sciendo

Production Engineering Archives 2022, 28(2), 123-131

PRODUCTION ENGINEERING ARCHIVES

ISSN 2353-5156 (print)
ISSN 2353-7779 (online)

Exist since 4th quarter 2013
Available online at https://pea-journal.eu

Influence of the heat insulation layer on the thermally stressed condition of the facade wall

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Article history
Received 08.09.2021
Accepted 28.12.2021
Available online 23.05.2022

Keywords
temperature stress
concrete facade wall
heating system
numerical modeling
heat-insulating layer

Abstract
The temperature-stress state of the concrete facade wall with a window opening, which is the external enclosing structure of the room with a steel heating device, was investigated by the method of numerical modeling. Estimated studies were performed for winter period when the heating system of the building is functioning. According to the results of solving the system of equations of thermal stress and equation of thermal conductivity, the temperature distribution over the wall volume and distribution of normal and tangential stresses were determined. Areas of the wall where these stresses are maximum were identified. The research was performed for cases of both, absence and presence of a heat-insulating layer on the outer surface of the facade wall. From comparison of the results obtained for these two options, it follows that the external thermal insulation coating not only helps to reduce dissipative heat loss through the facade wall, but also reduces the absolute values of stresses in the concrete wall arising resulting from temperature deformations. In some cases, the sign of stresses changes from stretching (wall without external insulation) to compressive (wall with insulation).

DOI: 10.30657/pea.2022.28.14

JEL: L69, M11

1. Introduction

During the operation of the building mechanical stresses in its wall structures are constantly present, as the facades of buildings are under constant aggressive influence of the external environment: sun, rain, temperature changes and other weather factors (Lechner, 2014). The consequence of such influence is formation of deformations, which occur both due to the own weight of the walls and floors and due to the uneven distribution over time of temperature and moisture in the wall material (Kamal, M., 2020; Boley, 2013; Barashkov, 2012; Kovalenko, 1970). As a result of mechanical stresses, damage to the outer and inner surfaces of the fences appear in the form of cracks (Arvind, 2016). Cracks not only spoil the appearance of the building, but can reduce its structural reliability. In this regard, it is important to take into account the influence of the temperature factor on the stress-deformation state of the enclosing structures. When choosing a strategy for designing energy-efficient facade structures, it is necessary to take into account the climatic conditions in which the building is located (Harkouss, 2018; Albatayneh, 2018), its orientation relative to the sides of the world, geometry (Alshboul, 2019; Albatayneh, 2021; Hemsath, 2015). No less important factor is the ratio of the area of the window to the wall, as this parameter determines the amount of heat from solar radiation and energy consumption by the facade of the building (Aksamija, 2015). The most unfavourable factors that can lead to significant temperature stresses in the facades of buildings are low outdoor temperatures in winter, high air permeability of the wall enclosure, the type of installed heating devices and insufficient level of heat insulation of the outer shell of the building. In addition, significant temperature deformations can occur in the area of the walls located directly next to the heating devices, where the temperature field of the wall is the most uneven (Aleksandrovskii, 1966; Krichevskii, 1984; Snegirev, 2008; Paruta, 2011; Umnyakova, 2013). An effective method of reducing the heat loss through the enclosing structures of buildings is application of a heat insulation layer on its outer surface (Basok, 2013; Basok, 2016). These measures also lead to a decrease in temperature stresses in the wall (Kalema, 2008; Kossecka, 2002; Al-Sanea, 2012; Aste, 2015).

2. Literature review

The study of energy efficiency problems of buildings is associated with study of the heat transfer processes through enclosing structures. It is known that, in most cases, the heat transfer through external enclosing structures occurs in a non-stationary mode under the influence of the environment, which is characterized by the time-varying outdoor air temperatures and intensity of solar radiation (Reynders, 2013; Kylili, 2015). Heat transfer processes through internal enclosing structures can be regulated by heating, ventilation and air conditioning systems (Costanzo, 2016), so they are considered as stationary. For example, in (Tariku, 2010) experiments and modelling are used to develop a holistic model that takes into account the constant dynamic interaction of heat, air and moisture transfer processes and combines building envelopes, interior, heating, ventilation and air conditioning and generation mechanisms of heat and humidity in the room and, at the same, time solves the relevant design parameters.

There are two main approaches to application of numerical simulation methods to study the characteristics of building structures. The first approach is based on the use of real climatic data in mathematical models to study the influence of weather conditions on external enclosing structures (Tariku, 2010; Abahri, 2011). Another method of numerical simulation assumes that the dependence of temperature on time is described by sinusoidal function (Kontoleon, 2008; Zhang, 2009; Viot, 2015). However, in these works, the temperature field in the wall was not considered as a reason for reducing the durability of the wall structure due to the occurrence of alternating thermal stress in it with fluctuations of temperature decomposition.

This work is devoted to the problem of appearance of stress-deformed states in the enclosing structures of buildings, which are formed due to the influence of the temperature factor and are the cause of their damage. To determine the maximum temperature stresses that can occur in the wall, the method of numerical simulation is used, which involves determining the temperature distribution in the wall volume under certain external climatic conditions and the air temperature inside the room. The problem of determining the deformation-stress state of building structures is solved having taken into consideration the temperature distribution in the wall. The method of numerical modelling involves a compatible finite-difference solution of the system of equations of deformation-stress state of building structures and equation of the thermal conductivity. The influence of the thermal insulation layer on distribution of thermal stresses in the facade wall structures of buildings is determined.

