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Research paper

Standardization of Required Level Probability of No-Failure Operation of the Building Envelopes by the Criterion of Total Thermal Resistance

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Abstract

The paper provides analysis of the state of the building envelope thermal reliability issue in Ukraine. It has been found that ensuring the reliability of the building envelope results only in economic losses and is not related to human losses, and therefore the question of normalization of no-failure performance probability of the construction upon the criterion of insufficient value of the reduced total thermal resistance is purely economic. The paper develops normalization of the required level of building envelope no-failure performance probability upon the criterion of reduced total thermal resistance. The suggested method of the required level standardization of building envelope no-failure performance probability upon the criterion of insufficient value of the reduced total thermal resistance of building envelope is proposed for the developers of normative documents, state standards, company standards or technical specifications. Designers should use only the calculated and average values of the minimum permissible thermal resistance, specified in the above-mentioned documents.

Keywords: *building envelope, reliability, total thermal resistance*.

1 Introduction

One of the important drivers of the economic growth in Ukraine is the development of preservation and energy efficiency in construction, therefore, providing thermal reliability of building envelope is quite a topical issue today. Reducing the cost for house heating is possible with the use of both renewable energy sources and increasing requirements for building envelope. Methods of reliability theory under thermal climatic effects on building constructions were studied in works by V.D. Reiser [1], R. Kliukas, A. Kudzys [2].

The concept of thermal reliability in Ukraine was first introduced by H.H. Farenyuk. According to [3], thermal reliability is the property of an object (building envelope) to store over time within established limits the values of all parameters, which characterize the ability to perform required functions in the given modes and conditions of application, that is, to maintain their thermo-technical properties within permissible limits in given life span of the building.

Subsequently, this research was continued by V.A. Pashynskyi scientific school [4]. They proposed methods for numerical estimation of the probability of homogeneous building envelopes failure upon the following criteria: failure to achieve a sufficient level of thermal resistance due to the variability of geometrical and thermophysical characteristics of building envelope materials; exceeding the maximum permissible value of the heat flow density through the building envelope.

Further research in the field of thermal reliability of building envelopes, and walls made from thin-walled steel structures in particular, was carried out in PoltNTU [5-9]. Thermotechnical research on building envelope was also done in [10-16, 18].

Thus, when using the minimum permissible thermal resistance of building envelopes in the thermotechnical calculations (1), based on average values of thermal conductivity of the materials, thickness of layers, etc.; state construction standards determine the level of assurance (probability of no-failure performance) of the reduced total thermal resistance calculated value as 0.5. In other words, half of the constructions designed may have actual thermal resistance, which is much lower than R_{qmin}, and the other half may have higher thermal resistance.

$$Q_{Rtot} = prob\left\{R_{tot} < R_{q\min}\right\} = F_{R_{tot}}\left(R_{q\min}\right), \tag{1}$$

where $F_{Rtot}(\ldots)$ is the function of normal distribution of the reduced total thermal resistance of the building envelope to linear thermal conductors with the mathematical expectation (2) and standard (3).

$$\bar{R}_{\Sigma tot} = \frac{F_{\Sigma}}{\sum\limits_{i=1}^{n} \frac{F_i}{\bar{R}_{\Sigma i}} + \sum\limits_{j=1}^{m} \bar{k}_j^{unit} \cdot L_j}, \tag{2}$$

$$R_{\Sigma tot} = \sqrt{\sum_{i=1}^{n}\left(\frac{F_{\Sigma}\cdot F_i}{\bar{R}_{\Sigma i}^2\left(\frac{F_i}{\bar{R}_{\Sigma i}}+\sum_{j=1}^{m}\bar{k}_j^{unit}\cdot L_j\right)^2}\times R_{\Sigma i}\right)^2 + \sum_{j=1}^{m}\left(\frac{F_{\Sigma}\cdot L_j}{\left(\sum_{i=1}^{n}\frac{F_i}{\bar{R}_{\Sigma i}}+\bar{k}_j^{unit}\cdot L_j\right)^2}\times k_j^{unit}\right)^2}, \quad (3)$$

where $\bar{R}_{\Sigma i}$, $R_{\Sigma i}$ are mathematical expectation and standard of the thermal resistance distribution function of an **i** thermally homogeneous and non-transparent building envelope, m^2×K/W.

