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Heat loss from defects of hinged facade systems of buildings

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Abstract. The object of investigation hinged facade systems (HFS) used in buildings. Characteristic violations of the HFS technology were identified. The heat loss which depends on a range of structural features of HFS, such as geometrical, thermal, and physical properties of HFS elements, was analyzed. The effect of HFS properties on changes in heat flow and temperature fields was studied. An experiment was designed, computer simulation and laboratory tests were conducted. Different types of HFS defects were analyzed. Finite-element models were developed in the software ELCUD. Laboratory tests proved the adequacy of finite-element models. The comparative results obtained from tests and numerical models were consistent. Mathematical models of the joint effect of these factors were developed. An analysis of the factors' effect on heat loss through HFS elements was performed. An effective way to ensure the energy efficiency of buildings – energy certification with control at the construction stage, was considered. The results can be used for the energy classification of buildings.

1. Introduction

The object of study was the hinged facade systems of civil buildings. The purpose of the study was to determine the effect of defects in the HFS on heat loss. Scientific findings were used to improve the quality control of the HFS and increase the energy efficiency of buildings.

The objectives of the study were:

- to analyze damage to the structure of HFS affecting the heat-shielding properties of structures, and the rationale for computer simulation of defects;
- to determine the combined effect of defects of HFS on the level of thermal protection of building envelopes;
- to develop organizational and technological solutions for HFS aimed at ensuring standardized indicators of energy efficiency of buildings.

Recently, more and more attention has been paid to studying the energy efficiency of buildings, the temperature and humidity conditions of building envelopes, as well as improving their heat-shielding properties [1–41]. The variety of applied hinged facade systems (HFS) and materials for their elements is noted [1, 5, 12, 13, 16, 17, 21, 25, 28–31]. In the construction industry of Russia, the number of tenders for the construction of HFS is 16 %, and the total area of the facades erected in one year reaches 20 million square meters [32]. At the same time, studies of the influence of design features of HFS on the amount of heat loss have become important [2, 11, 13, 22, 27, 29, 33, 36–40], including when taking into account the operation of ventilated channels [20, 24, 26, 30]. In addition to the estimated energy efficiency of buildings with consideration of their life cycle [2, 9, 10, 31] experimental analysis and construction control are required [3, 4, 6–8, 18, 19, 36–40].

During the construction of new buildings or thermal renovation of old buildings, it is necessary to confirm the class of their energy efficiency by various methods [3, 6–8, 14, 15, 19, 23, 36, 38]. As practice shows, in the applied HFS there are numerous violations of the project during construction which negatively affect the

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energy efficiency of buildings [1, 18, 19, 31–34, 36–40]. Construction control during the installation of building envelopes is often carried out without the use of scientifically based quality control cards or quantitative assessments of the effects of defects on the level of thermal protection.

The analysis of the results of the statistical processing of thermovision control data [36–39] shows that more than a half of the structures examined (62 %) have defects, which indicates their massive occurrence. The overwhelming majority of defects (90 %) are traced at the connection nodes of window units and wall apertures [34, 37].

Neglecting thermal bridges presence can lead to significant underestimation of actual heat flows which can account for 5 % to almost 20 % of total heat flows through the building envelope [40]. Studies have shown, that the value of the point thermal transmittance, which depended on the thermal properties of the envelop and thickness of the layers, might increase to 35 % [39].

The thermograms obtained through thermovision control [34, 36–40] allowed revealing thermotechnical defects:

- local defects of building envelope;
- defects of translucent building envelope elements;
- temperature anomalies in the junction nodes of external wall;
- defects of erection joints in the connection nodes of window units and wall apertures.

The joint effect of defects on heat loss through HVF has not been studied enough. The study [34] was based on similar methods, but focused on a different structure HVF.

It is necessary to conduct research on the assessment of construction discrepancies due to the need to establish a balance between the design decisions made and the actual execution. The compliance of the actual values of the energy passport of the building with design decisions is established by the results of field tests after construction has been completed. The existing practice of applying energy passport, as a rule, boils down to determining heat loss. Defects in thermal protection must be identified in the process of construction control and their significance must be evaluated promptly.

2. Methods

The study of the effect of defects on the thermal protection of HFS was carried out using computer simulation in the ELCUT software package (certificate of compliance for use in construction No. RU.SP15.H00904).