3. Experimental

Under conditions of heterogeneity of temperature fields in the wall, positive (tensile) and negative (compressive) temperature stresses are formed. Positive stresses lead to stretching of the wall material and contribute to cracks. To estimate the levels of positive and negative mechanical stresses, the problem of the thermo-stressed state of the wall is solved, which consists in solving a system of equations:

$$\frac{\partial}{\partial x}\left[\lambda\left(\frac{\partial u_x}{\partial x}+\frac{\partial u_y}{\partial y}+\frac{\partial u_z}{\partial z}\right)+2\mu\frac{\partial u_x}{\partial x}\right]+ \\ +\frac{\partial}{\partial y}\left[\mu\left(\frac{\partial u_y}{\partial x}+\frac{\partial u_x}{\partial y}\right)\right]+\frac{\partial}{\partial z}\left[\mu\left(\frac{\partial u_z}{\partial x}+\frac{\partial u_x}{\partial z}\right)\right]+\rho X= \\ =\frac{\partial}{\partial x}\left[\beta_T(3\lambda+2\mu)(T-T_0)\right]; \quad (1)$$

$$\frac{\partial}{\partial x}\left[\mu\left(\frac{\partial u_y}{\partial x}+\frac{\partial u_x}{\partial y}\right)\right]+ \\ +\frac{\partial}{\partial y}\left[\lambda\left(\frac{\partial u_x}{\partial x}+\frac{\partial u_y}{\partial y}+\frac{\partial u_z}{\partial z}\right)+2\mu\frac{\partial u_y}{\partial y}\right]+ \\ +\frac{\partial}{\partial z}\left[\mu\left(\frac{\partial u_z}{\partial y}+\frac{\partial u_y}{\partial z}\right)\right]+\rho Y=\frac{\partial}{\partial y}\left[\beta_T(3\lambda+2\mu)(T-T_0)\right]; \quad (2)$$

$$\frac{\partial}{\partial x}\left[\mu\left(\frac{\partial u_z}{\partial x}+\frac{\partial u_x}{\partial z}\right)\right]+\frac{\partial}{\partial y}\left[\mu\left(\frac{\partial u_z}{\partial y}+\frac{\partial u_y}{\partial z}\right)\right]+ \\ +\frac{\partial}{\partial z}\left[\lambda\left(\frac{\partial u_x}{\partial x}+\frac{\partial u_y}{\partial y}+\frac{\partial u_z}{\partial z}\right)+2\mu\frac{\partial u_z}{\partial z}\right]+ \\ +\rho Z=\frac{\partial}{\partial z}\left[\beta_T(3\lambda+2\mu)(T-T_0)\right], \quad (3)$$

where $x; y; z$ – rectangular coordinates, m; u_x, u_y, u_z – displacements in the directions of the axes $0X$, $0Y$ and $0Z$ respectively, m; $\beta_{T,}$ – coefficient of linear temperature deformation, 1/K; μ; λ – Lame coefficients, Pa; $T(x;y;z)$ – temperature at a point with coordinates $x; y; z$, K; T_0 - temperature at which the wall is in an undeformed state (this is the ambient temperature during the construction of the building), K; X; Y; Z – projections of the acceleration vector of external bulk forces, m/s^2; ρ - density of the material, kg/m^3.

From solution of this system, the displacements u_x, u_y, u_z, are determined and from their values we found the thermal stresses. Normal and tangential stresses are calculated by the formulas:

$$\sigma_{xx}=\lambda\left(\left(\frac{\partial u_x}{\partial x}+\frac{\partial u_y}{\partial y}+\frac{\partial u_z}{\partial z}\right)\right)+2\mu\frac{\partial u_x}{\partial x}-\beta_T(3\lambda+2\mu)(T-T_0);$$

$$\sigma_{yy}=\lambda\left(\left(\frac{\partial u_x}{\partial x}+\frac{\partial u_y}{\partial y}+\frac{\partial u_z}{\partial z}\right)\right)+2\mu\frac{\partial u_y}{\partial y}-\beta_T(3\lambda+2\mu)(T-T_0);$$

$$\sigma_{zz} = \lambda\left(\left(\frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} + \frac{\partial u_z}{\partial z}\right)\right) + 2\mu\frac{\partial u_z}{\partial z} - \beta_T(3\lambda + 2\mu)(T - T_0);$$

$$\tau_{xy} = \mu\left(\frac{\partial u_y}{\partial x} + \frac{\partial u_x}{\partial y}\right);\ \tau_{xz} = \mu\left(\frac{\partial u_z}{\partial x} + \frac{\partial u_x}{\partial z}\right);$$

$$\tau_{yz} = \mu\left(\frac{\partial u_z}{\partial y} + \frac{\partial u_y}{\partial z}\right).$$

To determine the temperature distribution inside the wall structure, the thermal conductivity equation is solved. For the stationary heat transfer conditions, this equation has the form:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = 0. \qquad (4)$$

For the system of equations (1) – (4) the corresponding boundary conditions are formulated. From the numerical solution of this system, the temperature distributions, as well as the temperature stresses in the wall structure, are determined.