$\bar{k}_j^{unit}$, k_j^{unit} – mathematical expectation and the distribution function standard of the linear thermal coefficient of a **j** thermally conductive inclusion (k_{unit}), W/(m×K).

The fulfillment of the building envelope reliability condition (1) leads only to economic losses and is not related to human losses, therefore the issue of normalization of the no-failure performance probability of a construction upon the criterion of insufficient value of the reduced total thermal resistance is purely economic.

2 Main Body

There are two approaches to solving this problem:
1) with the help of physical control of building envelope thermal resistance at the construction site;
2) by increasing the probability of building envelope no-failure performance upon the criterion of insufficient value of the reduced total thermal resistance at the design stage.

The disadvantage of the first approach is the high cost of work on the full-scale measurements of building envelope thermal resistance, which can significantly outweigh the potential savings in subsequent performance. Besides, during construction it is difficult to determine reliable values of thermal conductivity of materials for the building envelope, due to the presence of construction moisture in their stratum and due to the incompleteness of constructive solutions, etc.

We find the second approach more realistic. The proposed method of standardizing the required level of no-failure performance probability of building envelope upon the criterion of insufficient value of the its reduced total thermal resistance is proposed for the developers of normative documents, state standards, standards of organizations or technical specifications. Designers should use only the calculated and average values of the minimum permissible thermal resistance, specified in the above-mentioned documents.

We take basic preconditions for solving this problem.

The minimum permissible value of thermal resistance R_{qmin} is taken as a calculated value with assurance equal to the probability of no-failure performance of the building envelope upon the criterion of insufficient value of the reduced total thermal resistance.

The average value of the reduced total thermal resistance of a construction corresponds to the minimum value of the total risk of the building envelope construction cost and the expenses on energy consumption through it.

Variation of constructive decisions occurs by changing only one parameter that is the thickness of building envelopes, spacing, steel sections, etc. To combine the influence of these factors, solving several problems is necessary. Further, we are reviewing the case of increasing the thickness of the building envelope.

When solving the problem we consider relative, not absolute economic expenses, that is the expenses that differentiate the considered construction from the basic one.

By the basic construction we mean such a construction, the reduced total thermal resistance of which equals the minimum permissible thermal resistance, established by normative documents.

Calculations are made for a building envelope with an area of 1 m^2.

Based on the above-mentioned preconditions, the value of the average reduced total thermal resistance of a building envelope corresponds to the minimum value of the total risk of the expenses on construction and heating

∑R:

$$\sum R = R_C + R_{TR}, \quad (4)$$

where R_C is the risk of expenses for increasing thermal resistance of the building envelope, UAH;

R_{TR} – the risk of additional energy costs compared to the cost through the building envelope for the basic case, UAH.

The risk of expenses for increasing the building envelope thermal resistance is equal to the product of the excess expenditure probability (Q_C) on the expenses on increasing the building envelope thickness (B_C, UAH):

$$R_C = Q_C \cdot B_C. \quad (5)$$

If thermal resistance of the building envelope is increased by means of increasing the thickness of the structure, the probability of excess expenditure will be equal to 1.

Increasing the cost of construction because of its increase in thickness (B_C) is deducted from the cost of additional steel structures and insulation. The outer layers of the design are considered to be the same for all cases of the building envelope, and therefore they do not affect the increase in the cost of the construction.

The risk of additional energy expenses compared to energy expenses on the building envelope for the basic case is equal to the product of failure probability according to the criterion of exceeding the minimum permissible value of thermal resistance (Q_{TR}) on value of the additional energy expenses (B_{TR}, UAH).

$$R_{TR} = Q_{TR} \cdot B_{TR}. \quad (6)$$

The probability of failure upon criterion of exceeding the minimum allowable value of thermal resistance Q_{TR} is based on formula (7).

$$Q_{R_{TR}} = 0{,}5 - F(\beta), \quad (7)$$

where β is the safety characteristics:

$$\beta = \frac{\bar{R}_{\Sigma ttr} - R_{q\min}}{R_{\Sigma ttr}}. \quad (8)$$

Yearly heat consumption on 1m^2 of the building envelope is calculated using the formula (H.3) of the State Construction Standards of Ukraine (ДБН) В.2.6-31:2006.