To confirm the adequacy of the computer calculation, the most characteristic defects in the laboratory were simulated on a fragment of the HFS. The tests were carried out in a certified research laboratory at South Ural State University (Chelyabinsk, Russia). The test procedure was in accordance with State Standard of Russia 56623-2015 “Non-destructive testing. The method for determining the heat transfer resistance of building envelopes”, State Standard of Russia 54853-2011 “Buildings and structures. The method for determining the heat transfer resistance of enclosing structures using a heat meter”, and State Standard 25380-2014 “Buildings and structures. The method for measuring heat fluxes passing through a structural enclosure.” These standards establish methods for measuring the density of heat fluxes through single-layer and multi-layer building envelopes and their resistance to heat transfer in laboratory and field conditions.

The conditions of stationary heat flow were provided by the LTHC-24.0 climatic chamber with a useful volume of 24 m^3. The experiment was carried out in the climactic conditions of the city of Chelyabinsk, Russia (55 degrees N, heating degree-day of 6000). The temperature in the room was 21 °C and -34 °C in the chamber. The set of instrumentation equipment included: a FLIR E60 thermal imager; a ITP-MG4.03.10 Potok 10-channel device; a TGTs-MG4 thermohygrometer; a TEMP-3.2 thermohygrometer; a ISP-MG4 Zond heat conductivity meter, etc.

The object of the laboratory study was a fragment of the building envelope of the HFS. Fragment dimensions: height – 1275 mm, width – 1255 mm, thickness – 300 mm, usable area – 1 m^2. As a carrier layer, masonry from tongue-and-groove aerated 625×250×200 mm D500 concrete blocks was used. Vertical and horizontal masonry joints were made with 5 mm thick Ceresit CT 21 glue. LINEROCK mineral wool boards γ = 80 kg/m^3 of 1000×500×100 mm were used as the heat-insulating layer. To fasten the insulation, 160×8 mm Mungo MDD-S plate-shaped dowels with a metal nail were used. The HFS guide rails were fastened using a 150-50×50 mm KR Alternative bracket and wall dowel with a 10×100/50 MBK-STB screw. The values of the thermal conductivity coefficients of the materials used: D500 gas concrete block – 0.181 W/(m °C); insulation – 0.037 W/(m °C).

After obtaining the results of the laboratory experiment, numerical simulation was performed using the ELCUT software package and the consistency of the results was evaluated.

3. Results and Discussion

Industrial studies of the quality of the HFS were performed on 20 precast-monolithic, monolithic, and brick civil buildings in Chelyabinsk (Russia). The main defects of thermal protection were established: gaps in the joint of insulation boards; gaps at the junction of the bracket with the insulation board; detachment of the insulation from the foundation; gaps in the expansion joint between the foundation and the floor slab; deviations of insulation thickness; and deviations of thermal conductivity coefficients of foundation materials, heat-insulating layer, bracket, and expansion joint. Industrial studies have established that the first four defects are the most characteristic (Fig. 1).

Figure 1. Defects in thermal protection: from top to bottom and from left to right: gap at the junction of the insulation boards; gap at the junction of the bracket with insulation; detachment of the insulation from the foundation; defects in materials; level defects.

The defectiveness characteristics for technological deviations from tolerances were studied during the construction of the HFS (Table 1). The defect level in some parameters reaches 35–45 %. The identified defects can reduce the level of thermal protection of walls to 30–50 %, which is confirmed by research data [7, 11, 18, 22, 31, 32, 37] on significant differences between the design and actual thermal characteristics of building shells.

Table 1. Defectiveness in some quality parameters.

Monitored parameters	$\overline{X}$	S_x	δX_n	Q
Gap at the junction of insulation boards	0.63	0.70	2.00	0.45
Gap at the junction of the bracket with the insulation board	1.47	0.62	5.00	0.41
Peeling of insulation boards from the foundation	1.58	0.52	6.00	0.35
Gap in the expansion joint between the foundation and the floor slab	3.36	0.25	30.00	0.43

Notes: $\overline{X}$ is average value of the parameter; S_x is standard deviation; δX_n is standard deviation of the parameter; Q is defective level.

Simulations were carried out in the program ELCUT o study the effect of these defects on the level of thermal protection. The adequacy of the simulation was verified through laboratory studies and subsequent analysis of the reliability and consistency of the results. The influence of thermal protection defects was modeled using typical HFS defects: gaps (t = 10 mm) at the junction of the insulation boards, gaps (t = 15 mm) at the junction of the bracket with the insulation board, and peeling (t = 10 mm) of the insulation boards from the load-bearing foundation (Fig. 2).