Analysis of influence of the temperature state of a wall structure on the distribution of thermal stresses is performed on the example of a concrete wall with a window opening. The element of the wall structure, which is rigidly fixed by the ends with the adjacent walls, has a height H = 3 m and a width L = 3 m and a wall thickness δ_w = 0.25 m. The wall has a window opening 1.5 m high and 1.8 m wide. Under the window near the inner surface of the concrete wall is a steel heating device - a radiator. The radiator is located under the window closer to the right-hand side wall of the room. In winter, from the radiator to the area of the wall located directly next to the radiator, radiant and convective heat flows is coming. To other parts of the inner surface of the wall, the heat flow is transferred from the indoor air by natural convection. Based on this, the boundary conditions on the inner surface of the wall (z = 0) are formulated as:

- for the area of the inner surface of the wall behind the radiator:

$$-k\frac{\partial T}{\partial z}\bigg|_{z=0} = \alpha_{in}\left(T_{in} - T(x,y,0)\right) + \frac{c_0}{1/\varepsilon_r + 1/\varepsilon_w - 1}\left[\left(\frac{T_r}{100}\right)^4 - \left(\frac{T(x,y,0)}{100}\right)^4\right] \qquad (5a)$$

- for other areas of the inner surface of the wall:

$$-k\frac{\partial T}{\partial z}\bigg|_{z=0} = \alpha_{in}\left(T_{in} - T(x,y,0)\right) \qquad (5b)$$

where T_{in} - indoor air temperature; T_r – radiator temperature; α_{in} – heat transfer coefficient for natural convection, W/(m^2·K); ε_r ; ε_w - coefficients of emissivity of radiator surface and concrete wall, respectively; k - thermal conductivity coefficient of concrete, W/(m·K).

On the outer surface of the wall ($z = \delta_w$) in contact with the outside air, the boundary conditions have the form:

$$-k\frac{\partial T}{\partial z}\bigg|_{z=\delta_w} = \alpha_{out}\left(T(x,y,\delta_w) - T_\infty\right). \qquad (6)$$

The end surfaces of the wall, as well as the surfaces of the window opening, are considered as thermally insulated.

The system of equations of elasticity (1) – (3) is solved under the conditions that on the end surfaces of the concrete wall all the displacements are considered to be zero, i.e. the ends are considered rigidly fixed. On free surfaces z = 0 and z = δ_w normal stresses σ_{zz}, as well as tangents τ_{zx}; τ_{zy} stresses are zero. On the left-hand and right-hand surfaces of the window opening, which are considered free, normal stresses σ_{xx} take zero values and on its upper and lower surfaces normal stresses σ_{yy} have zero values.

Numerical solution of the system of equations (1) – (4) is performed by the finite difference method. When solving the problem of thermoelasticity, the action of external bulk forces is not taken into account.

4. Results and discussion

Calculations of the temperature-stress state of the concrete wall are performed for the case of the radiator temperature +60°C. Indoor air temperature is +20°C. The temperature of the outside air (environment) is -10°C. The heat transfer coefficient on the outer surface is α_{out} = 23 W/(m^2·K). The heat transfer coefficient on the inner surface of the wall α_{in} is determined by the known dependences for the natural convection on the vertical surface (Isachenko, 1975).

The temperature distribution on the inner surface of the wall (z = 0) is shown in Fig. 1a, and on the outer surface of the wall (z = 0.25 m) - in Fig. 1b. As can be seen from the figures, the highest temperature of the inner surface of the wall is observed in the area near which the radiator is located. The maximum temperature in this area is 27°C. Outside this area, the temperature drops to 12°C. On the outer surface of the wall, the maximum temperature in the area behind the radiator is -3°C, and on the other part of the outer surface -6°C.

Under conditions of significant inhomogeneity of the temperature field in the wall there are significant positive and negative temperature stresses. The distributions of normal stresses σ_{xx} and σ_{yy} on the outer on the inner surfaces of the wall under conditions that the temperature at which the temperature deformations are absent is equal to t_0 = 15°C (this is the average temperature at which construction took place) are shown in Fig. 2 and Fig. 3.

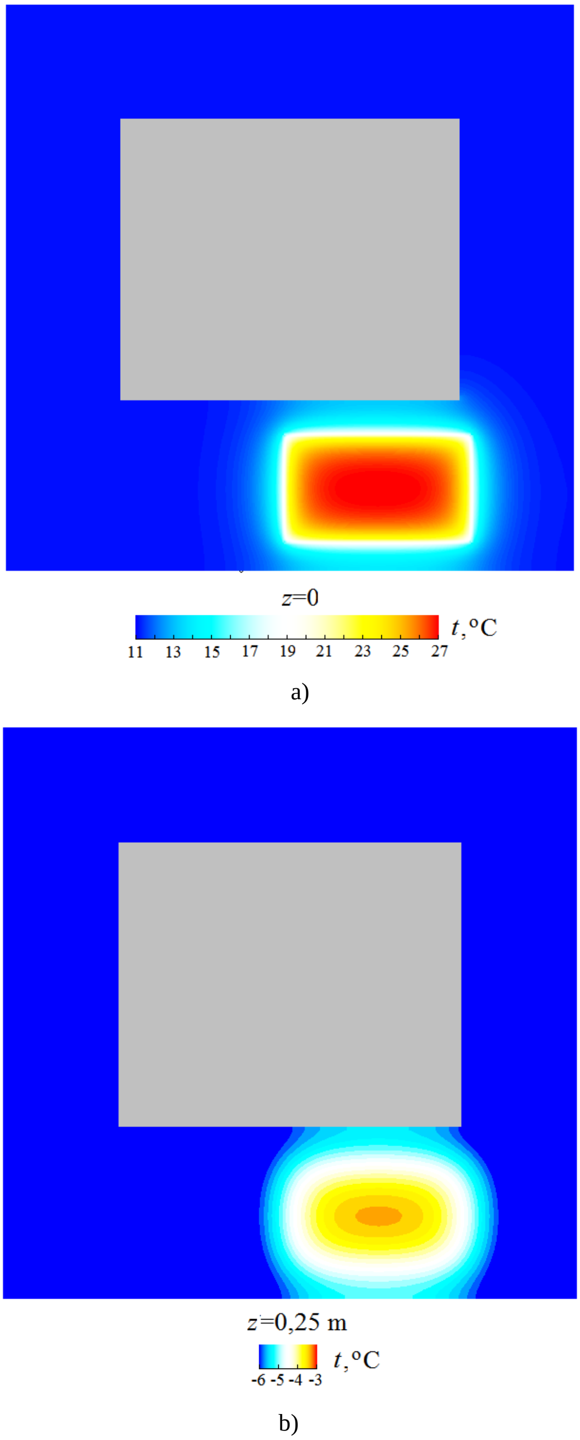


Fig. 1. Temperature distribution on the inner (a) and outer (b) surfaces of the wall

