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Probabilistic Analysis of Window Frame Junctions' Thermal Reliability Indicators to Precast Concrete and Brick Walls

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Abstract: The side junctions of metal-plastic block frame windows to the walls of residential buildings at different positions of window frames in the wall cavity are analysed. The duration of thermal failure state by the condensate formation criterion was used as a probabilistic indicator of reliability. The units of uninsulated walls, erected in the second half of the 20th century, have a clearly insufficient thermal reliability level. Thermal insulation of walls according to current design standards in most cases ensures an acceptable of the thermal failure state duration.

Keywords: condensate; thermal failure state duration; window junctions

1 INTRODUCTION

A necessary condition for ensuring the comfort of buildings is a sufficient thermal reliability level of enclosing structures. A significant number of studies and regulations are devoted to solving this problem, which establish general criteria for ensuring thermal reliability [1, 2], performed climatic zoning of territories [3, 4], investigated the thermal characteristics of insulating materials and enclosing structures [5, 6], the optimal characteristics of thermal insulation are calculated [7-9] and heat losses are analysed in order to minimize them [10-12].

In [1, 13] it is shown that one of the dangerous types of thermal failures is the condensate formation in areas of high thermal conductivity. Condensation can form if the temperature of the inner surface falls below the dew point temperature [1, 2, 13]. This phenomenon can be prevented by sufficient insulation and the choice of a rational design scheme that eliminates areas of high thermal conductivity or reduce their impact.

A typical example of such zones of high thermal conductivity are the junctions of the windows to the walls. The study of temperature regime and heat loss depending on the location of windows in the cavity wall was performed in [13-18] by constructing a mathematical model of two-dimensional temperature fields. In these works, it is shown that shifting the window inside can significantly increase the internal jamb temperature and thus reduce the risk of condensation. This applies both to windows in the walls of modern structures [13, 14] and to old buildings that are subject to thermal modernization. [17, 18]. In the study [13], based on the data of temperature fields in seven junctions of window frames to walls of different construction, it is shown that high-quality wall insulation drastically increases the temperature of window jamb. The block frame window position in a cavity of the sufficiently insulated wall affects the temperature in critical areas of the nodes slightly.

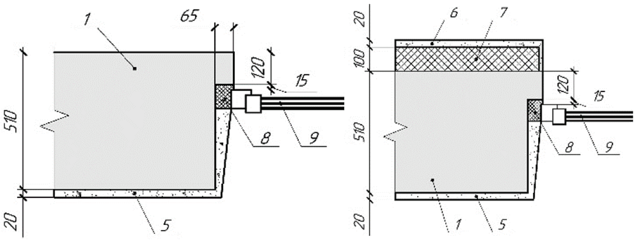
The main disadvantage of the studies above is the use of fixed values of the design parameters without considering their random nature. To adequately evaluate the possibility of thermal failure based on the criterion of condensation formation, it is worth to consider random nature of the both outside and the inside air temperatures, temperatures of inner surface and the dew point. Probabilistic methods are widely used for evaluating the reliability level by the criterion of loss strength of load-bearing structures [19-22].

A much smaller number of studies are devoted to the probabilistic approach of assessing the thermal reliability level of enclosing structures. In particular, in [1] the general requirements for thermal reliability are stated. Article [22] is devoted to the assessment of the thermal failures probability of enclosing structures that are made of lightweight expanded polystyrene concrete with a frame made of bent steel profiles. In article [23] it is proposed to use the probability level of failure and the possible absolute (in units of time) or relative (fraction of the service life) thermal failure state duration as a thermal reliability indicator. The principles of estimating the thermal failure durations according to the comfort criteria and condensate formation in areas of high thermal conductivity are substantiated there.

This study aim is to develop a practical method that allows to estimate the thermal failure duration by the condensate formation criterion and to analyse the thermal reliability of the window frame nodes to walls of residential and public buildings taking into account real climatic conditions and variable position of this windows in a wall cavity.

