

RELIABILITY OF ENCLOSING STRUCTURES ACCORDING TO A GIVEN CRITERION OF THERMAL PROTECTION

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Abstract: The requirements of thermal protection, along with the requirements of mechanical strength and stability imposed on enclosing structures, are among the key requirements that must be taken into account, taken into account and monitored not only when developing building projects, but also after their construction, since it is these indicators that will determine the energy efficiency and cost-effectiveness of the construction projects being implemented. These requirements are presented in the current regulatory documentation of the Russian Federation and are described by certain mathematical models consisting of a set of parameters. When using these models, the expert (or the designer) can conclude whether the enclosing structure meets a certain requirement, for example, the requirement for reduced heat transfer resistance, or does not meet this requirement, however, he (the expert) cannot say and assess how reliable this structure is by one or another criterion of thermal protection or by a set of criteria. This article presents specific methods for determining the quantitative indicator of the reliability of thermal protection of enclosing structures and proposes to reduce the reliability assessment to a value or range of values that will range from 0 to 1. This approach will allow for a multifactorial assessment of the energy efficiency of enclosing structures and allows experts, based on the results obtained, to draw conclusions about reliability. enclosing structures according to various criteria of thermal protection.

Keywords: reliability, enclosing structures thermal protection, climatic parameters, resistance to heat transfer, possibility, probability, probability of uptime, the need for trouble-free operation

НАДЕЖНОСТЬ ОГРАЖДАЮЩИХ КОНСТРУКЦИЙ ПО ЗАДАННОМУ КРИТЕРИЮ ТЕПЛОВОЙ ЗАЩИТЫ

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Аннотация: Требования тепловой защиты наряду с требованиями механической прочности и устойчивости, предъявляемые к ограждающим конструкциям являются одними из ключевых требований, которые необходимо принимать во внимание, учитывать и контролировать не только при разработке проектов зданий, но и после их возведения, т.к. именно от этих показателей будет зависеть энергоэффективность и экономичность эксплуатации реализуемых строительных объектов. Данные требования представлены в действующей нормативной документации Российской Федерации и описаны определенными математическими моделями, состоящими из набора параметров. При использовании этих моделей эксперт (или проектировщик) может сделать вывод соответствует ли ограждающая конструкция определенному требованию, например, требованию к приведенному сопротивлению теплопередачи, или не соответствует этому требованию, однако, он (эксперт) не может сказать и оценить насколько данная конструкция надежна по тому или иному критерию тепловой защиты или по совокупности критериев. В настоящей статье представлены частные методики для определения количественного показателя надежности тепловой защиты ограждающих конструкций и предлагается привести оценку надежности к значению или интервалу значений, которые будут находиться в диапазоне от 0 до 1. Такой подход позволит проводить многофакторную оценку энергетической эффективности ограждающих конструкций и дает возможность экспертам, на основе полученных результатов, делать выводы о надежности ограждающих конструкций по различным критериям тепловой защиты.

Ключевые слова: надежность, ограждающие конструкции, тепловая защита, климатические параметры, сопротивление теплопередаче, возможность, вероятность, вероятность безотказной работы, необходимость безотказной работы

INTRODUCTION

The current regulatory documents of the Russian Federation, the requirements of which must be taken into account when designing enclosing structures forming the heat-protective shell of buildings to provide thermal protection, establish a certain set of requirements, including a requirement for the value of the reduced resistance to heat transfer [1]. At the design stage of the building, design engineers, based on the initial data obtained in the terms of reference, develop design solutions for enclosing structures, which are confirmed not only by appropriate engineering and technical calculations, but also by the results of modeling temperature fields in various specialized software packages, in particular, it can be the Elcut software package, which allows to accurately simulate the distribution of temperatures along the thickness of various types of enclosing structures [2-4, etc.]. After the implementation of the building project under development, its construction, or after a certain period of time, after the facility is put into operation, it is possible that the entire enclosing structure or its individual fragments do not meet the thermal engineering indicators stated in the developed building project (i.e., the values may be lower than those set by the project), as well as the requirements stated in current regulatory documents, which in the future, the operation of the building will lead to increased energy consumption. Such discrepancies can be caused by various factors: a. deviation from the accepted design decisions, for example, the use of analog materials during the construction of a building (in particular, external enclosing structures), the thermal properties of which may not correspond to the design values; b. violation of production technologies during the installation of facade systems; c. deterioration of thermal engineering properties of external enclosing structures as a result of exposure to an aggressive environment, including atmospheric influences, duration of operation of the enclosing structure, etc. If the first two (a, b) of the above-mentioned causes of deterioration of the thermal