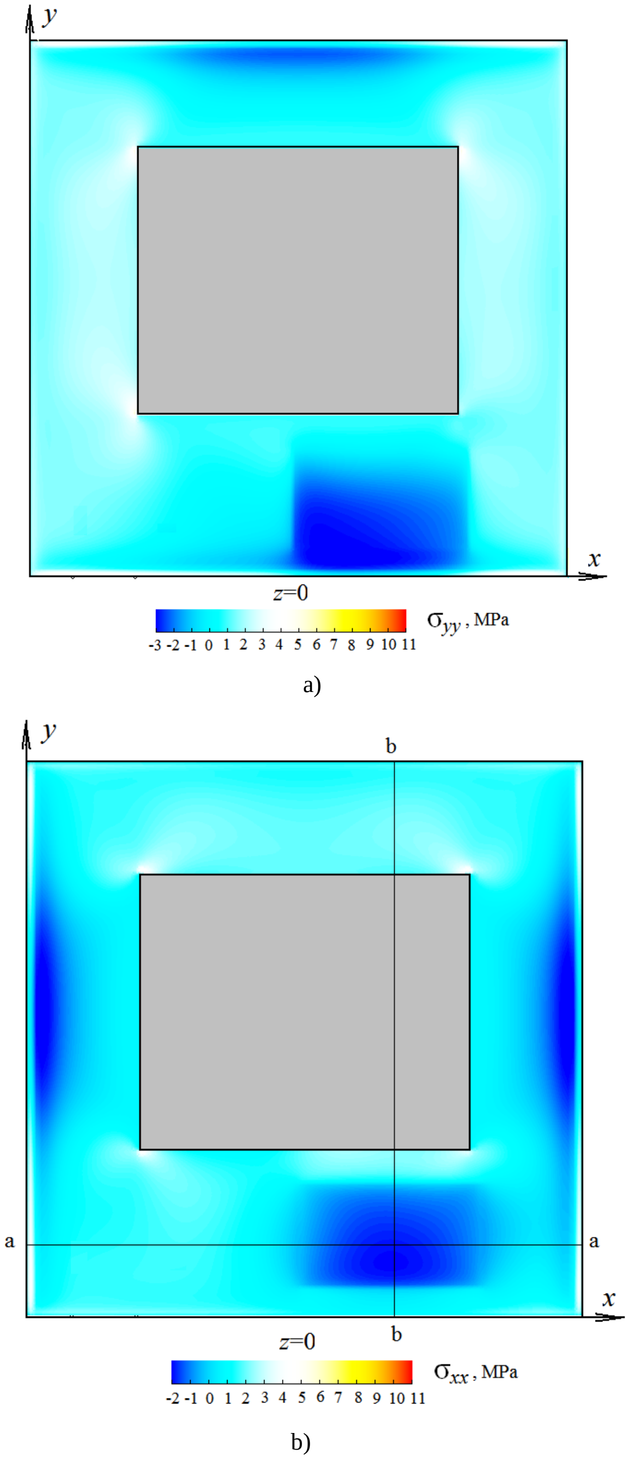
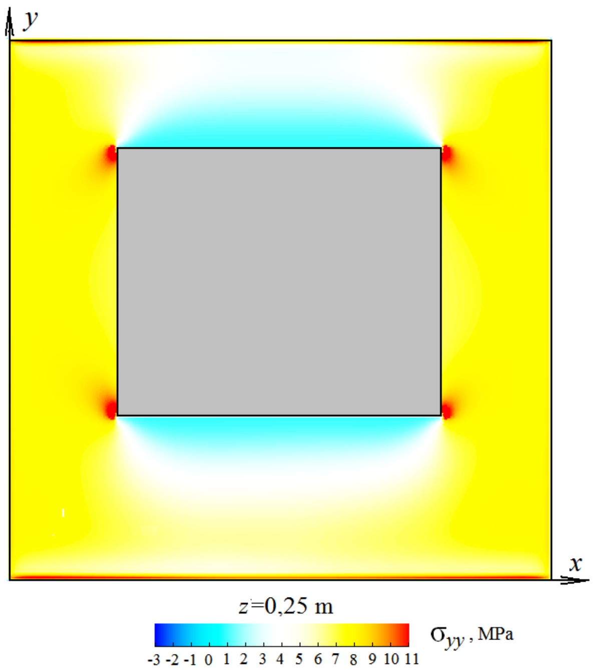
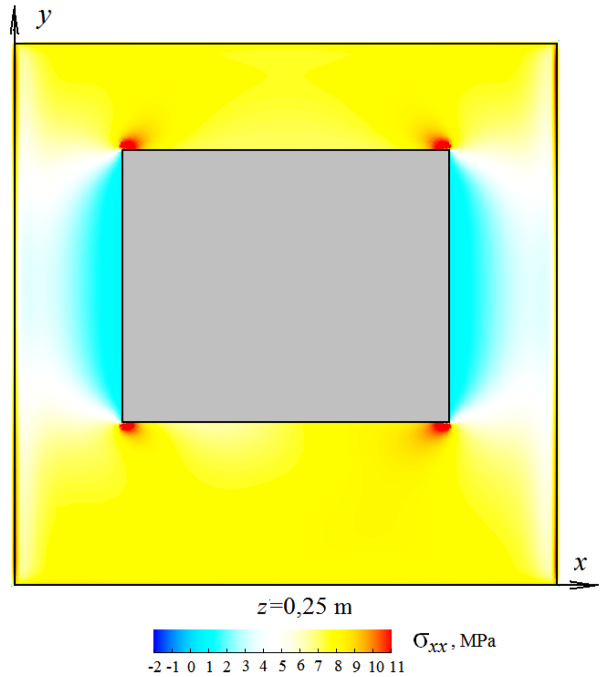