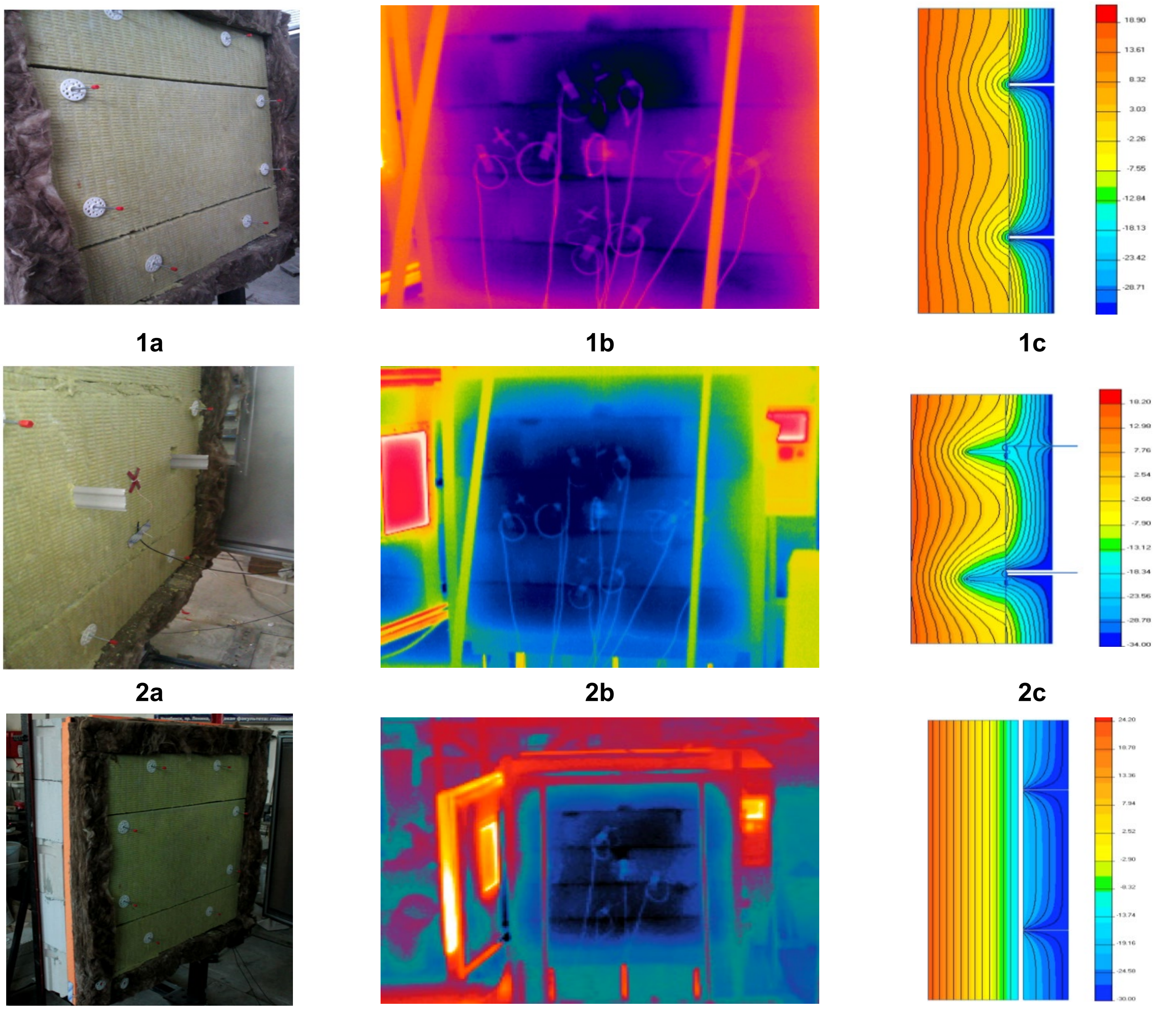


Figure 2. Tested wall fragments with defects in thermal protection:
1) gap at the junction of the insulation boards;
2) gap at the junction of the insulation boards and the bracket;
3) peeling of insulation boards from the foundation;
a) fragment of the enclosing structure; b) thermogram of the fragment;
c) temperature field of the cross section of the fragment.

