Energy Efficient Wall Enclosing Structures

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Abstract. The study describes climate changeability on the territory of the Russian Federation and in particular gives climate parameters for the area of St. Petersburg. It raises issues of energy efficiency of buildings' enclosing structures. Some results of field surveys conducted at cast-in-place civil buildings are compared with their design values. The study also updates issues of thermotechnical defects and thermal bridges in the structure in question, as well as the degradation of comfort level indicators. It also offers new types of structures ensuring heat insulation characteristics of civil buildings are not lower than the specified values. Moreover, the study presents the calculation model to determine the temperature field in the floor slab – wall connection node, as well as providing steady-state heat conductivity equations. There are also recommendations developed on how to apply the new types of enclosing structures in modern conditions of construction.

1. Introduction

According to different estimates, values of the annual average global temperature have increased by 0.6 $^{\circ}$C [1,2]. During this time, climatic parameters in St. Petersburg have also changed. This has resulted in a shortening of winter periods by 13 days in comparison to the first half of the 20th century, and mainly due to the earlier oncoming of spring. Winter's end has shifted to the colder part of the year. The beginning of winter period has remained unchanged. In the region of St. Petersburg, winters have become more severe [3,4,5].

In this regard, the energy efficiency issue is raised in relation to the housing stock erected in St. Petersburg starting from the end of 1990s using cast-in-place frame technology. As a rule, this type of building involves a cross-wall structural system. Many options of structural solutions for such buildings' enclosing structures [6,7], as well as a variety of conducted surveys indicate [8] that the required level of temperature and humidity is not always maintained, and this level has a considerable impact on providing a comfortable living environment [9,10]. The floor slab – wall connection node is considered a destructor of providing such comfortable conditions [11]. Many specialists have studied thermotechnical characteristics of enclosing structures of such type, applying a comprehensive approach which includes field tests and calculation and theoretical research [12,13]. Despite the huge number of conducted studies, the implementation of some of these structural solutions is technically complicated, expensive and not energy efficient enough.

The purpose of this study is further research of specific features of behavior of the floor slab – wall connection node in a cast-in-place building with a cross-wall structural system under the conditions of the North-West region, using the example of St. Petersburg's climatic parameters.

2. Description of suggested structural solutions

The suggested structural solutions are patented [14,15] and aimed at improving the thermotechnical characteristics of enclosing structures in cast-in-place buildings; there are two options of such solutions.
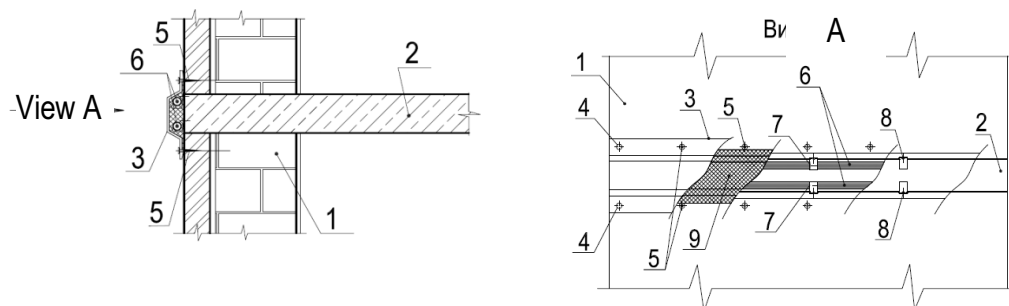
The heat insulation guard for external walls (Option 1) consists of a trapezoidal frame formed through connecting vertical and inclined surfaces, ensuring precipitation is taken away. The space formed between the frame and the external wall is intended for heat insulation material. The vertical surfaces have holes for screw anchors to be fixed in the external wall. Figure 1 shows the heat insulation guard for external walls to cover the ends of floor slabs [14]. The frame can be made of metal profile, e.g. galvanized steel, aluminum, duralumin, or weather resistant polymer, e.g. glass reinforced plastic, carbon fiber reinforced plastic, or spheroplastic. A layer of the heat insulation material, e.g. extruded polystyrene foam, mineral wool (rock wool, glass wool), contained inside the frame does not decrease the required level of building heat insulation. The frame's vertical surfaces with holes are fastened to the external wall of a building using screw anchors. In addition, the vertical walls placed at the frame sides are folded at points of fastening to the external wall surface, and upon installation, works are to be covered with water proof materials, e.g. acetate, polyurethane or silicone sealants, in order to protect them from precipitation.
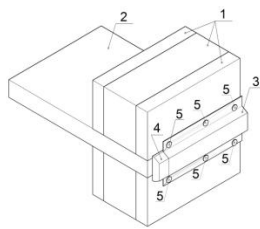
Figure 1. Heat insulation guard for external wall of building. Option 1.
1 – External wall; 2 – Floor slab; 3 – Guard's frame; 4 – Heat insulation material; 5 – Holes for fastening elements