Fig. 2. Distribution of normal stresses σ_{yy} (a) and normal stresses σ_{xx} (b) on the inner surface of the facade wall



a)



b)

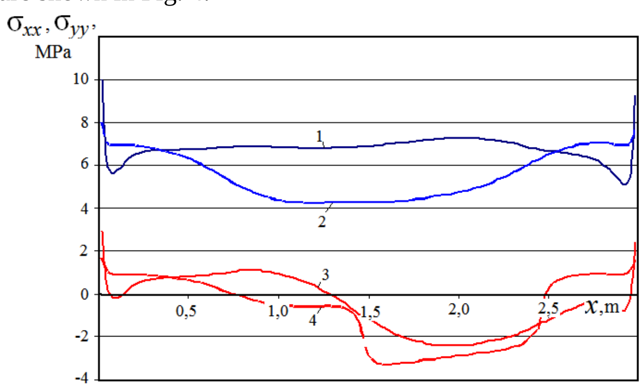
Fig. 3. Distribution of normal stresses σ_{yy} (a) and normal stresses σ_{xx} (b) on the outer surface of the facade wall

It should be noted that on the end surfaces of the wall all the displacements are considered to be zero (the ends are fixed) and on the free surfaces $z = 0$ and $z = 0.25$ m normal σ_{zz}, as well as tangential τ_{zx}; τ_{zy} stresses are zero. As can be seen from Fig. 2, on the inner surface of the wall, the normal stresses σ_{xx} and σ_{yy} acquire both negative (compressive) and positive (tensile) values. They reach the minimum values (~ -2… -3 MPa) in the area of the wall behind the radiator and near the end surfaces of the wall. These stresses reach maximum values (~ +4 MPa) in the area of corner points of the window opening. In other areas, these stresses do not exceed +2 MPa.

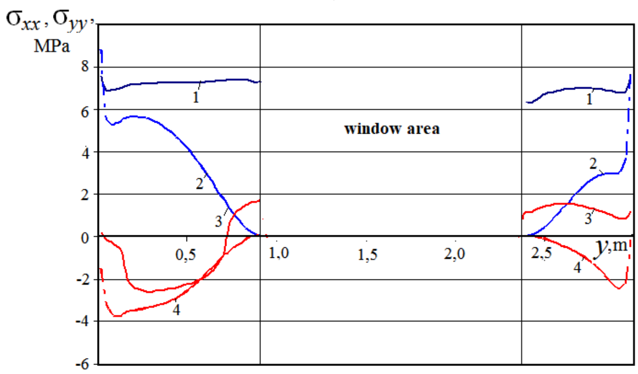
The opposite picture is observed on the outer (cold) surfaces of the wall. On these surfaces, the normal stresses σ_{xx} and σ_{yy} are positive (tensile). They acquire the smallest values (~ + 2 MPa) near the surfaces of window openings (except for the areas of corner points). The concentration of the positive normal stresses σ_{xx} and σ_{yy} is observed in the region of corner points of the window opening, where their values reach ~ + 12 MPa. Approximately the same values of normal stresses σ_{xx} are reached near the right-hand and left-hand end surface (Fig. 3b). In the areas above the window opening and under the window opening σ_{xx} is +7…+8 MPa. Approximately the same values have the stresses σ_{yy} on the left-hand and right-hand sides of the window opening.

Stress distribution in the picture can be explained by the fact that the value of the wall temperature on most of its outer and inner surfaces is less than the temperature $t_0 = 15$°C, at which the temperature deformations are absent. The exception is the area of the inner surface of the wall behind the radiator, where the temperature significantly exceeds the value of t_0. As a result, the normal stresses σ_{xx} and σ_{yy} in this area behind the radiator are negative.

The distributions of normal stresses σ_{xx} and σ_{yy} on the inner and outer surfaces of the wall along lines a-a and b-b (Fig. 2a) are shown in Fig. 4.



a)



b)

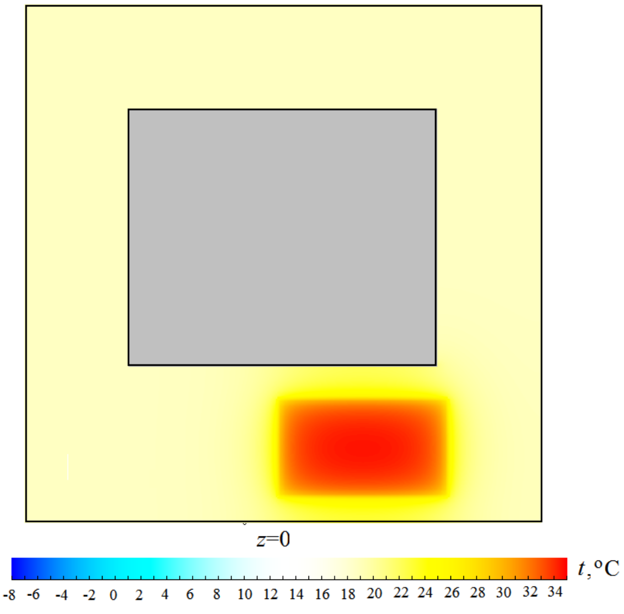
Fig. 4. Distributions of normal stresses on the inner and outer surfaces of the wall along the lines a-a (a) and b-b (b): 1 – σ_{xx} on the outer surface; 2 – σ_{yy} on the outer surface; 3 – σ_{xx} on the inner surface; 4 – σ_{yy} on the inner surface

Line a-a is parallel to the axis 0X and passes through the middle of the wall behind the radiator. Line b-b is parallel to the axis 0Y and passes through the middle of the area behind the radiator and crosses the window opening. As can be seen from Fig. 4a, normal stresses σ_{xx} and σ_{yy} on the inner surface of the wall, along the line a-a, are significantly reduced within the area of the wall behind the radiator (up to -3.5 MPa). In other areas of the inner surface, they vary within -1.0…+2.0 MPa.

