Energy efficient wall design with stay-in-place formwork

A V Kyanets
Department of Building Construction and Structural Theory, South Ural State University, 76, pr. Lenina, Chelyabinsk 454080, Russia
E-mail: kyanets2007@mail.ru

Abstract. In this paper we analyze contemporary solutions of external wall structures made of cast-in-situ concrete with the use of stay-in-place formwork panels. The advantages of these systems are to reduce the labor input and construction period and to obtain a variety of architectural and planning concepts for buildings. Such systems are widely used in the world. This study is aimed at solving the issues of energy efficiency of external walls with the use of stay-in-place formwork. Some of the most common design solutions are considered. To determine the energy-efficient solution to the stay-in-place formwork option, we used the method of numerical simulation of heat flow processes in structures using the ELCUT 5.1 program. Based on the data obtained, the following results were achieved: an analysis was made of the applied technologies of stay-in-place formwork used to increase the energy-saving characteristics of residential buildings; the thermo-technical characteristics of the selected solutions by numerical simulation were analyzed.

1. Introduction
The method of wall construction using stay-in-place formwork combines cast-in-situ housing construction and wall construction from hollow blocks or panels [1,2].

The main advantage of stay-in-place formwork is a small mass of products, simple technology, and the ability to carry out construction without the use of heavy equipment.

The disadvantages are poor bearing capacity, the need to have a lot of different types of blocks for the implementation of the architectural elements of the building, and difficult additional surface finishing of finished walls [3].

Currently, there are two types of stay-in-place formwork. The first is a fairly large hollow blocks, of which walls and ceilings are mounted. After installation, they are filled with concrete mixture. Blocks are made of foam cellular plastic (foam polystyrene), based on sawdust-cement mixtures. Hollow claydite and slag concrete blocks are also used. Thus, the concrete core provides structural strength, and the light shell of the blocks provides the necessary heat insulation [4].

The second stay-in-place formwork type is special shuttering panels from which the formwork of walls and floors is assembled. The space between shuttering panels is filled with concrete, claydite concrete, or foam concrete. In the future, the formwork panels are not removed, but only exposed to decorative finishes.

Materials for stay-in-place shuttering panels are glass fiber reinforced concrete, pressed sawdust-cement slab, and extruded polystyrene foam [5]. For a rational combination of thermal insulation and strength properties, two-layer combinations of these materials are often used [6].

One of the main purposes of stay-in-place formwork structures is the creation of a wall structure that meets all modern requirements related to energy efficiency. Therefore, it is extremely important to...
study the thermotechnical properties of such structures and choose the optimal structural solution [7].

Many scientists conduct their studies in this direction [8-10]. The use of three-layer walls with stay-in-place formwork allows erecting wall structures that meet modern requirements and significantly exceed similar brick and large-panel structures in terms of strength and thermal insulation characteristics.

Thus, this paper aims to find an optimal energy-efficient design solution for a three-layer wall using stay-in-place formwork.

To achieve this goal it is necessary to solve a number of research tasks:

1. Analysis of modern types of stay-in-place formwork for erecting multi-layer external walls of buildings in cast-in-situ construction.
2. Simulation the proposed design solutions for three-layer cast-in-situ walls built in stay-in-place formwork in the ELCUT program.
3. Perform a comparative analysis of the thermal characteristics of the studied design solutions.

2. Methodology

To determine the energy-efficient solution of the stay-in-place formwork variant, we applied the method of numerical simulation of heat flow processes in structures using the ELCUT program [11,12].

Simulation in the ELCUT software system is based on the finite element method. Model building in the ELCUT is performed as follows [13-15]: layout geometry building; the assignment of properties; the assignment of boundary conditions; finite element mesh generation; calculation.

The results of the calculation of this program are the temperature at the mesh nodes and the value of the heat flux.

Almost all the enclosing structures of modern buildings are thermotechnically heterogeneous [16]. The calculation is based on the representation of a fragment of the thermal protective shell of the building in the form of a set of independent elements, each of which affects the heat loss through the fragment [17].

When solving heat engineering problems, the “Heat Transfer” module is used. The physical model of thermotechnical problems to be solved is the heat equation. In the case of solving the problem in two-dimensional space [18], in parallel-plane geometry

\[
\frac{\partial}{\partial x}(\lambda(T)\frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(\lambda(T)\frac{\partial T}{\partial y}) = -q(T) - c(T)p\frac{\partial T}{\partial t}
\]  

(1),

in axially symmetric geometry

\[
\frac{1}{r}\frac{\partial}{\partial r}(\lambda(T)\frac{\partial T}{\partial r}) + \frac{\partial}{\partial z}(\lambda(T)\frac{\partial T}{\partial z}) = -q(T) - c(T)p\frac{\partial T}{\partial t}
\]  

(2)

where \( T \) is the temperature; \( t \) is time; \( \lambda(x,y,z,r) \) are components of heat-conduction tensor (in linear performance); \( \lambda(T) \) is the thermal conductivity (temperature function); \( q \) is the specific heat output; \( c(T) \) is the specific heat capacity; \( \rho \) is the density of material.