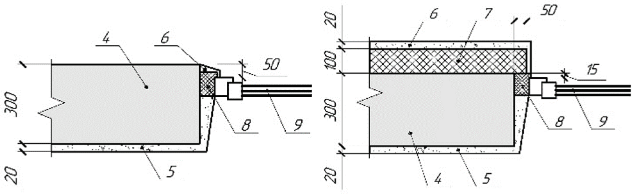
2 RESEARCH OBJECTS

The side junctions of metal-plastic windows of different structures are analysed, the schemes of which are shown in Fig. 1 according to the article [13]. Units of "a" and "c" types correspond to typical brick and panel walls of residential buildings of the last century, in which worn-out wooden windows are replaced by modern metal-plastic block frame windows with 70 mm thick elements and double-glazed frames. Units of "b" and "d" types are formed as a result of thermal modernization of such buildings by performing facade insulation. Units of types "e", "f" and "g" are typical for bearing and self-bearing walls of modern residential buildings that are insulated according with the requirements of the DBN [2]. Sealing of the wall junctions is performed according with [24]. Thermal insulation of walls is made with mineral wool or expanded polystyrene insulation slabs, which have very close coefficients of thermal conductivity. The thickness of the thermal insulation layer provides a heat transfer resistance of not less than 3.3 m^2·K/W, established by the standards [2] for the first temperature zone of Ukraine. Thermophysical characteristics of all materials that are shown in Fig. 1 are taken according to the standard [25].



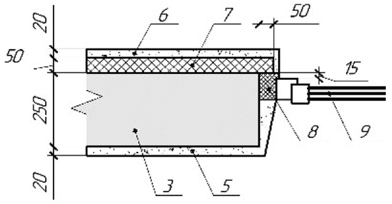
a) uninsulated wall made of solid brick

b) insulated wall made of solid brick

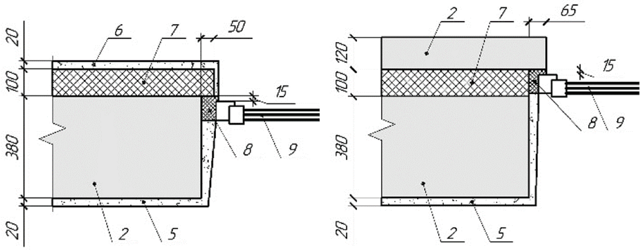


c) uninsulated precast concrete walls

d) insulated precast concrete wall



e) aerated concrete wall



f) insulated wall made of hollow brick

g) three-layer wall made of hollow brick

Figure 1 Schemes of block frame windows side junctions to the walls
1 – solid brick; 2 - hollow brick; 3 - aerated concrete blocks; 4 - expanded clay concrete wall; 5 - lime-sand mortar plaster; 6 - cement-based plaster; 7 - mineral wool insulation; 8 - polyurethane foam; 9 - triple-glazed window.

Fig. 1 shows the diagrams of the block frame windows junctions to walls along their thickness. In order to find a rational position of the windows, each of these junctions is analysed by different shift of window inside the building in relation to their normal position. The cavities formed on external jambs as a result of such shift are filled with mineral wool or expanded polystyrene which are protected from atmospheric influences by external plaster based on cement mortar along a reinforcing mesh.

3 TEMPERATURE REGIME OF NODES

The temperature regime of the units shown in Fig. 1 was investigated in our work [13]. The critical zones of all nodes are the junction points of the internal jamb to the block frame window, where the inside surface of the wall has the lowest temperature. Temperature fields of nodes at different positions of windows are constructed by computer simulation using the THERM program. The dimensions of the simulated nodes correspond to Fig. 1, and the thermophysical properties of the materials were taken as in [25]. The temperature of external atmospheric air is considered as –24 °C and the temperature of air indoors as +20 °C.