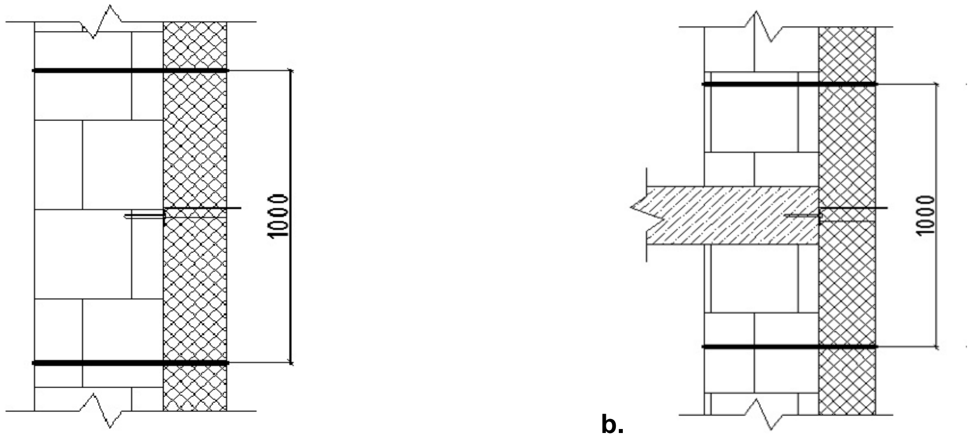
Computer modeling of the wall fragments was carried out subject to the equality of geometric and physical and technical characteristics, boundary conditions of the computer model, and the experimental fragment. Generalized results of the level of thermal protection were obtained through laboratory research and modeling (Table 2). The reduction in the heat transfer resistance was from 5 to 52 %, which correlates with research data [32] on the influence of such defects – up to 52–55 %. The discrepancy between the results of laboratory studies in the climate chamber and computer simulation ranged from 0.65 to 6.64 %. Thus, we can conclude that the numerical models used are adequate.

Table 2. Generalized results of the assessment of the impact of separate defects.

Object of study	R_o^{np} *exp*, (m²·°C)/W	R_o^{np} *ELCUT*, (m²·°C)/W	Discrepancy, %
Fragment of structure without defects	3.24	3.39	4.63
Fragment with peeling of insulation boards from the foundation (t = 10 mm)	1.56	1.58	1.28
Fragment with a gap at the junction of insulation boards (t = 10 mm)	2.26	2.41	6.64
Fragment with a gap at the junction of the bracket with the insulation board (t = 15 m)	3.08	3.10	0.65

Based on the results obtained on the reliability of computer modeling in ELCUT, a mathematical experiment was conducted to determine the combined effect of the main defects of thermal protection.

A numerical experiment was conducted for a blank section of the outer wall (Fig. 3a) and for a plot in the zone of the floor slab (Fig. 3b). Based on the results of calculating the temperature field and the heat flux power, the reduced heat transfer resistance of the HFS wall fragment was determined.



a. b.

Figure 3. Fragment of the outer wall with the HFS:
a) scheme of the blind section; b) scheme of the section in the area of the floor slab.

A multifactor model was implemented by the methods of planning the experiment, in which the characteristic defects of the thermal protection of the HFS were taken as factors. The values of the levels of variation of factors were determined based on the results of production studies of the quality of work, as well as from analysis of regulatory documents and technical certificates for HFS.

After eliminating insignificant factors, mathematical models were constructed of the combined influence of significant defects on the level of thermal protection of the blind section of the HFS wall (1) and the section in the zone of the floor slab (2). The adequacy of the constructed mathematical models is proved using the Fisher criterion:

$$\begin{aligned} k_I = {} & 0.6684 - 0.0837 \cdot X_1 - 0.0163 \cdot X_2 - 0.1761 \cdot X_3 + 0.0287 \cdot X_4 - \\ & -0.0768 \cdot X_5 - 0.1676 \cdot X_6 + 0.0829 \cdot X_7 + 0.0441 \cdot X_1 \cdot X_3 - 0.0266 \cdot X_1 \cdot X_5 - \\ & -0.0471 \cdot X_1 \cdot X_6 + 0.0165 \cdot X_1 \cdot X_7 + 0.0160 \cdot X_3 \cdot X_4 - 0.0324 \cdot X_3 \cdot X_5 - \\ & -0.0698 \cdot X_3 \cdot X_6 + 0.0503 \cdot X_3 \cdot X_7 - 0.0334 \cdot X_4 \cdot X_5 + 0.0229 \cdot X_4 \cdot X_6 \end{aligned} \tag{1}$$