engineering properties of the enclosing structure may arise as a result of the “human factor” and can be eliminated by introducing stricter control over the materials and structures used, as well as the process of building construction, then the third (c) possible cause may be the result of natural deterioration of thermal engineering properties resulting from: 1. wear and aging of materials and components of the facade system; 2. various possible adverse effects on the exterior enclosing structure, i.e. natural processes occur that occur during the entire period of operation of the enclosing structure, leading to irreversible changes in the properties of materials, in other words, natural wear of the enclosing structure occurs, which is not always possible to stop. At the design stage of the enclosing structure, a certain level of its thermal reliability is laid, the value of which will change over time as a result of changes in the properties of materials. It is known that reliability is the property or ability of an object, building element, or building structure to maintain its functions that ensure its normal operation over time. The existing regulatory documents do not contain information on how to quantify the reliability of thermal protection of the enclosing structure. The issues of evaluation and development of reliability calculation methods are presented in a fairly large number of scientific papers [5-12, etc.]. However, in most cases they are aimed specifically at finding methods for determining reliability and evaluating it according to criteria such as strength, stability, etc. From the point of view of decision-making, a building or a certain structure can be considered as a system that consists of a certain set of elements, each of which will have its own impact on the overall reliability of the entire system. when assessing the overall reliability, for example, of a building as a whole or its individual external enclosing structure, it is necessary to identify a list of criteria, including not only criteria for mechanical strength and stability of system elements, but also criteria describing the requirements for their thermal protection. In the proposed article: 1. the methods of determining the quantitative indicator of the

reliability of a fragment of an external enclosing structure according to one of the criteria of its thermal protection are shown (an element-by-element requirement is considered), using the provisions of mathematical statistics, probability theories and fuzzy set theory; 2. it is proposed to reduce the assessment of the thermal reliability of enclosing structures to a value or range of values that will range from 0 to 1.

METHODS

In the framework of this work, particular methods for calculating the reliability of the enclosing structure are considered according to the criterion of meeting the element-by-element requirement for thermal protection established by the regulatory document SP 50.13330.2024, respectively, for two variants of the initial data set for controlled parameters. The mathematical model describing the condition of the element-by-element requirement in relation to the thermal protection of a fragment of the enclosing structure can be written as follows:

$$R_o^r \geq R_o^{reg}, \quad (1)$$

where R_o^r and R_o^{reg} are the values of the reduced and normalized heat transfer resistance, respectively, $m^2 \cdot ^\circ C/W$. For a thermally homogeneous fragment, condition (1) can be written as $R_o \geq R_o^{reg}$. To calculate a quantitative indicator that will characterize the thermal reliability of a fragment of the enclosing structure, it is necessary to conduct a preliminary examination, during which the following must be performed: 1. identification of the enclosing structure according to the available design documentation (installed: the type of enclosing structure, the number of layers, their compositions, components, for example, which were used to attach thermal insulation boards to a load-bearing base, etc.); 2. preliminary thermal imaging examination in order to identify thermal inhomogeneities; 3. assessment of the multiplicity of room air exchange. Based on the results of the survey, the expediency and

possibility of conducting field tests of the selected fragment of the enclosing structure is established in order to collect the necessary information on the controlled parameters. One of the options in which a fragment of the enclosing structure cannot be used for conducting field studies is the case in which there are defects caused, for example, by infiltration of the enclosing structures, etc. A preliminary examination of the building's enclosing structures in order to select the fragments under study is an important step in assessing their reliability, which helps to obtain the most reliable calculation results. Since the parameters included in equation (1) may be variable, equation (1) can be written as:

$$\tilde{R}_o^r \geq \tilde{R}_o^{reg} \text{ (or } \tilde{R}_o \geq \tilde{R}_o^{reg}), \quad (2)$$

where $R_o^{reg} = (a \cdot (t_{int} - t_{ht}) z_{ht}) + b) \cdot m_r$ (a , b are coefficients taken depending on the building group; $m_r = 1$ is a coefficient that takes into account the specifics of the construction region) in the problem considered in the article can be considered as a deterministic value, because all the parameters included in the formula for its determination can be taken strictly in accordance with the requirements of the current regulatory documentation, but it is likely that it may be necessary to determine the value of the parameter R_o^{reg} for a certain location of the construction site for which official statistics on the required climatic parameters are not available, in particular in this case, the parameter \tilde{R}_o^{reg} can be considered as a random variable or a fuzzy variable, for example, the parameters: a , b and t_{int} can be taken as deterministic quantities, and t_{ht} or z_{ht} can be taken as a random variable or a fuzzy variable, depending on the completeness and quality of the initial set of information, according to controlled parameters that can be used in calculations. For example, in [8-11 and et al.], the issues of probabilistic and statistical modeling of climate data arrays, including using artificial intelligence, are raised and a conclusion is given on the applicability and expediency of such an approach. In other words, the parameter \tilde{R}_o^{reg} in some cases can be represented as a certain set of values: $\{R_{0,1}^{reg}, R_{0,2}^{reg}, \dots, R_{0,n}^{reg}\} m^2 \cdot ^\circ C/W$. Let's assume

that there are no official climate data for the geographical location on which the construction object is located, while the specified object is located at approximately the same but sufficiently large distance from the nearest settlements for which official climate statistics are available and these data have a significant (for a certain situation) difference in temperature values and may further affect influence on the decisions made based on the results of calculations, it is necessary to analyze the available information, Mathematical data modeling can be used. In some cases, fuzzy set theory can be used to enable data description. To determine the set of statistical information for the parameter \tilde{R}_0 (or \tilde{R}_0^r), it is necessary to conduct field studies, as a result of which a certain set of values will be determined: for a thermally homogeneous fragment – $\{R_{0,1}^r; R_{0,2}^r, \dots, R_{0,n}^r\}$ m²·°C/W or for thermally inhomogeneous – $\{R_{0,1}; R_{0,2}, \dots, R_{0,n}\}$ m²·°C/W. For this purpose, depending on the task, enclosing structures oriented to N, N-W or N-E are selected in accordance with the requirements of the national standard GOST R 59939-2021. As a result of the research, sets of statistical data are obtained on the following parameters: temperatures (1. internal (t_{int}) and external (t_{ext}) air; 2. internal (τ_{int}) and external (τ_{ext}) surfaces of the surveyed enclosing structure); actual heat flux density (q). For a thermally homogeneous fragment of the enclosing structure, the parameter \tilde{R}_0 can be determined for each set of the above parameters according to the equation: $\tilde{R}_0 = \frac{(t_{int} - \tau_{int})}{\tilde{q}} + \frac{(\tau_{int} - t_{ext})}{\tilde{q}} + \frac{(t_{ext} - \tau_{ext})}{\tilde{q}} = \frac{(t_{int} - \tau_{ext})}{\tilde{q}}$, m²·°C/W (written \tilde{R}_0 , because the thermally homogeneous fragment); for a thermally inhomogeneous fragment of the enclosing structure – $\tilde{R}_0^i = A / (\sum A_i / \tilde{R}_{0i})$, m²·°C/W, where A is the area of the enclosing structure under examination, m²; A_i is the area of the characteristic isothermal zone, which is determined by the results of thermal imaging of a fragment of the structure under examination, m²; \tilde{R}_{0i} is the heat transfer resistance of the characteristic zone, m²·°C/W. \tilde{R}_0^i (or \tilde{R}_0), depending on the completeness obtained as a result of field tests, statistical information about the parameters \tilde{t}_{int} , \tilde{t}_{ext} , $\tilde{\tau}_{int}$, $\tilde{\tau}_{ext}$ and q can be represented as random variables or fuzzy variables. Next, it is

necessary to analyze the data on the parameters \tilde{R}_0^r and \tilde{R}_0^{reg} and, depending on the completeness of the information received, methods of probability theory can be applied to determine the reliability of the enclosing structure (or its fragment) according to the criterion of fulfilling the piecemeal requirement for thermal protection. or fuzzy set theory. Let's consider two options for calculating reliability using the mathematical model (2):