$$TB_Q = \chi_1 \cdot K_{build} \cdot D_d \cdot F_{\Sigma}, \quad (9)$$

Where χ_1=0,024 is the dimension factor;

F_{Σ} is the building envelope area, which in our case equals 1 m^2;

K_b is the overall coefficient of thermal transmission of a building. Since we are considering a separate construction, we can take the value of $1{,}13/R_{\Sigma ttr}$ *for* residential buildings and $1{,}11/R_{\Sigma ttr}$ for any other construction;

D_d is the number of heating-degree days, determined according to effective normative documents;

$R_{\Sigma ttr}$ is the reduced total thermal resistance of the building envelope, m^2×K/W.

Additional heat consumption through a building envelope ΔTB_Q will have the value of

$$\Delta TB_Q = TB_Q(R_{\Sigma ttr}) - TB_Q(R_{q\min}), \qquad (10)$$

where $TB_Q(R_{qmin})$ is the heat consumption through the building envelope, for which reduced total thermal resistance is equal to the minimum permissible thermal resistance, kWh;
$TB_Q(R_{\Sigma ttr})$ is the heat consumption through the building envelope under consideration, kWh.
In the case where the value of building envelope reduced total thermal resistance is greater than the minimum permissible value, then the additional heat consumption will be negative, which means saving energy resources.
The cost of additional heat consumption B_{TR} is calculated using the formula

$$B_{TR} = \Delta TB_Q \cdot 0{,}0009 \cdot B_{Gcal}, \qquad (11)$$

where 0,0009 is the transition coefficient from kWh to Gcal;
B_{Gcal} is the cost of 1 Gcal, UAH.
Taking into account that the reduced total thermal resistance, determined in accordance with the effective normative documents, describes the average value of the building envelope thermal resistance (see Figure 1), the component of the formula (10) of the TB_Q ($R_{\Sigma ttr}$) does not take into account the possible increase in heat consumption due to the lower actual thermal resistance of the actual construction.
It is possible to take into account heat consumption incidental to variability of reduced total thermal resistance value, by reducing the average value of the reduced total thermal resistance to the calculated value with the given assurance. For most of constructional materials strength characteristics, the assurance level used is 0.95. Within the limits of scientific researches, it is possible to consider different assurance levels of the total reduced thermal resistance calculated value of the building envelope.
Then the formula (10) may be written as:

$$\Delta TB_Q = TB_Q(R^n_{\Sigma ttr}) - TB_Q(R_{q\min}), \qquad (12)$$

where $TB_Q(R^n_{\Sigma ttr})$ is the heat consumption through the building envelope total reduced thermal resistance of which equals the calculated thermal resistance with the set assurance level, kWh.

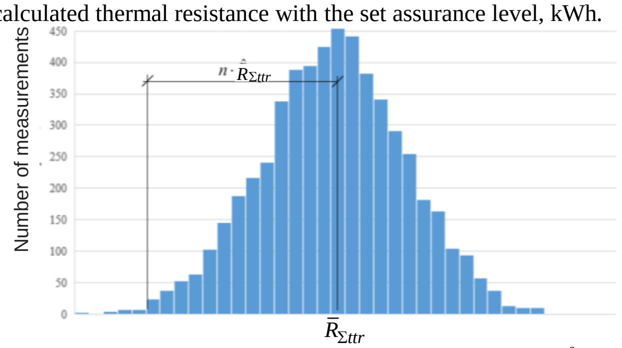

Fig. 1: Histogram of total reduced thermal resistance distribution of the building envelope

To illustrate the proposed method, we determine the economically feasible value of building envelope no-failure performance probability upon the criterion of reduced total thermal resistance on an example of a floor slab structure of an unheated attic. According to the rules of the State Construction Standards of Ukraine B.2.6-31: 2006. Thermal insulation of buildings. Change 1 and B.2.6-31: 2016. Thermal insulation of buildings, the minimum permissible thermal resistance R_{qmin} = 4.95 m²×K/W. The design model of the floor slab is shown in Figure 2.
The floor slab represents a structure formed by steel beams of a C-shaped solid cross-section with a height of 250 to 350 mm. The width of the flange is 60 mm, the side bend is 20 mm. The thickness of the plate, from which the beams are made is 1,3 mm. The space between the beams is filled with insulation, which is set on a steel net, fixed to the lower flange of girders (not included in the calculation scheme). An additional layer of insulation of 20 mm thickness is set on the upper flange of girders. Thermal conductivity of the insulation λ = 0,039 W/(m×K), coefficient of variation of insulation thermal conductivity V = 10%. The floor slab is located in a residential building, which is under construction in Poltava, Ukraine.