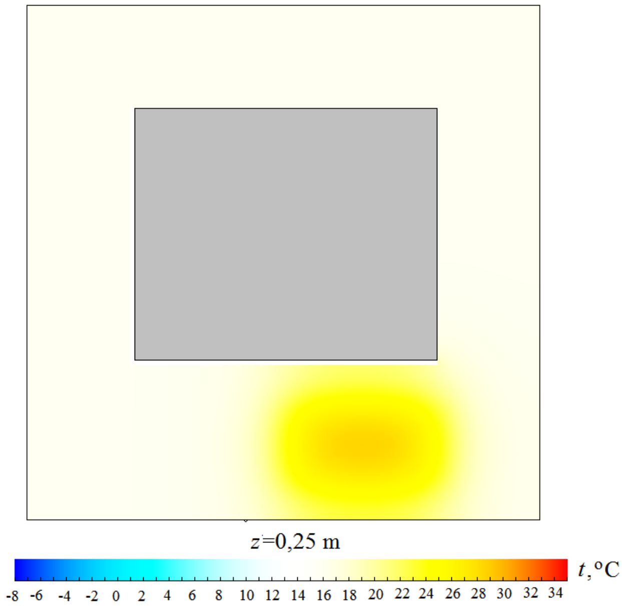
On the outer surface, these normal stresses are positive and vary within +6.0…+8.0 MPa. Along the line b-b (Fig. 4b) the nature of the normal stresses distribution is generally similar to the distribution along the line a-a. Only near the lower and upper limits of the window cut, the stresses σ_{yy} decrease to zero on both the outer and inner surfaces of the wall, which is a condition for solving this problem on the free end surfaces of the window opening.

In the presence of the heat insulation on the outer surface of the enclosing structure of the house, the distributions of temperature and thermal stresses in the concrete wall will be different. The case of presence of a heat-insulating layer of insulation with a thickness of δ_i = 10 mm made of mineral wool k_i = 0.041 W/(m·K) on the outer surface of the concrete wall is considered. Temperature conditions outside and inside the room are the same as in the case of uninsulated walls.

Temperature distributions on the inner surface of the wall with insulation (z = 0) are shown in Fig. 5a and on the outer surface of the concrete wall (z = 0.25 m) - in Fig. 5b.



a)



b)

Fig. 5. Temperature distributions on the inner (a) and outer (b) surfaces of the concrete facade wall in the presence of heat insulation on its outer surface

As can be seen from the figures, the highest temperature of the inner surface of the wall is observed in the area of the wall behind the radiator. The maximum temperature in this area, in the presence of heat insulation on the outer surface, is 35°C. Outside this area, the temperature drops to +21…22°C. On the outer surface of the wall (under the heat insulation) the maximum temperature in the area of the wall behind the radiator remains relatively high +22…+25°Cand on the other part of the outer surface it is +14…+16°C. The temperature drops most significantly in the thickness of the heat insulation. On the outer surface of the heat insulation, it is -8…-7°C. The conditions in which the concrete wall itself is located in the presence of heat insulation on its outer surface are characterized by higher temperature values and a more uniform distribution over the volume of the wall structure compared to the case when there is no heat insulation.

Under conditions when the temperature of the wall rises and becomes higher than t_0 = 15°C in most of its areas, as well as under conditions of more uniform temperature distribution by volume, its thermal stress state changes markedly. Normal stresses σ_{xx} and σ_{yy} on the outer and inner surfaces of the wall decrease and in some areas change from positive to negative. Their distributions on the inner and outer surfaces of the wall are shown in Fig. 6 and Fig. 7.

As can be seen from Fig. 6 on the inner surface of the wall normal stresses σ_{xx} and σ_{yy} have values close to zero. In the area of the wall behind the radiator, they become negative (-2… -3 MPa).