The solution of the equations is provided if the boundary conditions are satisfied being specified in the process of temperature, heat flux, convection, and radiation simulation.

As a result of solving the problem, we obtain the temperature, heat flow, temperature gradient, combined heat losses in any area and other integrated magnitudes.

The calculation is performed for the city of Chelyabinsk. The data is taken in accordance with current regulatory and technical documentation [19-24]: the estimated temperature of the internal air is 20°C; the estimated outdoor temperature is -34°C; the heating period is 218 days; the average outdoor temperature during the heating period is -7.3°C; heating degree day is 5951°C-days.
Four most common types of stay-in-place formwork with different locations of thermal insulation and structural layers of materials were selected for the research (Tables 1-4). In the experiment, connection of the balcony to the external load-bearing wall of the building was simulated as the most indicative.

**Table 1.** Composition of layers and their characteristics for the “Type 1” construction.

| Element                        | Layer thickness, mm | $\lambda$, W/(m·°C) |
|--------------------------------|---------------------|----------------------|
| Artificial stone panels        | 25                  | 3.49                 |
| Levelling course of sand-cement | 15                  | 0.81                 |
| Penoplex                        | 80                  | 0.031                |
| Concrete                        | 160                 | 1.86                 |
| Foam glass                      | 60                  | 0.08                 |
| Gypsum boards                   | 13                  | 0.21                 |

**Table 2.** Composition of layers and their characteristics for the “Type 2” construction.

| Element                        | Layer thickness, mm | $\lambda$, W/(m·°C) |
|--------------------------------|---------------------|----------------------|
| Concrete (inner layer)         | 50                  | 1.69                 |
| Polystyrene foam               | 150                 | 0.038                |
| Concrete (outer layer)         | 50                  | 1.69                 |

**Table 3.** Composition of layers and their characteristics for the “Type 3” construction.

| Element                        | Layer thickness, mm | $\lambda$, W/(m·°C) |
|--------------------------------|---------------------|----------------------|
| Gypsum mix                     | 100                 | 0.3                  |
| Polystyrene foam               | 125                 | 0.038                |
| Gypsum mix                     | 75                  | 0.3                  |

**Table 4.** Composition of layers and their characteristics for the “Type 4” construction.

| Element                        | Layer thickness, mm | $\lambda$, W/(m·°C) |
|--------------------------------|---------------------|----------------------|
| Artificial stone panels        | 25                  | 3.49                 |
| Gypsum-fiber sheet             | 10                  | 0.3                  |
| Polystyrene foam               | 60                  | 0.038                |
| Gypsum concrete                | 200                 | 0.03                 |
| Foam plastic                   | 60                  | 0.037                |
| Gypsum boards                  | 13                  | 0.21                 |

3. Results and Discussions

The results of numeric simulation are presented in Figures 1-4 and Tables 5. These results demonstrate that the choice of a specific design and technological solution significantly affects the amount of heat flow passing through the balcony connection. An increase in the heat flux leads to an increase in heat losses and, consequently, to the necessity for large expenses to heat such a building, which is consistent with the work of other researchers [25-28].

**Table 5.** Comparative analysis of thermotechnical characteristics of the design solutions studied.

| Design solution | Heat losses through the region of computation, W/m | Reduced heat transfer resistance, m²·°C/W | Thermotechnical uniformity coefficient | Temperature of the coldest part of the inner surface |
|-----------------|---------------------------------------------------|------------------------------------------|---------------------------------------|---------------------------------------------------|
| Type 1          | 304.71                                            | 2.00                                     | 0.54                                  | 19.85                                             |
| Type 2          | 331.41                                            | 1.01                                     | 0.242                                 | 19.90                                             |
| Type 3          | 277.50                                            | 1.18                                     | 0.293                                 | 19.84                                             |
| Type 4          | 295.69                                            | 1.12                                     | 0.277                                 | 19.86                                             |
Figure 1. The results of the “Type 1” wall structure simulation: a geometric model (finite element mesh automated sampling), heat flow isotherms, and thermal field.

Figure 2. The results of the “Type 2” wall structure simulation: a geometric model (finite element mesh automated sampling), heat flow isotherms, and thermal field.

Figure 3. The results of the “Type 3” wall structure simulation: a geometric model (finite element mesh automated sampling), heat flow isotherms, and thermal field.
Figure 4. The results of the “Type 4” wall structure simulation: a geometric model (finite element mesh automated sampling), heat flow isotherms, and thermal field.

4. Conclusions
The results of the studies allow us to draw the following conclusions.

The simulation data and results of economic analysis prove that stay-in-place formwork, made using the method of shotcreting concrete mix or gypsum concrete, demonstrates the best heat engineering properties, which leads to a reduction in heating costs. The “Type 3” wall structure showed a significant difference by 9% heat loss reduction compared with the “Type 1” polystyrene foam formwork and by 16% compared with the “Type 2” technology. Formwork with gypsum concrete as a middle layer (“Type 4”) turned out to be 3% more economical than polystyrene foam formwork filled with concrete.