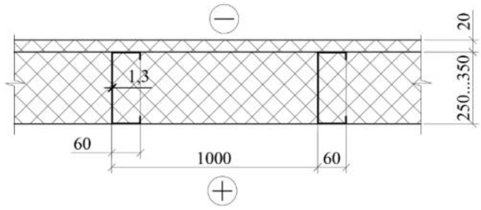

Fig. 2: Structural design of a floor slab structure

Statistical characteristics of thermal resistance distribution of homogeneous areas of the floor slab are calculated by the formulas (13) and (14). Table 1 demonstrates the results of the calculation.

$$M_{R_\Sigma} = \frac{1}{\alpha_3} + \frac{1}{\alpha_6} + \sum_{i=1}^{n} \frac{M_{\delta_i}}{M_{\lambda_i}}, \qquad (13)$$

$$S_{R_\Sigma} = \sqrt{\sum_{i=1}^{n}\left[\left(\frac{S_{\delta_i}}{M_{\lambda_i}}\right)^2 + \left(\frac{S_{\lambda_i} \cdot M_{\delta_i}}{M^2_{\lambda_i}}\right)^2\right]}, \qquad (14)$$

where n is the number of layers of building envelope;
$M_{\delta i}$ and $S_{\delta i}$ are mathematical expectation and thickness standard of the ***i*** layer;
$M_{\lambda i}$ and $S_{\lambda i}$ are mathematical expectation and the standard of thermal conductivity coefficient of the ***i*** layer.

Table 1: Statistical characteristics of thermal resistance distribution of homogenous areas of the floor slab with various thickness

Slab thickness, m	Average value of insulation thermal conductivity, W/(m×K)	Standard value of insulation thermal conductivity, W/(m×K)	Average value of thermal resistance, m²×K/W	Standard value of thermal resistance, m²×K/W
0,27	0,039	0,0039	7,081	0,692
0,28			7,338	0,718
0,29			7,594	0,744
0,3			7,851	0,769
0,304			7,953	0,779
0,31			8,107	0,795
0,32			8,364	0,821
0,33			8,620	0,846
0,34			8,876	0,872
0,35			9,133	0,897
0,36			9,389	0,923
0,37			9,646	0,949

The next step is to determine the statistical characteristics of the distribution function linear coefficient of heat transfer of a unit with a thermally conductive inclusion (steel girder). The distribution function of the linear heat transfer coefficient of a unit can be calculated by performing a two-factor mathematical experiment and establishing a regressive dependence. In our case, the factors of influence are the thickness of the structural steel section and its height. The probabilistic nature of these factors is centered on the tolerance level to the thickness of a sheet, from which the steel section is made, and the admission to the height of the profile when it is rolled. The rolled thickness tolerance is 0.11 mm, and the accuracy tolerance of the height of the steel section is 1.25 mm. Then, according to formula (15), the standard of the distribution function of the girder thickness will be 0.067 mm, and the standard of the distribution function of the girder height will be 0.7622 mm.

$$S_i = \frac{\Delta_i}{1,64}, \tag{15}$$

where Δ_i is the tolerance value for the considered element, determined in state standards of Ukraine or other countries, *m*.
The distribution function of the linear heat transfer coefficient of the unit with a thermally conductive inclusion, calculated by the method proposed in section 7.3 [17], is as follows:

$$\begin{aligned}\tilde{k}_{unit} &= 0,04879 + 8,22\cdot10^{-5}\tilde{h} + 0,02323\cdot\tilde{t} - \\ &-2,959\cdot10^{-7}\cdot\tilde{h}^2 - 3,705\cdot10^{-3}\cdot\tilde{t}^2 + 3,101\cdot10^{-5}\cdot\tilde{h}\cdot\tilde{t},\end{aligned} \tag{16}$$