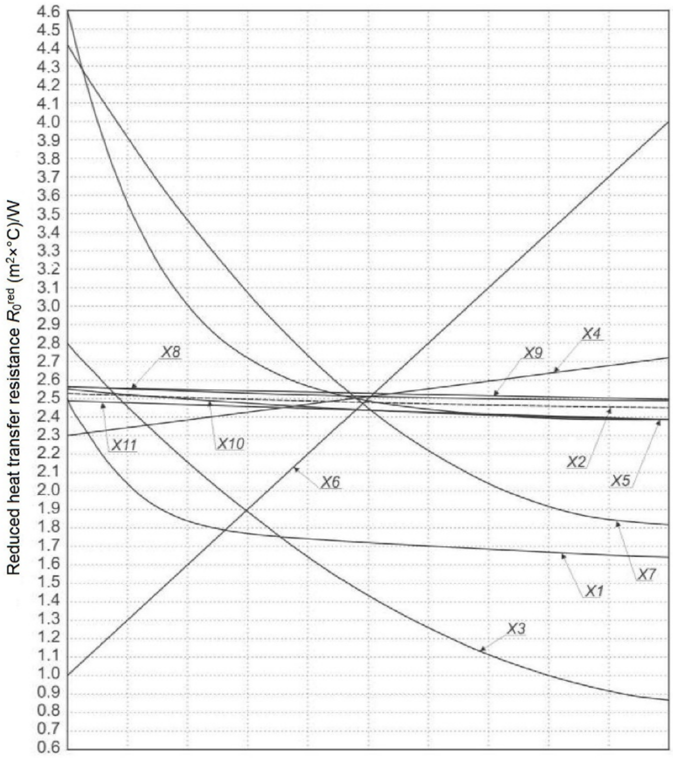
$$\begin{aligned} k_{II} = {} & 0.4920 - 0.0896 \cdot X_1 - 0.1696 \cdot X_3 + 0.0687 \cdot X_5 - 0.1683 \cdot X_6 + \\ & +0.0736 \cdot X_7 - 0.1003 \cdot X_{10} + 0.0497 \cdot X_1 \cdot X_3 - 0.0391 \cdot X_1 \cdot X_6 + \\ & +0.0236 \cdot X_1 \cdot X_{10} - 0.0425 \cdot X_3 \cdot X_6 + 0.0336 \cdot X_3 \cdot X_7 + 0.0433 \cdot X_3 \cdot X_{10} - \\ & -0.0284 \cdot X_5 \cdot X_6 + 0.0531 \cdot X_5 \cdot X_{10} - 0.0232 \cdot X_6 \cdot X_7 \end{aligned} \tag{2}$$

where k_I is the coefficient of the combined influence of factors on the thermal protection of the blind part of the outer wall of the HFS; k_{II} is coefficient of the joint influence of factors on the thermal protection of the HFS wall section in the area of the floor slab; X_1 is the gap at the junction of the insulation boards; X_2 is the gap at the junction of the bracket and insulation board; X_3 is detachment of the insulation from the foundation; X_4 is deviation of the thickness of the foundation; X_5 is deviation of the coefficient of thermal conductivity of the foundation material; X_6 is deviation of the thickness of the insulating layer; X_7 is deviation of the coefficient of thermal conductivity of the material of the insulating layer; X_8 is deviation of the thickness of the bracket; X_9 is deviation of the coefficient of thermal conductivity of the material of the bracket; X_{10} is gap in the expansion joint between the foundation and the floor slab; X_{11} is deviation of the coefficient of thermal conductivity of the material filling the expansion joint between the foundation and the slab. The influence of these factors on the level of thermal protection is presented in Fig. 4.