Table 1 The results of estimating the duration of thermal failures

Wall type	x, mm	ϑ_{cr}, °C	R_{ef} m^2·K/W	Duration of thermal failure (h/year)		
				Kropyvnytskyi	Krivoy Rog	Semenivka
a) uninsulated wall made of solid brick	0	7,7	0,411	334,3	289,8	483,9
	30	8,4	0,436	239,7	206,0	355,6
	60	8,9	0,456	183,8	157,1	277,5
	90	9,4	0,477	137,4	116,8	211,1
	120	9,7	0,491	113,9	96,5	176,8
	150	10,3	0,521	75,9	63,9	120,1
b) insulated wall made of solid brick	0	10,7	0,544	56,5	47,4	90,5
	30	11,2	0,575	37,9	31,7	61,6
	60	11,4	0,588	32,1	26,8	52,3
	90	11,8	0,617	22,5	18,7	37,0
	120	11,9	0,624	20,5	17,1	33,8
	150	12,3	0,657	14,0	11,7	23,2
c) uninsulated precast concrete wall	0	8,4	0,436	239,7	206,0	355,6
	25	8,9	0,456	183,8	157,1	277,5
	50	9,5	0,482	129,2	109,7	199,2
	75	9,5	0,482	129,2	109,7	199,2
	100	9,6	0,486	121,4	102,9	187,8
e) aerated concrete wall	0	12,8	0,702	8,42	7,00	14,01
	25	12,7	0,693	9,35	7,77	15,55
	50	12,7	0,693	9,35	7,77	15,55
	75	13,2	0,744	5,45	4,53	9,08
	100	13,1	0,733	6,09	5,06	10,15
f) insulated wall made of hollow brick	0	13,1	0,733	6,09	5,06	10,15
	25	13,0	0,722	6,80	5,65	11,32
	50	13,0	0,722	6,80	5,65	11,32
	75	13,1	0,733	6,09	5,06	10,15
	100	13,0	0,722	6,80	5,65	11,32
	125	13,2	0,744	5,45	4,53	9,08
	150	13,1	0,733	6,09	5,06	10,15
g) three-layer wall made of hollow brick	0	13,4	0,766	4,35	3,62	7,24
	25	13,4	0,766	4,35	3,62	7,24
	50	13,5	0,778	3,88	3,23	6,45
	75	13,5	0,778	3,88	3,23	6,45
	100	13,4	0,766	4,35	3,62	7,24
	125	13,4	0,766	4,35	3,62	7,24
	150	13,5	0,778	3,88	3,23	6,45

According to calculations performed in [13] the critical zone ϑ_{cr} temperatures are obtained for all nodes at different values of displacement x of the window from the normal position, shown in Fig. 1. The results of the study [13] are shown in Tab. 1. Taking into account the architectural and ergonomic requirements, as well as the design of the wall, the shift of the window varied within x = 0-150 mm. Tab. 1 shows that for walls of types "a", "b" and "c", ie walls made of solid brick and uninsulated precast concrete walls, the shift of the block window inside the building results in a considerable increase in the critical area temperature of the node. This effect is little expressed or even practically absent for nodes of other types.

4 METHOD OF THE PROBABILISTIC ESTIMATION OF THE THERMAL RELIABILITY LEVEL

The method is based on the representation of outdoor and indoor air temperature in the form of sequences of random variables with a normal distribution law for 12 months of the year. It also based on introduced by the authors concept of heat transfer resistance [23], which connects outdoor air temperature and a specified point of the enclosure. Statistical characteristics of outside air temperature can be established according to the data of works [4, 26], or by processing the results of meteorological observations.

As a numerical indicator of the thermal reliability, it is proposed in [23] to use the probable thermal failure state duration. This value is a physically understandable indicator that allows to compare different design solutions of junctions and to make conclusions about their suitability for operation. Principles and general methods for estimating the probable thermal failure state duration of enclosing structures using various criteria are proposed in the work of the authors [23]. In paper, these methods are adapted for estimation of the probable the thermal failure state duration by the condensate formation criterion in the zone of increased thermal conductivity. The basic thermal characteristic of the window side junction to the wall is the conditional value of heat transfer resistance R_{ef} for the suggested critical zone of the inside window jamb surface proposed in [23]

$$R_{\mathrm{ef}}=\frac{\vartheta_{\mathrm{in}}-\vartheta_{\mathrm{out}}}{\alpha_{\mathrm{in}}\left(\vartheta_{\mathrm{in}}-\vartheta_{\mathrm{cr}}\right)} \tag{1}$$

where ϑ_{out} and ϑ_{in} – outdoor and indoor air temperatures; α_{in} – internal heat transfer coefficient.

Random variable has expected value and the value of standard deviation of the critical zone temperature of the node in the i^{th} month that is calculated by the formulas obtained in [23]. These formulas are based on the method of linearization of functions of random variables [27]:

$$\begin{aligned} M_{\mathrm{cr},\,i}&=\frac{1}{R_{\mathrm{ef}}\cdot\alpha_{\mathrm{in}}}\left[M_{\mathrm{in}}\left(\alpha_{\mathrm{in}}\cdot R_{\mathrm{ef}}-1\right)+M_{\mathrm{out},\,i}\right]\\ S_{\mathrm{cr},\,i}&=\frac{1}{R_{\mathrm{ef}}\cdot\alpha_{\mathrm{in}}}\sqrt{S_{\mathrm{out},\,i}^{2}+S_{\mathrm{in}}^{2}\left(\alpha_{\mathrm{in}}\cdot R_{\mathrm{ef}}-1\right)^{2}} \end{aligned} \tag{2}$$

where R_{ef} – conditional heat transfer resistance of the node; M_{in} and S_{in} – expected value and the standard deviation of a random variable of indoor air temperature; $M_{\mathrm{out},i}$ and $S_{\mathrm{out},i}$ – expected value and the standard deviation of a random variable of outdoor air temperature in the i^{th} month.