1. Let the parameters \tilde{R}_0^r and \tilde{R}_0^{reg} be used to obtain complete statistical information, according to which the law of their distribution (the normal distribution law) and its parameters were established: $m_{R_0^r}$, $m_{R_0^{reg}}$, $S_{R_0^r}$, $S_{R_0^{reg}}$ – i.e. \tilde{R}_0^r and \tilde{R}_0^{reg} are random variables. In this case, the reliability of the fragment under study will be characterized by an indicator of uptime according to a given criterion and a safety characteristic can be used: $\gamma = \frac{m_{R_0^r} - m_{R_0^{reg}}}{\sqrt{S_{R_0^r}^2 + S_{R_0^{reg}}^2}}$, according to which the value of the probability of uptime according to criterion (2) can be determined using tables of normal distribution functions:

$$P(R_0^r \geq R_0^{reg}) = \Phi(\gamma), \quad (3)$$

2. Let's assume that there are limited statistical data available for the parameters \tilde{R}_0^r and \tilde{R}_0^{reg} , i.e. the statistical information turned out to be incomplete. In this case, \tilde{R}_0^r and \tilde{R}_0^{reg} are considered as fuzzy variables that will be characterized by the same opportunity distribution function (ODF) of the form:

$$\pi_R(R) = e^{-[(R - a_R)/b_R]^2}, \quad (4)$$

where $a_R = (R_{max} + R_{min})/2$, $b_R = (R_{max} - R_{min})/(2\sqrt{-\ln \alpha})$, $\alpha \in [0; 1]$, α – the risk level. The use of this function (ODF) to describe uncertainty and determine reliability indicators (the possibility method) was shown in the works of Doctor of Technical Sciences, Professor V.S. Utkin, as well as in the works of his students [13-15 et al.] applied to building structure elements. For the case considered in the article, for fuzzy variables \tilde{R}_0^r and \tilde{R}_0^{reg} we will have:

$$\begin{cases} \pi_{\tilde{R}_o^{reg}}(R_o^{reg}) = e^{-\left[\frac{(R_o^{reg} - a_{R_o^{reg}})}{b_{R_o^{reg}}}\right]^2} \\ \pi_{\tilde{R}_o^r}(R_o^r) = e^{-\left[\frac{(R_o^r - a_{R_o^r})}{b_{R_o^r}}\right]^2} \end{cases}, \quad (5)$$

Graphically, the functions $\pi_{\tilde{R}_o^{reg}}(R_o^{reg})$ and $\pi_{\tilde{R}_o^r}(R_o^r)$ can be represented as shown in Fig. 1.

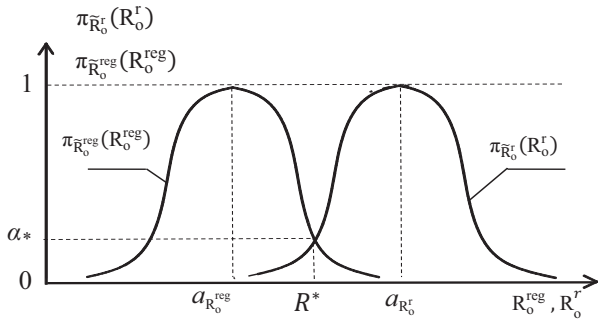


Figure 1. Graphical representation of functions: $\pi_{\tilde{R}_o^{reg}}(R_o^{reg})$ and $\pi_{\tilde{R}_o^r}(R_o^r)$

According to Fig. 1, if $a_{R_o^r} > a_{R_o^{reg}}$, then the possibility of trouble-free operation will be equal to $R=1$ (not to be confused with the designation of heat transfer resistance). The value of the possibility of failure can be found by finding the abscissa of the intersection point R^* ODF: $\pi_{\tilde{R}_o^{reg}}(R_o^{reg})$ and $\pi_{\tilde{R}_o^r}(R_o^r)$ and substituting this value into any of the values specified in equations (4), for example, $Q = \pi_{\tilde{R}_o^r}(R^*) = e^{-\left[\frac{(R^* - a_{R_o^r})}{b_{R_o^r}}\right]^2}$. The need for uptime: $N = I - Q$ and, therefore, the reliability interval will have the form: $[R; N]$.