X_1, X_2 and X_3 are significant defects for the blind sections of the HFS walls and X_1, X_3, and X_{10} for sections of HFS walls in the area of the floor slab. Of the characteristic defects, the greatest influence on the reduced heat transfer resistance is exerted by: peeling of 10 mm of insulation boards from the foundation is 52 %; a gap of 10 mm at the junction of insulation boards is 15 %; a gap of 15 mm at the junction of the bracket and insulation is 3 %, and combined defects. The results obtained nearly coincided with the data of [32] – a decrease in heat transfer resistance by 10–16 % with a gap at the junction of 8 mm single-layer insulation boards.

In addition to the defects studied, a great influence on the thermal protection of HFS is exerted by:

- filling masonry voids with mortar using hollow brick – a decrease of 13–41 % [18];
- use of single-layer thermal insulation with an increase in the gaps between the insulation boards to 4–8 mm – a decrease of 4–16 % [32] as calculated by taking into account the highly ventilated gap according to DIN EN ISO 6946 [35];
- heat engineering heterogeneities of the mounting frame (substructure) [12, 13, 31, 33] – reduction by 30–40 % (coefficient of heat engineering heterogeneity r = 0.6–0.7); heat loss through window sills [34];
- geometric and thermophysical characteristics of the ventilated gap – the effect depends on the conditions of heat and moisture transfer in the gap [1, 30, 33].



X1	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009	0.010
X2	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009	0.010
X3	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009	0.010
X4	0.120	0.172	0.224	0.276	0.328	0.380	0.432	0.484	0.536	0.588	0.640
X5	0.120	0.313	0.506	0.699	0.892	1.085	1.278	1.471	1.664	1.857	2.050
X6	0.040	0.061	0.082	0.103	0.124	0.145	0.166	0.187	0.208	0.229	0.250
X7	0.032	0.0378	0.0436	0.0494	0.0552	0.061	0.0668	0.0726	0.0784	0.0842	0.090
X8	0.001	0.0014	0.0018	0.0022	0.0026	0.003	0.0034	0.0038	0.0042	0.0046	0.005
X9	58.0	74.3	90.6	106.9	123.2	139.5	155.8	172.1	188.4	204.7	221.0
X10	0.01	0.014	0.018	0.022	0.026	0.030	0.034	0.038	0.042	0.046	0.050
X11	0.035	0.1245	0.214	0.3035	0.393	0.4825	0.572	0.6615	0.751	0.8405	0.930

Figure 4. Dependence of the reduced heat transfer resistance of the external wall with the HFS on the factors X1–X11: X1 is gap at the junction of the insulation boards; X2 is gap at the junction of the bracket with the insulation plate; X3 is peeling of the insulation boards from the foundation; X4 is deviation of the thickness of the foundation; X5 is deviation of the thermal conductivity of the foundation material; X6 is deviation of the thickness of the insulating layer; X7 is deviation of the coefficient of thermal conductivity of the insulation material; X8 is deviation of the thickness of the bracket; X9 is deviation of the thermal conductivity of the bracket; X10 is gap in the expansion joint between the foundation and the floor slab; X11 is deviation of the coefficient of thermal conductivity of the material filling the expansion joint between the foundation and the slab.

To reduce the defectiveness of the HFS, it is necessary to develop organizational and technological measures: strengthen technological discipline; regulate operational control using special control cards; justify tolerances and confirmation of energy passport data taking into account technological deviations.

In the course of construction, checklists for the registration of thermal protection defects should be drawn up. These sheets are part of the as-built documentation for the HFS, represented by sections of three types: I – the blind section of the outer wall; II – the section of the outer wall in the area of the floor slab, III – sections of the wall with a window. The sheets indicate: controlled work zones; type of section of the outer wall; thermal conductivity coefficients of wall materials; wall layer thicknesses; window construction; and defects of thermal protection with an indication of their values and quantity on a controlled work zone. If defects are corrected, sheet inspection should be repeated.

Upon receipt of the work zone, the coefficient of the combined influence of significant heat protection defects is calculated and the actual value of the reduced heat transfer resistance is determined:

$$R_{w,i} = R_w \cdot k_{j,i}. \quad (3)$$

where R_w is calculated value of the reduced heat transfer resistance of the outer wall; i is work zone number; $R_{w,i}$ is value of the reduced heat transfer resistance of the outer wall, taking into account the combined influence of significant defects on the i-th work zone; $k_{j,i}$ is coefficient of joint influence of significant defects on the i-th work zone of the j-th wall section (type I, II or III).