The Option 2 guard structure contains a layer of heat insulation material with self-regulating heating cables fixed to the end of the floor slab [15]. The essense of this heat insulation guard for external walls of a building is shown in Figure 2. This figure presents the vertical section of an external wall taken at points where the wall is supported by the floor slab end and the suggested heat insulation guard with trapezoidal frame is placed, as well as shows the generalized front view of fastening the guard to the wall structure. It is obviuos that floor slab ends 2 reaching the external wall surface are the thermal bridges. Under the climate conditions when outdoor air negative temperature has an adverse impact on indoor climate (the difference between indoor temperature and floor surface temperature is higher than the permissible values equaled to 2^0C, see Construction Norms and Regulations (SNiP II.3-79*), additional heating can be required which leads to increase of loads on electric mains during the cold period. External heating of a reinforced-concrete floor slab from the facade surface allows ensuring the required level of thermal comfort inside residential premises during the cold period and therefore reducing dwellers' material expenses related to use of additional heating devices.

Figure 2. Heat insulation guard with trapezoidal frame for external wall of building. Option 2.

2.1   Results of calculations and theoretical research

To estimate the efficiency of the solutions described above, calculations and theoretical research were conducted, which considered three structure options: the base model, and the suggested options 1 and 2. The base structure model accepted for calculation involved elements of a flat enclosing structure consisting of a multi-layered homogeneous wall with Thicknesses δ_1 (delta) and δ_2 (delta) and a non-homogeneous floor slab punched for placing heat insulation material and with Height *h* and Length *l*. The structure to be studied is under such thermal loads when on one side the temperature equals t_{ext} and on the other side the temperature equals t_{in}. Heat exchange with the environment is under the law of convection. The wall has Temperature T_w, outdoor air temperature equals T_{ext}, and α_{ext}, α_{in} (alpha) are the coefficients of convective heat exchange on external and internal surfaces of the enclosing structure, respectively. The description above is also true for the Option 1 heat insulation guard. As for the Option 2 structure, on the external part of the wall there is the heat insulation guard consisting of the frame, which contains self-regulating heating cables with Temperature T_c.

In order to determine the temperature distribution along the floor slab, for all cases considered below the following dimensions of the enclosing structures and boundary conditions were accepted:

- External walls are 0.42 m thick and constitute a homogeneous two-layered structure. The first layer is made of brick and 0.12 m thick, the second layer is made of foamed concrete and 0.3 m thick. The height of the wall is 0.5 m, except on each of the top and bottom of the floor slab falls 0.25 m;
- Floor slab is 0.2 m thick with a total length of 2.0 m; taking into account the wall thickness supported by the slab, the width of the area is accepted to be equal to 1.35 m.
- Polystyrene foam heat-insulating inserts have dimensions of 0.3x0.12x0.2 m and are placed at a distance of 0.3 m from each other.
- Borders of each of the domains of the calculation model were assigned with the specified values of temperatures and heat transfer coefficients. For external surfaces t_{ext}=-26°C, for internal surfaces t_{int}=20°C.
- Values of heat transfer coefficients for external and internal surfaces are set to α_{ext}=23W/m^2 ^{o}C and α_{int}=8.7 W/m^2 ^{o}C respectively.

Dimensions of materials of the enclosing structure accepted for the calculation complied with the effective regulatory documents and equaled: clay brick – 120 mm, D300 foamed concrete – 300 mm, B 35 reinforced-concrete – 200 mm, heat-insulating inserts – 150x200 mm.

Analytical solution of the structure in question can be reduced to determination of temperature at any point of the considered temperature field using the formula: $t_x = t_{int} - (t_{int} - t_{ext})\dfrac{R_{xi}}{R_0}$; where t_{int} is indoor air temperature; t_{ext} is outdoor air temperature; R is heat transfer resistance.