where *h* is the steel girder depth, *mm*; *t* is the thickness of a sheet steel, from which the girder is made, mm; k_{unit} – linear coefficient of thermal transmission of the unit.
Function statistical characteristics (16) are calculated by the Monte Carlo method and shown in Table 2. Statistical characteristics of the distribution of reduced total thermal resistance of a 1 m^2 floor slab fragment are calculated by formulas (2) and (3).
Table 2 shows that the floor slabs with a thickness of 0.304 m have thermal resistance practically equal to the minimum permissible value of thermal resistance established for floor slabs under unheated attics. This construction is considered as the basic version.
Next, we determine the cost of increasing the building envelope thickness B_C. We determine the value in tabular form (see Table 3). The cost of delivery and installation of constructional materials is added to the cost of steel and insulation.
Due to the fact that the probability of materials over-consumption in the event of a change in the thickness of the structure (as compared to the thickness calculated by the effective standards) is equal to 1, the risk of expenses on the additional increase in the thickness of the protective structure R_C will be equal to the difference in the cost of the floor slab compared with the base case of the B_C.

Table 2: The statistical characteristics of the distribution function linear coefficient of the heat transfer of a unit and reduced total thermal resistance of floor slabs with various thickness

Slab thickness, m	Average value of linear coefficient of heat transfer, W/(m×K)	Standard value of heat transfer linear coefficient, W/(m×K)	Average value of reduced total thermal resistance, m^2×K/W	Standard value of reduced total thermal resistance, m^2×K/W
0,27	0,0849	0,00145	4,596	0,276
0,28	0,0846	0,00147	4,702	0,279
0,29	0,0842	0,00149	4,807	0,282
0,3	0,0838	0,00151	4,912	0,285
0,304	0,0837	0,00152	4,954	0,288
0,31	0,0834	0,00153	5,017	0,289
0,32	0,0829	0,00155	5,122	0,292
0,33	0,0823	0,00157	5,227	0,296
0,34	0,0816	0,00160	5,332	0,299
0,35	0,0809	0,00162	5,439	0,303
0,36	0,0802	0,00164	5,547	0,307
0,37	0,0794	0,00166	5,656	0,311

Table 3: Calculation of difference in value of a floor slab compared to the base case for 1m^2

Slab thickness, m	Girder weight, kg	Difference between weights, compared to the base case, kg	Insulation volume, m	Difference between volumes, compared to the base case, m^3	Cost of steel 1kg, UAH	Cost of insulation 1m^3, UAH	Difference in cost, compared to the base case, B_K
0,27	4,184	-0,347	0,27	-0,034	25	2000	-76,67
0,28	4,286	-0,245	0,28	-0,024	25	2000	-54,12
0,29	4,388	-0,143	0,29	-0,014	25	2000	-31,57
0,3	4,490	-0,041	0,3	-0,004	25	2000	-9,02
0,304	***4,531***	***0***	***0,304***	***0***	***25***	***2000***	***0,00***
0,31	4,592	0,061	0,31	0,006	25	2000	13,53
0,32	4,694	0,163	0,32	0,016	25	2000	36,08
0,33	4,796	0,265	0,33	0,026	25	2000	58,63
0,34	4,898	0,367	0,34	0,036	25	2000	81,18
0,35	5,000	0,469	0,35	0,046	25	2000	103,74
0,36	5,103	0,571	0,36	0,056	25	2000	126,29
0,37	5,205	0,674	0,37	0,066	25	2000	148,84

We calculate additional heat consumption through the building envelope ΔTB_Q by formula (9). For Poltava, the number of heating degree-days is Dd = 3702.4. Cost of 1 Gcal = 1350 UAH.
To calculate heat consumption $TB_Q(R^n_{\Sigma ttr})$, we determine the value of the calculated total reduced thermal resistance with different levels of assurance: 0,5; 0.7; 0.9; 0.95 and 0.99 (see Table 4). In this case, the level of assurance $R^n_{\Sigma ttr}$ indicates the probability of taking heat consumption into account, that is 50%, 70%, 90%, 95% and 99%, respectively. For the proposed levels of assurance of the calculated thermal resistance, we calculate the additional annual heat consumption and its cost (see Table 5).
Since the risk of expenses on additional increase in the building envelope thickness is distributed on the whole life span of the building envelope, the cost of additional annual energy consumption B_{TR} must be calculated for the life span of the structure. We take a life span of 50 years and determine the risk of additional energy consumption R_{TR} (see Table 6).
Based on data in tables 3 and 6, we construct the graphs presented in Figure 3. The graphs of the total risks of construction and heating expenses are presented in Figure 4. The negative values of the risks of additional energy consumption in Table 6 and in Figure 3 are explained by the fact that when increasing thermal resistance of the building envelope in relation to the base design, the reduction of heat consumption occurs, and, consequently, the reduction of the expenses for compensation for the cost of heat. It is also worth noting that when increasing the thermal resistance of the structure, the risk of additional energy consumption R_{TR} approaches 0, due to the fact that the probability of building envelope failure of the enclosing structure goes to 0.