For example, for the wall sections of type I and II:

$$k_{I,i} = k_{I,i}^{X_1} \cdot k_{I,i}^{X_2} \cdot k_{I,i}^{X_3}; \qquad k_{II,i} = k_{II,i}^{X_1} \cdot k_{II,i}^{X_3} \cdot k_{II,i}^{X_{10}}, \quad (4)$$

where $k_{I,i}^{X_1}, k_{I,i}^{X_2}, k_{I,i}^{X_3}$ are coefficients of influence factors X_1, X_2, X_3 on thermal protection of the i-th work zone of a blank section of the outer wall the HFS; $k_{II,i}^{X_1}, k_{II,i}^{X_3}, k_{II,i}^{X_{10}}$ are coefficients of influence factors X_1, X_3, X_{10} on thermal protection of the i-th work zone of the HFS wall section in the area of the floor slab.

Tolerances in the performance of work are assigned based on the conditions:

$$k_I^{X_1} \cdot k_I^{X_2} \cdot k_I^{X_3} > k_{cal}; \quad k_{II}^{X_1} \cdot k_{II}^{X_3} \cdot k_{II}^{X_7} > k_{cal}, \quad (5)$$

where k_{calc} is calculated boundary value of the coefficient of influence of defects, at which the heat-shielding properties of the outer walls satisfy the requirements of thermal protection established by the norms:

$$k_{cal} = \max\left\{R_{\min}, R_{req}\right\} / R_w, \quad (6)$$

where $R_{\min}$ is minimum permissible value of reduced heat transfer resistance; and R_{req} is boundary value of the reduced heat transfer resistance, which provides a sanitary-hygienic indicator of thermal protection.

Acceptance control for HFS is carried out through construction control by the client as part of the assessment of the compliance of building envelopes with the requirements of design documentation, including the requirements of thermal protection and energy efficiency. In some cases, by decision of the client or the state construction supervision body, continuous or selective instrumental control may be assigned to determine the actual values of the monitored parameters and for filling out the energy passport of the building upon commissioning.

Due to the design features of HFS, instrumental control of thermal protection of external walls is time-consuming and expensive. It is possible to complete this control with satisfactory error level only after the completion of construction. An alternative is to calculate the value of the reduced heat transfer resistance during the construction process, which makes it possible to quickly make decisions to eliminate possible violations. In case of violations during construction control that affect the thermal protection of the external walls, it may be necessary to recalculate the value of the reduced resistance to heat transfer of the external walls, which is entered in the energy passport.

The results of this study are reflected in the standard "Union of construction companies of the Urals and Siberia" 02–2013 "Assessment of the energy efficiency of buildings. Monitoring compliance with the requirements of thermal protection of building envelopes." Energy certification with control at the construction stage made it possible to increase the reliability of assessing the compliance of buildings with energy saving requirements. The research results can be used for the energy classification of buildings, both in Russia and abroad (taking into account the requirements of national standards).

4. Conclusions

1. We studied the main defects of thermal protection through HFS which have a significant impact on the energy efficiency parameters of civil buildings. Production studies of defects were carried out in the city of Chelyabinsk (Russia, 55 deg. N) in summer and winter conditions. The main defects: gaps in the junction of insulation boards; gaps at the junction of the bracket with the insulation plate; detachment of the insulation from the foundation; gaps in the expansion joint between the foundation and the floor slab. For some

parameters, the level of defectiveness reaches 35–45 %, which, given combined manifestation of defects, can significantly reduce the heat transfer resistance of the shell. Laboratory experiments in the climate chamber on fragments of real structures substantiated the reliability of the assessment of the influence of defects on the level of thermal protection by numerical simulation in ELCUT.

2. The dependencies of the influence of the main defects on the reduced heat transfer resistance of the wall are revealed and mathematical models of the combined effect of the defects of the HFS on the level of their thermal protection are constructed. The reduction in reduced heat transfer resistance was from 5 to 52 %. Models make it possible to quickly assess the significance of defects, substantiate regulatory tolerances, and draw up scientifically based quality control cards.

3. Organizational and technological solutions for quality control of the device of enclosing structures are proposed, aimed at increasing the energy efficiency of buildings. Based on these solutions, regulations were developed to confirm the energy passport of the building, taking into account the real-world execution of design decisions. The methodology for assessing manufacturing defects with corrections to buildings' energy passport of can be used not only in Russia, but also in other countries, taking into account national standards for energy saving in construction.

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