The calculations and theoretical research are conducted using the COSMOS/2M software package. Figure 3 shows the structure accepted as the base model and indicates distribution of temperature fields inside the enclosing structure.
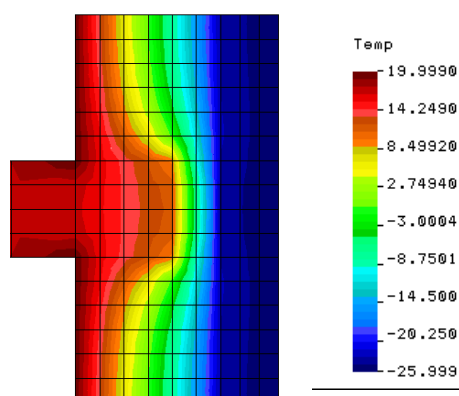

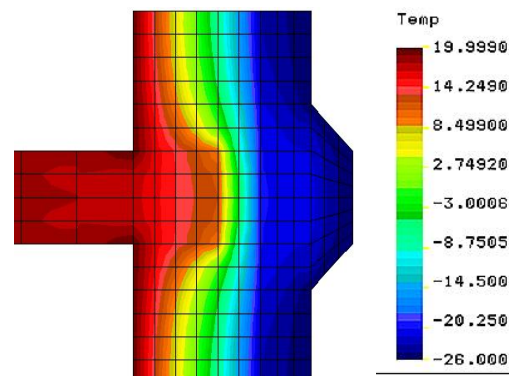**Figure 3.** Base model of floor slab – wall connection node.

Figure 4. Option 1. Temperature distribution inside structure**.**

In the case of the base model, temperature values in the area of the floor slab connection with the internal side of the wall equaled 16.86^{0} C at the distance of 500 mm from the internal side of the wall and 17.63^{0} C respectively.

For the suggested Option 1, temperature values for curve 2 at the point of the floor slab connection with the wall equaled 17.00^{0}C. At the distance of 1,500 mm from the wall the maximum temperature values were within the limits of 17.73 ^{0}C. During the structure calculation the numerical solutions were received for Options 1 and 2 and they are given in Figures 4 and 5.
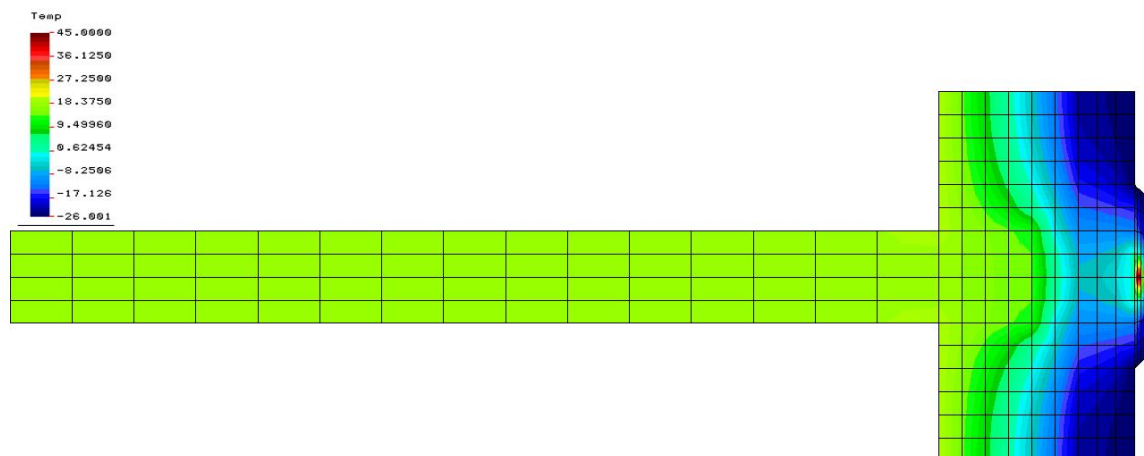
Figure 5. Option 2. Temperature distribution with heat insulation guard applied for external wall of building. Case of floor slab with heat insulation.

For Option 2, temperature values for curve 3 at the point of the floor slab connection with the wall equaled 17.49 ^{0}C. At a distance of 1,500 mm from the wall, an increase in temperature of up to 18.00 ^{0}C was recorded.

The received values show that Option 1 and 2's structures are the most efficient.