Failure by the condensate formation criterion occurs due to temperature drop of the inner surface ϑ_{cr} below the dew point temperature ϑ_{dew}, so the reliability condition can be written in the form of an inequality

$$\vartheta_{\mathrm{cr}}-\vartheta_{\mathrm{dew}}\geq 0 \tag{3}$$

Considering the random nature of both temperatures, the expected value and the standard deviation in the i^{th} month in (3) are as follows:

$$M_{i}=M_{\mathrm{cr},\,i}-M_{\mathrm{dew}}\,;\;S_{i}=\sqrt{S_{\mathrm{cr},\,i}^{2}+S_{\mathrm{dew}}^{2}} \tag{4}$$

where M_{cr} and S_{cr} – expected value and the standard deviation of random value of internal surface temperature of the wall according to (2); M_{dew} and S_{dew} – expected value and the standard deviation of random dew point temperature.

The presence of statistical characteristics (4) allows us to estimate the thermal failure state duration due to the probability of a random value of the thermal reliability reserve (3) below zero. The absolute and relative thermal failure state duration for one year are equal

$$Q_{\mathrm{abs}}=\sum_{i=1}^{12}\left[\tau_{i}\;F_{i}(0)\right];\;Q_{\mathrm{rel}}=\frac{1}{12}\sum_{i=1}^{12}F_{i}(0) \tag{5}$$

where $F_i(0)$ – normal distribution function of thermal reliability reserve for the i^{th} month; τ_i – duration of the i^{th} month.

The absolute duration of the thermal failure state during the year Q_{abs} is expressed in units of time, in which to the formula (5) durations of months τ_i are substituted. The relative thermal failure state duration Q_{rel} is a part of the enclosing structure service life, during which the thermal failure of the unit is occurred. Essentially, the values Q_{abs} and Q_{rel} determine the time during which the formation of condensate on the internal window jamb surface may occur.

5 THE RESULTS OF ASSESSING THE THERMAL RELIABILITY LEVEL OF THE NODES

The side junctions of block frame windows to the walls of different structures, which are shown in Fig. 1 and listed in Tab. 1, were analysed. For each node, the table shows the conditional heat transfer resistance for the critical zone of the node Ref by Eq. (1) and the absolute thermal failure state duration by the condensate formation criterion Q_{abs} in hours per year. These values are calculated by Eq. (5) for different positions of the windows, with the value of the shift x. Climatic conditions of the cities of Kropyvnytskyi, Kryvyi Rih and Semenivka of Chernihiv region were taken into account. The cities of Kryvyi Rih and Semenivka are selected as areas with the highest and lowest average annual air temperature within the first temperature zone of Ukraine according to the DBN map [2].

Expected values $M_{\mathrm{out},i}$ and standard deviations $S_{\mathrm{out},i}$ of the atmospheric air temperature in each month for the three cities of Ukraine are taken according to [4, 26]. The indoor air temperature is also a random variable, its statistical characteristics are established by the results of field observations in several dwellings during the heat season. The generalization of these data performed in [23], taking into account the regulatory requirements [2] for the temperature in dwellings allowed to take M_{in} = 20 °C, S_{in} = 0,6 °C.

The dew point temperature ϑ_{dew} at deterministic values of air temperature and relative humidity is determined by psychometric tables. Random variability of microclimate parameters in the room determines the random nature of the dew point temperature. Taking into account the possible variability of these parameters, the expected value and the standard deviation of the random dew point temperature in residential premises were established in [23] as M_{dew} = 10,6 °C, S_{dew} = 1,7 °C, which were taken into account when estimating the thermal failures duration of the considered nodes.

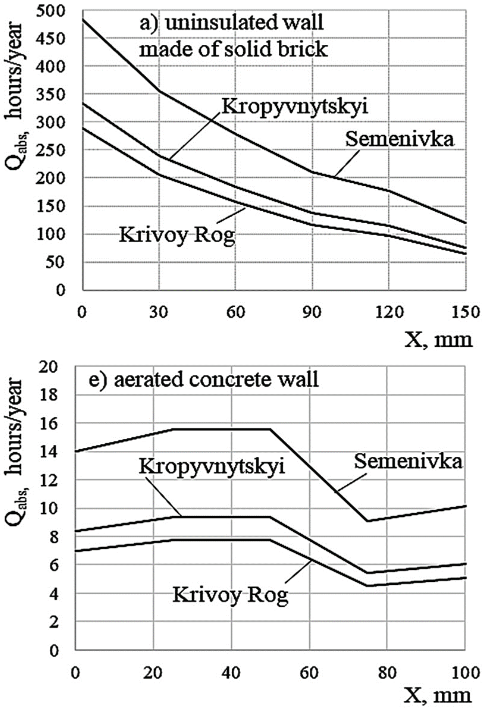


Figure 2 Dependences of the thermal failure state duration of the nodes on the position of the window frames.