We associate our further research related to improving the energy efficiency of the studied structures with the study of solutions that most affect the thermal characteristics: improving the technology with the use of shotcrete, increasing the environmental friendliness of the materials used, and combination of stay-in-place formwork and ventilated facade.

References
[1] Berkasova T A 2010 Production of exterior wall panels of Ankom panels using lightweight spatial structure-forming aggregate Bulletin of SibADI 3 46
[2] Fedyuk R S 2013 Monolithic reinforced concrete building envelopes with the use of fixed formwork made of expanded polystyrene Vestnik ISTU 10 185
[3] Fukazawa K, Takahashi S, Kogure N, Shimojyo Y and Eguchi T 2017 Mechanical property evaluation of insulated formwork made from extruded polystyrene foam Journal of Technology and Design 23 7
[4] Nikolaev A E 2009 About the influence of the choice of a constructive solution and manufacturing technology on increasing the thermotechnical uniformity and durability of building envelopes Academia. Architecture and construction 5 329–335
[5] Ruttico P and Pizzi E 2020 Development of a system for the production of disposable carbon fiber formworks Research for Development 221
[6] Kiselman A, Portnyagin D and Shibaeva G 2019 Estimation of influence of heat-conducting inclusions on thermal protection of filler constructions of buildings 22nd International Scientific Conference on Construction the Formation of Living Environment 97 04026
[7] Pedrero M, Flores-Colen I, Silvestre J D, Gomes M G, Silva L, Sequeira P and de Brito J 2020 Characterisation of a multilayer external wall thermal insulation system. Application in a Mediterranean climate Journal of Building Engineering 30 101265
[8] Pukhkal V A and Mottaeva A B 2018 FEM modeling of external walls made of autoclaved aerated concrete blocks Magazine of Civil Engineering 81 202
[9] Larionov A and Minnullina A 2017 Analysis of heat-conducting inclusions in exterior walls of residential building *IOP Conference Series: Earth and Environmental Science* **90** 012188

[10] Tsvetkov N, Khutoroin A, Kozlobrodov A, Romanenko S, Shefer Y and Golovko A 2018 Influence of metal frame on heat protection properties of a polystyrene concrete wall *MATEC Web of Conferences* **143** 01005

[11] Tabunshchikov Yu A 2002 *Mathematical modeling and optimization of thermal efficiency of buildings* (Moscow: AVOK-PRESS) p 194

[12] Fokin K F 2006 *Construction heat engineering of enclosing parts of buildings* (Moscow: AVOK-PRESS) p 256

[13] Dubitsky S D and Ilyina O Ya 2010 Elcut – Engineering tool for FEM modeling of thermal conductivity *International Scientific and Technical Conference "Modern Methods and Means of Researching the Thermophysical Properties of Substances"* 290

[14] Dubitsky S D and Tray V G 2010 ELCUT – engineering system for modeling two-dimensional physical fields *CADmaster* **1** 17

[15] Zinevich L V 2011 Solving construction problems using the ELCUT software package *Construction – shaping the living environment: The fourteenth international inter-university scientific and practical conference of young scientists, doctoral students and graduate students* 47

[16] V G Gagarin and A Yu Neklyudov 2014 Consideration of heat engineering heterogeneities of fences when determining the heat load on the heating system of a building *Housing construction* **6** 3

[17] Avdeev G L, Vakolyuk V S and Kopylov K P 1990 *Guidelines for the calculation of heat-shielding indicators of enclosing structures (external walls, windows, roofs). A guide for designers* (Moscow: MNIITEP) p 102

[18] SP 230.1325800.2015 *Construction enclosing of buildings characteristics of thermal conductive of inclusions*

[19] GOST 30494-2011 *Residential and public buildings. Microclimate parameters for indoor enclosures*

[20] SP 23-101-2004 *Design of thermal protection of buildings*

[21] SP 131.13330.2012 *Building climatology*

[22] SP 50.13330.2012 *Thermal performance of the buildings*

[23] SP 54.13330.2011 *Multicompartment residential buildings*

[24] GOST 26254-84 *Buildings and structures. Methods for determination of thermal resistance of enclosing structures*

[25] Cao V D, Bui T Q and Kjøniksen A L 2019 Thermal analysis of multi-layer walls containing geopolymer concrete and phase change materials for building applications *Energy* **186** 115792

[26] Tamene Y and Serir L 2019 Thermal and economic study on building external walls for improving energy efficiency *International Journal of Heat and Technology* **37** 219

[27] Baiburin A Kh, Rybakov M M and Vatin N I 2019 Heat loss through the window frames of buildings *Magazine of Civil Engineering* **85** 3

[28] Borodinecs A, Prozuments A, Zajacs A and Zemitis J 2019 Retrofitting of fire stations in cold climate regions *Magazine of Civil Engineering* **90** 85

**Acknowledgment**
The work was supported by Act 211 Government of the Russian Federation, contract No 02.A03.21.0011.