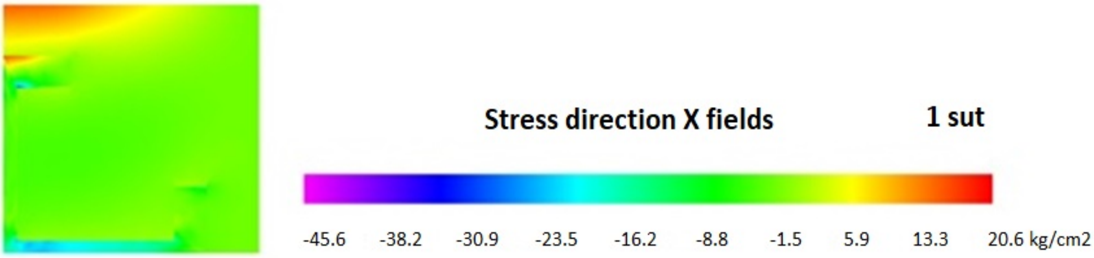

Figure 8. Stress direction fields in section of the column at the first day

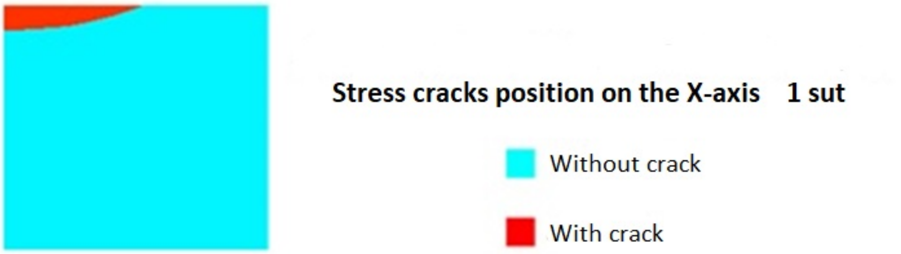

Figure 9. Stress cracks position at the first day

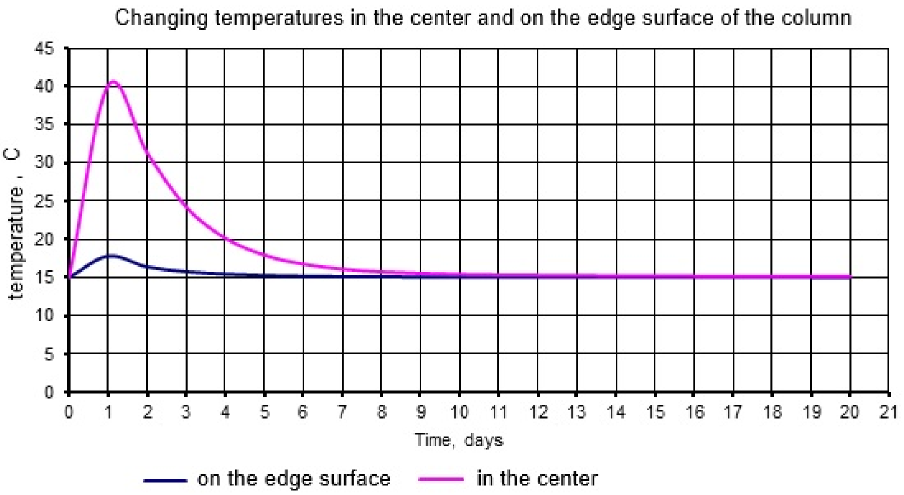

Figure 10. Graphs of changing temperatures in section of the column

To provide full crack resistance of the column in construction period, a covering of surfaces with special thermal insulation requires β_{red} = 4.92 W/m$^{2}\cdot{}^{0}$C (β_{red} match to the thermal insulation thickness 5 mm using thermal insulation with λ = 0.03 W/m$\cdot{}^{0}$C).

3.3. Results of applying the third analytical model

When all thermophysical characteristics of steel and concrete have been averaged, the maximum of the column tension surface stresses at the first day after concreting were equal σ = 11.4 kg/cm^{2}. Temperature maximum in the cross-section at the first day was equal 41.5^{0}C. Required thickness of the thermal insulation was 1 mm (β_{red} = 13.2 W/m$^{2}\cdot{}^{0}$C).

If the characteristics of heat release of materials were averaged, then maximum tension surface stresses of the column would occur at the first day after concreting and would be equal σ = 21.0 kg/cm^{2}. Maximum temperature in the cross-section at the first day was equal 53.7 ^{0}C. Required thickness of the thermal insulation was 7 mm (β_{red} = 3.7 W/m$^{2}\cdot{}^{0}$C).

3.4. Discussion

Thus, according to the paper [27, 28] it is important to possess knowledge of aspects having the greatest influence on data calculated while researching the thermal cracking resistance of massive concrete and reinforced structures. Calculation with an incorrectly chosen structural model or calculation implying a simplified approach could not be valid qualitative [30–32, 35, 36]. According to studies, those calculations of thermal stresses state of the massive steel-reinforced concrete structures in construction period by analytical models, which include the factor of steel profiles availability, are more appropriate and accurate in comparison with simplified methods.

4. Conclusion

The results of the experiments conducted lead us to the following conclusions:

1. The calculations of thermal crack resistance in construction period of steel-reinforced concrete structures by simplified analytical model (which assume absence of steel profiles in cross-section of the column) lead to significant errors. In comparison with the real situation (the second analytical model), maximum tension stresses from the simplified case more on 27.7 %. Required thickness of the thermal insulation is too high, which means that the first analytical model is economically unreasonable.

2. Averaging of thermophysical characteristics of steel and concrete in cross-section of the column also does not bring a satisfactory result. With all characteristics averaged, maximum tension stresses are less then real by 50.9% and thickness of the thermal insulation is less than required 5 times. Consequently, the calculation by this model may lead to the appointment of an incorrect stowage technique and cracking with subsequent full or partial destruction of the structure. When we are only averaging heat release characteristic, like in the first case, stresses rise and required thickness is too high.

3. The calculations of thermal stresses state of massive steel-reinforced concrete structures in construction period should be carried out with using analytical models, which assumed accounting of the

availability steel profiles in cross-section of the column. Structure heating and tension stresses are significantly lower in this case. This calculation should be called the most effective, economically feasible and structurally accurate.

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Aleksandra Bushmanova,
+7(981)822-34-63; nicealexa@mail.ru

Daria Kharchenko,
+7(952)242-65-44; dashulity@gmail.com

Kirill Semenov,
+7(921)781-19-57; kvsemenov@bk.ru

Yuriy Barabanshchikov,
+7(812)534-12-86; ugb@mail.ru

Victoria Korovina,
+7(911)785-54-29; vika9696@inbox.ru

Aleksandra Dernakova,
+7(911)774-90-23; sasha231296@mail.ru

Александра Васильевна Бушманова,
+7(981)822-34-63; эл. почта: nicealexa@mail.ru

Дарья Константиновна Харченко,
+7(952)242-65-44;
эл. почта: dashulity@gmail.com

Кирилл Владимирович Семенов,
+7(921)781-19-57; эл. почта: kvsemenov@bk.ru

Юрий Германович Барабанщиков,
+7(812)534-12-86; эл. почта: ugb@mail.ru

Виктория Константиновна Коровина,
+7(911)785-54-29; эл. почта: vika9696@inbox.ru

Александра Вячеславовна Дернакова,
+7(911)774-90-23;
эл. почта: sasha231296@mail.ru

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