As examples according to table 1 the dependences of the absolute thermal failure state duration on the amount of displacement of the window unit for nodes of type "a" and "e" are shown in Fig. 2. The figure shows that the the thermal failure state duration of nodes "a" in the initial state Q_{abs} = 290-484 hours/year is too high. Shifting the block frame window inside the building reduces the duration of the thermal failure state to about Q_{abs} = 100-150 hours per year, but it is also too high and will adversely affect the operation state of junction. The use of modern walls from aerated concrete with front insulation (node "e") reduces the duration of a thermal failure state to Q_{abs} = 4-16 h/year. The position of the window has less effect on the reliability of the node, although from Fig. 2 it is possible to determine the optimal shift value x = 80-100 mm.

The thermal failure state duration of other nodes in the first temperature zone [2] are shown in table 1. Similarly with the temperature of critical areas changes, nodes can be divided into two types. The reliability level of nodes "a", "b", "c" essentially increases with the shift of the window inside the wall cavity. As for nodes of other types, the displacement of the window has a small and unsystematic effect on the thermal failure state duration by the condensate formation criterion. Table 1 shows a significant variation in the thermal failure duration within the first temperature zone. During the transition from the city of Kryvyi Rih with the warmest climate to the city of Semenivka with the lowest air temperatures in the first zone, the duration of thermal failure increases by 1.7-2.0 times.

In the works of the authors based on the thermal reliability level analysis of the walls that meet the requirements of current regulations [2] on the inadmissibility of condensate on the inner surface, it is proposed to set the maximum allowable value of the relative duration of thermal failures equal to Q_{rel} = 0,005 for walls of residential and public buildings with a class of responsibility CC2 and Q_{rel} = 0,001 – for buildings with a class of responsibility CC3. The corresponding values of the absolute thermal failure state duration Q_{abs} = 43,8 hours/year and Q_{abs} = 8,8 hours/year. The table 1 data shows that in uninsulated brick and precast concrete walls of types "a" and "c" the duration of the thermal failure state always exceeds the recommended limits. Facade insulation of a brick wall (type "b" node) combined with the window shift inside the building ensures the implementation of these recommendations for buildings with the class of responsibility CC2. Nodes of type "d" in the insulated precast concrete walls always correspond to the given recommendations for buildings of a class of responsibility CC2, and at some positions of the block frame windows even correspond to the requirements of a class of responsibility CC3. The modern walls with nodes of types "e", "f" and "g" mainly fulfil the requirements for buildings of the responsibility class CC3. The exception is the city of Semenivka with a colder climate.

Recommendations on the maximum permitted value of the relative length of thermal failures based on the condensate formation criterion in the heat-conducting zones are obtained in accordance with [2] based on the analysis of enclosing structures with design values of air temperature –22 °C and –19 °C in the first and second temperature zones of Ukraine. The duration of the possible condensate formation period equal to 43.8 h/year is too long to ensure the normal operation of buildings. This encourages a possible revision of regulatory requirements, in particular the specified design values of air temperature.

6 CONCLUSIONS

1) The absolute and relative thermal failure state duration is a very convenient, scientifically proven and practically useful indicator of thermal reliability, which allows to compare different design solutions of enclosing

structures junctions by the condensate formation criterion.

2) The absence of facade insulation leads to the fact that the nodes of the side junction of windows to the brick and precast concrete walls are characterized by too large values of the thermal failure state duration, which makes it impossible for normal operation of buildings. n the vast majority of cases, insulation of existing or new walls in compliance with current design standards in Ukraine reduces the thermal failure state to 3... 30 hours per year.
3) The thermal failure state duration of the considered nodes by the condensate formation criterion may differ twice within the first climatic zone of Ukraine.
4) The existing recommendations on the maximum allowable value of the thermal failure state duration according to the condensate formation criterion in the heat-conducting zones should be revised and changed in the direction of reduction.

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