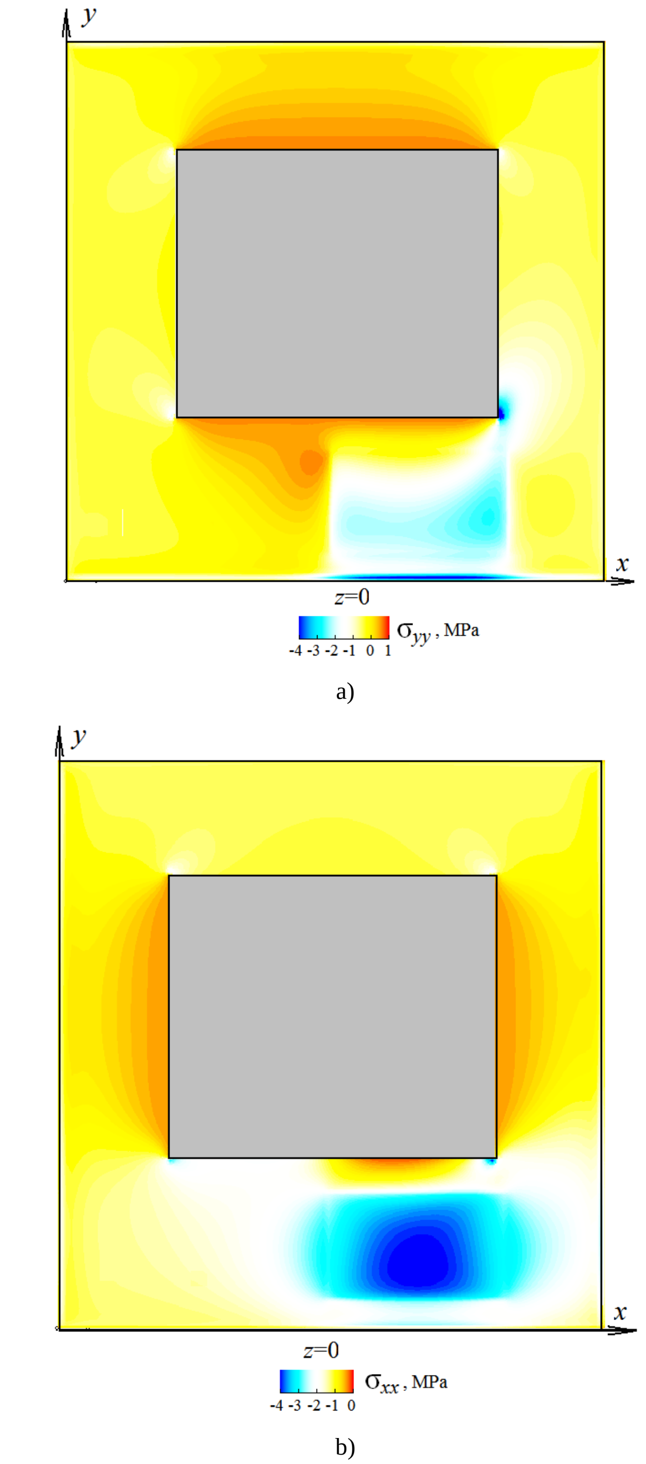


Fig. 6. Distribution of normal stresses σ_{yy} (a) and normal stresses σ_{xx} (b) on the inner surface of the concrete wall in the presence of a layer heat insulation on the outer surface of the facade

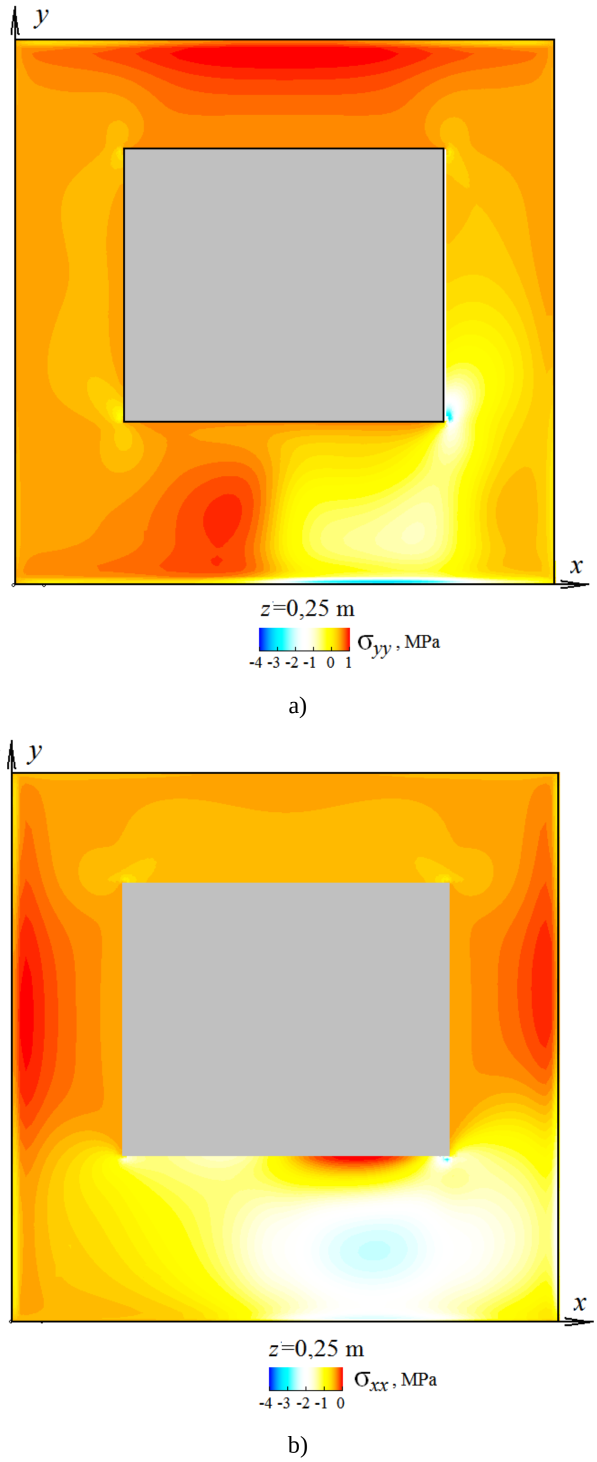


Fig. 7. Distribution of normal stresses σ_{yy} (a) and normal stresses σ_{xx} (b) on the outer surface of the wall in the presence of a layer of heat insulation on its outer surface

On the outer surface of the wall, their values also differ little from zero (Fig. 7). Only near the end surfaces, which are rigidly fixed, normal stresses σ_{xx} and σ_{yy} become positive, but their values do not exceed +2 MPa.