RESULTS AND DISCUSSION

As an object of research, we will take a fragment of the enclosing structure, which is a fragment of a blank exterior wall of a building with a hinged facade system (type FTCS, facade thermal insulation composite system). Let it be that, as a result of a preliminary thermal imaging examination of the fragment, the possibility and feasibility of field tests were established, no temperature anomalies were detected. The geographical location of the construction site is

Moscow, Moscow region. We will take the initial climatic parameters based on the data from the weather archive of the meteorological station No. 27612 (Exhibition of Achievements of National Economy, Moscow) for the period from 2014 to 2023. The results of the analysis of the arrays of climatic data obtained from the weather sensor for the specified period are summarized in Table 1.

Table 1. Climatic parameters

| No | Year | the average temperature of the period at $t_{\text{ext}} \leq 8 \text{ }^\circ\text{C}$ | Duration of the period, day |
|----|------|---|-----------------------------|
| 1 | 2014 | -1.5 | 195 |
| 2 | 2015 | 0.17 | 198 |
| 3 | 2016 | -1.9 | 195 |
| 4 | 2017 | -0.32 | 210 |
| 5 | 2018 | -3.28 | 183 |
| 6 | 2019 | 0.035 | 186 |
| 7 | 2020 | 1.11 | 192 |
| 8 | 2021 | -1.93 | 203 |
| 9 | 2022 | -0.9 | 194 |
| 10 | 2023 | -1.33 | 181 |

In table 2, the values of the parameters are determined based on the climatic data and the data in table 1.: 1. degree-day of the heating period (D_d); 2. the normalized value of the heat transfer resistance \tilde{R}_o^{reg} for a given location of the studied enclosing structure (Moscow).

Table 2. Parameter values: D_d and R_o^{reg}

| No | Year | $D_d, \text{ }^\circ\text{C}\cdot\text{day}$ | $R_o^{reg}, \text{ m}^2\cdot\text{ }^\circ\text{C}/\text{W}$ |
|----|------|--|--|
| 1 | 2014 | 4197.32 | 2.87 |
| 2 | 2015 | 3926.05 | 2.77 |
| 3 | 2016 | 4278.02 | 2.90 |
| 4 | 2017 | 4266.66 | 2.89 |
| 5 | 2018 | 4260.68 | 2.89 |
| 6 | 2019 | 3713.51 | 2.70 |
| 7 | 2020 | 3626.33 | 2.67 |
| 8 | 2021 | 4451.58 | 2.96 |
| 9 | 2022 | 4047.24 | 2.82 |
| 10 | 2023 | 3861.35 | 2.75 |