In addition to the calculation research, some field tests were performed to determine the distribution of temperature fields [16].
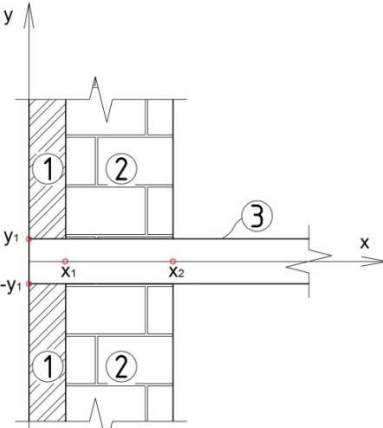
Analysis of the experimental data received in relation to temperature fields on the surface of the cast-in-place reinforced-concrete slab shows that temperature distribution is changeable. For some areas, the temperature difference on the floor slab surface was higher than 2^{0}C – the value specified by environmental health requirements - which leads to temperature discomfort for dwellers and a dew point shift to internal parts of enclosing structures, contributing to condensation formation on horizontal and vertical surfaces.

Values of experimental data were estimated in detail using the COSMOS/2M software package. Based on the structural solutions described above, the calculation model was created. This model took into account parameters of indoor climate and outdoor environment, plus thermotechnical and structural performance of materials consistent with field test values.

Let's consider one of the simplest structures of the floor slab – the wall connection node (Figure 6).

Three materials with different heat conductivity values (λ_1, λ_2 and λ_3 respectively) are used in the structure. To calculate the temperature field in such a structure, the steady-state 2D model of heat conductivity can be applied [17,18].

The suggested mathematical model includes steady-state heat conductivity equations for each of the three materials used in the connection node (1)-(3) and the boundary conditions of the first kind (4)-(5) setting the temperature at external boundaries of the connection node, as well as the boundary conditions of fourth kind (6)-(8) describing the surface contact of materials with different heat conductivity [17].

$$\frac{\partial^2 T_2(x,y)}{\partial x^2} + \frac{\partial^2 T_2(x,y)}{\partial y^2} = 0, \; npu \; \; x_1 \leq x \leq x_2, \; |y| \geq y_1, \tag{1}$$

Figure 6. Calculation model to determine temperature field in connection node.

$$\frac{\partial^2 T_1(x,y)}{\partial x^2} + \frac{\partial^2 T_1(x,y)}{\partial y^2} = 0, \; when \; \; 0 \leq x \leq x_1, \; |y| \geq y_1, \tag{2}$$

$$\frac{\partial^2 T_3(x,y)}{\partial x^2} + \frac{\partial^2 T_3(x,y)}{\partial y^2} = 0, \; when \; \; x \geq 0, \; |y| \leq y_1, \tag{3}$$

$$T_1(0,y) = T_3(0,y) = T_{out}, \tag{4}$$

$$T_2(x_2, y) = T_3(x, \pm y_1) = T_{in}, \; \; x \geq x_2, \tag{5}$$

$$T_1(x_1, y) = T_2(x_1, y),$$
$$\lambda_1 \frac{\partial T_1(x_1, y)}{\partial x} = \lambda_2 \frac{\partial T_2(x_1, y)}{\partial x}, \tag{6}$$

$$T_1(x, \pm y_1) = T_3(x, \pm y_1),$$
$$\lambda_1 \frac{\partial T_1(x, \pm y_1)}{\partial y} = \lambda_3 \frac{\partial T_3(x, \pm y_1)}{\partial y}, \tag{7}$$

$$T_2(x, \pm y_1) = T_3(x, \pm y_1),$$
$$\lambda_2 \frac{\partial T_2(x, \pm y_1)}{\partial y} = \lambda_3 \frac{\partial T_3(x, \pm y_1)}{\partial y}, \tag{8}$$

where $T_i(x,y)$ is the temperature field in i material; T_{out} is outdoor temperature; T_{in} is indoor temperature; x, y are coordinates; x_1, x_2, y_1 are typical dimensions of the structure.

The received boundary value problem can be solved using the finite difference numerical method [19, 20].

3. Conclusion

a) The variety of conducted field tests confirmed that there are thermal bridges in floor slab – external wall connection nodes. This destructor leads to the degradation of qualitative and quantitative parameters of building heat insulation and does not comply with environmental health requirements.

b) There are some structural solutions developed and protected by the Russian Federation patents, enabling the improvement of the energy efficiency of floor slab – external wall connection nodes.

c) The set of conducted calculation and theoretical research on the suggested solutions confirms the positive convergence with the specified parameters of building heat insulation.

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