Distributions of normal stresses σ_{xx} and σ_{yy} on the outer and inner surfaces of the walls along lines a-a and b-b are presented in Fig. 8. As can be seen from this figure, in the presence of heat insulation, values of these stresses in comparison with the case when the heat insulation was absent decrease and become mainly negative both on the inner and outer surfaces.

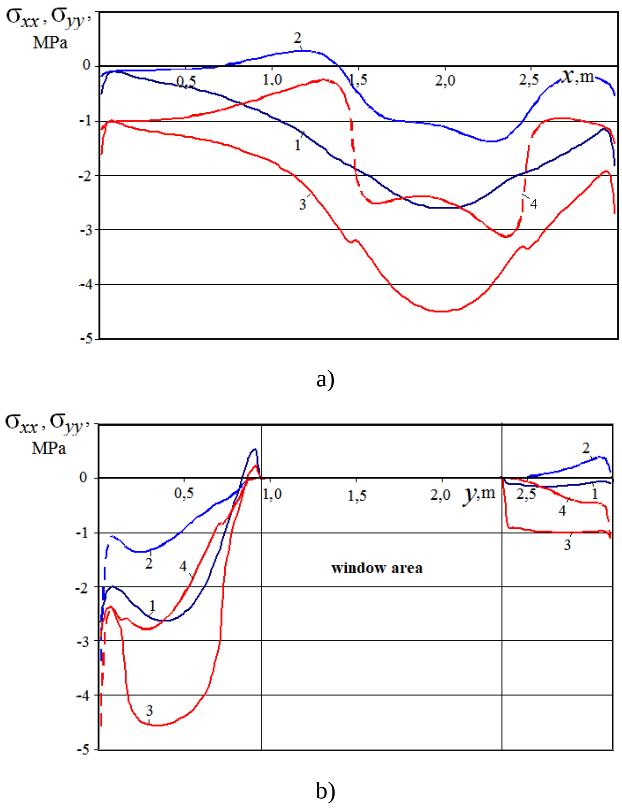


Fig. 8. Distributions of normal stresses on the inner and outer surfaces of the wall with heat insulation along the lines a-a (a) and b-b (b): 1 – σ_{xx} on the outer surface; 2 – σ_{yy} on the outer surface; 3 – σ_{xx} on the inner surface; 4 – σ_{yy} on the inner surface

From the above results it follows that the presence of a thermal insulation layer on the outer surface of the wall not only increases the temperature level of the wall, but also reduces the value of normal stresses σ_{xx} and σ_{yy} on its surfaces, which reduces the likelihood of cracks on the outer surface of the wall when it is cooled in the winter.

5. Summary and conclusion

According to the results of calculation studies, in the winter at certain values of outdoor temperature and indoor air, on the outer (cold) surface of the wall there are mostly positive normal temperature stresses. They can cause formation or development of cracks. On the inner surface of the wall, these stresses are mostly negative.

The installation of a heat-insulating layer on the outer surface of enclosing structures not only reduces heat loss from the room, but also helps to reduce the positive thermal stresses on the outer surface of the wall. As follows from the above results, the values of normal stresses on the outer and inner surfaces of the wall not only decrease, but in some areas can change from positive to negative. The decrease in temperature stresses is due to an increase in the temperature level of the concrete wall in the presence of a thermal insulation layer. The temperature distribution over the volume of the panel becomes more uniform. Thus, the thermal insulation layer on the outer surface of the wall prevents the occurrence and development of cracks and helps to increase the durability of building structures.

Since in Ukraine in many cases the insulation of old houses is not centralized, but is left to the initiative of individual apartment owners, the insulation layer is applied not to the entire outer surface of the building, but to some parts in accordance with the area of responsibility of individual owners. This method of insulation is called "patchwork" insulation. Under such conditions, the temperature of insulated and uninsulated rooms in one house will be different. The temperature distributions on the external facade walls will also differ. This can lead to the fact that the maximum temperature stresses caused by supercooling of the outer surface of the wall will be different in different parts of the facade of the building. As a result, it is thought that "patchwork" insulation may adversely affect the overall thermal stress state of the facade walls. However, it should be noted that the additional stresses caused by thermal deformation of the wall are usually less than the stresses arising under the influence of its own weight and the weight of the floors of the house. In addition, the design of concrete walls usually assumes the presence of heat-shrinkable joints between the individual panels to prevent additional temperature stresses. From this, based on authors' calculations, it follows that the "patchwork" insulation should not significantly affect the overall deformation-stress state of the concrete wall structure.

In addition to temperature stresses in the wall facade structures, there are also additional stresses associated with changes in the concentration of moisture in the building material under the influence of climatic conditions. Concentration deformations can also cause additional stresses in the wall structures. Therefore, further research on this topic will be associated with determining the combined effect of temperature and concentration (humidity) deformations on the stress state of the facade walls, which occur under the influence of external and internal climatic factors.

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隔热层对立面墙热应力状态的影响

關鍵詞
温度应力
混凝土外墙
加热系统
数值建模
隔热层

摘要
采用数值模拟的方法研究了带钢制加热装置的房间外围结构开窗混凝土立面墙的温度-应力状态。估计的研究是在一年中的冬季进行的，当时建筑物的供暖系统正在运行。根据热应力方程组和热导率方程的求解结果，确定了壁面上的温度分布和正切应力分布。确定了这些应力最大的墙壁区域。该研究针对外墙外表面隔热层不存在和存在的情况进行了研究。通过比较这两种方案的结果，可以看出外保温涂层不仅有助于减少通过立面墙的耗散热损失，而且还可以减少混凝土墙因温度变形而产生的应力的绝对值。在某些情况下，应力的符号从拉伸（没有外部绝缘的墙）变为压缩（有绝缘的墙）。