Thus, the parameter R_o^{reg} is represented as a certain set of values.: {2.87; 2.77; 2.90; 2.89; 2.89; 2.70; 2.67; 2.96; 2.82; 2.75} $m^2 \cdot ^\circ C/W$. Let's consider it as a random variable distributed according to the normal distribution law, with distribution parameters: $m_{R_o^{reg}} = 2.82 m^2 \cdot ^\circ C/W$; $S_{R_o^{reg}} = 0.091 m^2 \cdot ^\circ C/W$. Let's assume that in order to collect statistical information on the parameter \tilde{R}_o^r (or \tilde{R}_o), field studies were conducted, during which arrays of data on the parameters were obtained: 1. the temperatures of the outer (t_{ext}) and inner surfaces (t_{int}) of the fragment under study; 2. the density of the heat flux passing through the fragment (q) under natural conditions. Let's assume that the period during which the changes were carried out is 10 days. After the formation and processing of the obtained arrays of statistical data on the controlled parameters, the sets of values of the parameter \tilde{R}_o^r are determined. For a more visual representation of the problem being solved, we will generate a data array consisting of 100 values of the parameter \tilde{R}_o^r . For the resulting set of values { $R_{0,1}^r$; $R_{0,2}^r$, ... , $R_{0,100}^r$ }, we carry out statistical processing and analysis of data, after which we accept the parameter \tilde{R}_o^r as a random variable distributed according to the normal distribution law, with distribution parameters: $m_{R_o^r} = 3.06 m^2 \cdot ^\circ C/W$; $S_{R_o^r} = 0.07 m^2 \cdot ^\circ C/W$. A fragment of the array will look like this: {3.15; 2.97; 3.13; ... ; 3.07; 3.12} $m^2 \cdot ^\circ C/W$; maximum value: $R_{o,max}^r = 3.23 m^2 \cdot ^\circ C/W$; minimum value: $R_{o,min}^r = 2.89 m^2 \cdot ^\circ C/W$. Then, the probability of trouble-free operation under the condition of equation (2) using equation (3) will be equal to $P(R_o^r \geq R_o^{reg}) = \Phi(\gamma) = \Phi\left(\frac{3.06 - 2.82}{\sqrt{0.07^2 + 0.091^2}}\right) = 0.9817$. Let's consider the same example, but let's take both parameters \tilde{R}_o^r and \tilde{R}_o^{reg} as fuzzy variables that will be characterized by a set of the form (4). The parameters of the set are: 1. $\pi_{\tilde{R}_o^r}(R_o^r) - a_{R_o^r} = 3.06 m^2 \cdot ^\circ C/W$; $b_{R_o^r} = 0.10 m^2 \cdot ^\circ C/W$; 2. $\pi_{\tilde{R}_o^{reg}}(R_o^{reg}) - a_{R_o^{reg}} = 2.82 m^2 \cdot ^\circ C/W$; $b_{R_o^{reg}} = 0.11 m^2 \cdot ^\circ C/W$. The possibility of trouble-free operation will be equal to $R=1$, because $a_{R_o^r} = 3.06 m^2 \cdot ^\circ C/W > a_{R_o^{reg}} = 2.82$. The value of the abscissa of the intersection point R^* ODF: $\pi_{\tilde{R}_o^{reg}}(R_o^{reg})$ and $\pi_{\tilde{R}_o^r}(R_o^r)$ will be equal to 2.95

$m^2 \cdot ^\circ C/W$, then the value of the possibility of failure is substituted by R^* in any of equations (5), and will be equal to $Q = 0.27$, and the need for trouble-free operation will be equal to $N=1-0.27=0.73$. The reliability of the studied fragment of the enclosing structure under the condition of fulfilling the piecemeal requirement for thermal protection will be characterized by the interval [0.73;1]. The value of the reliability indicator $P=0.9817$, obtained using methods of probability theory, is more convincing for experts from the point of view of decision-making, since it is unambiguous, compared with the value of the reliability indicator in the form of an interval estimate [$N=0.73$; $R=1$], obtained using fuzzy set theory. In this case, the value of $P=0.9817$ falls within the range [0.73; 1], i.e. the true reliability value was inside the obtained range. The example considered in the article shows that when calculating reliability according to the criterion described by equation (2) for a fragment of an enclosing structure, some useful statistical information was lost when using the probability method. At the same time, one rather important point should be noted: the use of this method may be advisable in the absence of complete statistical information on controlled parameters from experts.

CONCLUSION

The proposed work presents methods for determining the quantitative indicator of the reliability of the enclosing structure according to the criterion of fulfilling a piecemeal requirement (requirements for reduced resistance to heat transfer), using the provisions of classical mathematical apparatus, namely the provisions of mathematical statistics, probability theory and theory of fuzzy sets. Depending on the amount of information available to experts about the controlled parameters obtained as a result of technical inspections and monitoring studies, a methodology is selected for calculating the reliability indicator. The presented approaches to calculating the quantitative indicator of thermal

reliability make it possible to bring the reliability estimate to a value that will be in the range [0; 1], which facilitates a multifactorial assessment of the energy efficiency of various types of enclosing structures.

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