Table 4: Calculation value of reduced total thermal resistance with a set assurance level

Slab thickness, m	Calculation value of reduced total thermal resistance with a set assurance level, m^2×K/W				
	0,5	**0,7**	**0,9**	**0,95**	**0,99**
0,27	4,596	4,449	4,242	4,143	3,955
0,28	4,702	4,554	4,345	4,244	4,054
0,29	4,807	4,658	4,446	4,344	4,152
0,3	4,912	4,761	4,547	4,444	4,250
0,304	4,954	4,802	4,586	4,482	4,286
0,31	5,017	4,864	4,648	4,544	4,347
0,32	5,122	4,967	4,748	4,643	4,444
0,33	5,227	5,070	4,849	4,742	4,541
0,34	5,332	5,174	4,950	4,842	4,639
0,35	5,439	5,279	5,052	4,943	4,737
0,36	5,547	5,384	5,154	5,044	4,836
0,37	5,656	5,491	5,258	5,147	4,935

Table 5: Additional heat consumption

Slab thickness, m	Additional heat consumption through the building envelope ΔTB_Q, kWh					Cost of additional annual energy consumption B_R, UAH				
	0,5	**0,7**	**0,9**	**0,95**	**0,99**	**0,5**	**0,7**	**0,9**	**0,95**	**0,99**
0,27	1,58	2,30	3,40	3,97	5,12	1,92	2,79	4,13	4,82	6,22
0,28	1,09	1,78	2,84	3,39	4,50	1,32	2,16	3,46	4,12	5,47
0,29	0,62	1,29	2,32	2,85	3,91	0,75	1,57	2,81	3,46	4,75
0,3	0,17	0,82	1,82	2,33	3,36	0,21	1,00	2,21	2,83	4,08
0,304	0,00	0,64	1,63	2,13	3,16	0,00	0,78	1,98	2,59	3,84
0,31	-0,25	0,38	1,34	1,83	2,83	-0,31	0,46	1,63	2,23	3,44
0,32	-0,66	-0,05	0,88	1,36	2,33	-0,81	-0,06	1,07	1,65	2,83
0,33	-1,06	-0,46	0,44	0,91	1,84	-1,28	-0,56	0,54	1,10	2,24
0,34	-1,44	-0,86	0,02	0,47	1,38	-1,75	-1,05	0,02	0,57	1,67

0,35	-1,81	-1,25	-0,39	0,05	0,93	-2,19	-1,51	-0,47	0,06	1,13
0,36	-2,16	-1,62	-0,79	-0,36	0,50	-2,63	-1,97	-0,96	-0,44	0,60
0,37	-2,51	-1,98	-1,17	-0,76	0,08	-3,05	-2,41	-1,42	-0,92	0,09

Table 6: Risk of additional energy consumption

Slab thickness, m	**Cost of additional energy consumption in 50 years B_{TR}, UAH**					**Failure probability**	**Risk of additional energy consumption, R_{TR}**				
	0,5	**0,7**	**0,9**	**0,95**	**0,99**		**0,5**	**0,7**	**0,9**	**0,95**	**0,99**
0,27	96	140	207	241	311	0,901	87	126	186	217	280
0,28	66	108	173	206	273	0,813	54	88	140	167	222
0,29	38	78	141	173	238	0,693	26	54	98	120	165
0,3	11	50	110	141	204	0,552	6	28	61	78	113
0,304	0	39	99	130	192	0,494	0	19	49	64	95
0,31	-15	23	81	111	172	0,408	-6	9	33	45	70
0,32	-40	-3	53	83	141	0,278	-11	-1	15	23	39
0,33	-64	-28	27	55	112	0,174	-11	-5	5	10	20
0,34	-1,44	-0,86	0,02	0,47	1,38	0,100	-9	-5	0	3	8
0,35	-1,81	-1,25	-0,39	0,05	0,93	0,053	-6	-4	-1	0	3
0,36	-2,16	-1,62	-0,79	-0,36	0,50	0,026	-3	-3	-1	-1	1
0,37	-2,51	-1,98	-1,17	-0,76	0,08	0,012	-2	-1	-1	-1	0

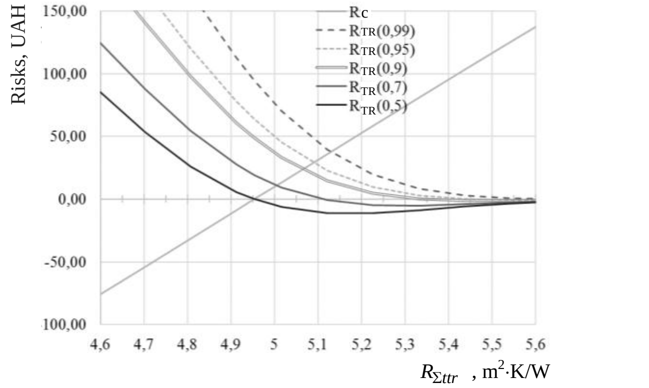

Fig. 3: The dependency diagram of the cost of additional insulation and the risks of additional energy consumption on the reduced total thermal resistance

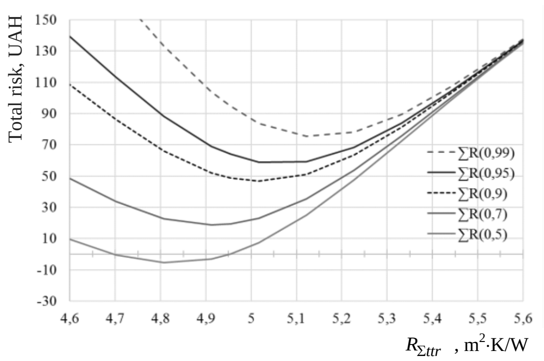

Fig. 4: Dependency graph of the total risks of construction and heating expenses on the reduced total thermal resistance (Poltava, residential building)

From the graphs presented in Figures 3 and 4, it is possible to determine the value of the reduced total thermal resistance of the floor slab, for which the total risk of construction and heating costs will be minimal. This value of thermal resistance corresponds to the average value, while the calculated value is the value of the minimum permissible thermal resistance with a set level of assurance *P*. To find the value of the calculated thermal resistance assurance, it is necessary to calculate the distance from the average to the calculated value.

$$n = \frac{\bar{R}_{\Sigma ttr} - R_{\Sigma ttr}}{R_{\Sigma ttr}}. \qquad (17)$$

For the total risk curve, which accounts for 95% possibility of taking into account all heat consumption of the building envelope, $\sum R(0{,}95)$, the average thermal resistance value is $\bar{R}_{\Sigma ttr} = 5{,}09$ m²·K/W. The calculation value equals the minimum permissible value: $R_{\Sigma ttr} = 4{,}95$ m²·K/W, we determine the standard according to Table 2 by interpolation of the average thermal resistance values $R_{\Sigma ttr} = 0{,}29$ m²·K/W.

$$n = \frac{5{,}09 - 4{,}95}{0{,}29} = 0{,}483.$$

The required level of the calculated value assurance of reduced total thermal resistance for the building envelope may be calculated by the formula

$$P = 0{,}5 + F(n), \qquad (18)$$

where *F(n)* is the Laplace's function for the value of *n*.

$P = 0{,}5 + 0{,}1855 = 0{,}6855.$

The calculated level of assurance of the reduced total thermal resistance calculated value for the building envelope corresponds to the standard value of no-failure performance probability of the building envelope by the criterion of reduced total thermal resistance.

Analyzing the graphs in Fig. 4, we can conclude, that with increasing the probability of taking into account all the thermal consumption of the building envelope, the average value of the thermal resistance increases, and consequently, the standard value of probability of no-failure performance of the building envelope increases according to the criterion of reduced total thermal resistance.

Figure 5 shows the graphs of total risks of construction and heating costs of a floor slab located in Kyiv, Ukraine. The slab is located in a civil building, for which the cost of 1Gcal = 1690 UAH. The graphs presented enable us to point out the increase of the standard value of no-failure performance probability of the construction (up to 0.825 – for the considered case), due to increase in the cost of heat consumption, which affected the increase in the value of thermal resistance of the construction, for which the total risk costs would have a minimal value.

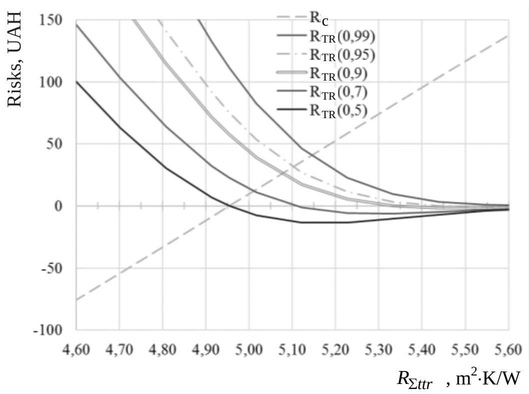

Fig. 5: Dependency graph of the total risks of construction and heating costs on the reduced total thermal resistance (Kyiv, civil building)

With a reduction in the life span of the construction from 50 years to 25 years, there occurs a change in the left-hand side of the graphs of the total risks of expenses (see Figure 6). The nature of the curves of total risk changes from parabolic into linear, approaching the line of expenses risks on the additional increase in thermal résistance.

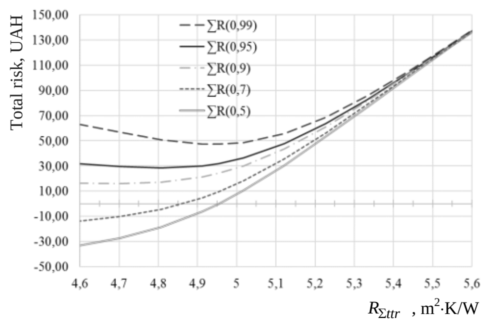

Fig. 6 : Dependency graph of the total risks of construction and heating expenses for on the reduced total thermal resistance (Poltava, 25 years)

When the lifetime of the building envelope is reduced to 25 years, the minimum total risk of construction and heating expenses corresponds to lower values of thermal resistance of the building envelope, than the minimum permissible thermal resistance, established by effective standards.

For example, for the total risk curve, which takes into account 95% probability of accounting for all the thermal consumption of the building envelope ΣR (0,95), the average thermal resistance value is $\bar{R}_{\Sigma ttr} = 4{,}807$ m^2·K/W. The calculation value equals the minimum permissible $R_{\Sigma ttr} = 4{,}95$ m^2·K/W, the standard is determined according to Table 2:

$R_{\Sigma ttr} = 0{,}282$ m^2·K/W.

$$n = \frac{4{,}807 - 4{,}95}{0{,}282} = -0{,}507.$$

The standard value of the floor slab no-failure performance probability upon the criterion of reduced total thermal resistance is calculated by the formula (18)

$P = 0{,}5 - 0{,}194 = 0{,}306.$

That is, in case of a construction a higher probability of no-failure performance there is an increased risk of economic expenses.

3 Conclusions

The paper addresses an important scientific and technical problem of normalizing of the required level probability of no-failure performance for building envelope according to the criterion of reduced total thermal resistance. The carried out research allows us to draw the following conclusions:

1) the set assurance level of the reduced total thermal resistance calculated value will correspond to the standard value of no-failure performance probability of the building envelope upon criterion of reduced total thermal resistance;

2) when the level of probability of taking into account all the thermal consumption of the building envelope is increased, the average value of thermal resistance increases as well, and consequently, the standard value of the probability of no-failure performance of the building envelope increases upon criterion of the reduced total thermal resistance;

3) on the basis of minimization of possible economic losses, the method of standardization of the required level of probability for the building envelope no-failure performance upon criterion of reduced total thermal resistance is proposed;

4) for designs with a life span of 50 years, the standard probability of failure is within the range from 0,5 to 0,9.

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