On the probability determination of the reliability of a technosphere object under hazardous influence

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Abstract. The use of various criteria characteristics included in the content of deterministic, statistical and probabilistic approaches is shown in this article for determination the indicators of safe permissible conditions of buildings (structures). A feature of assessing the reliability of buildings (structures) for their operation under additional loads (explosions, fires, vibration processes) is the determination of an indicator of a given safety margin and its stability under possible realized effects. The aim of the study is to develop an approach to determine the reliability indicator of a building (structure), for operation in conditions of additional loads. The subject of the study is the process associated with the determination of the reliability indicator of buildings (structures), for their further operation in the technological process, causing effects in the form of additional loads (explosions, fires, vibration processes). The solution to such problems is relevant for buildings (structures) that are acquired (leased) by the owner, for their further operation in the production process, in the technology of which fire and explosion hazardous substances (materials) are handled, stored or processed. To solve the tasks, it is proposed to use a simplified assessment of the safety margin of a building (structure) by yield strengths (for steel elements) and strength (for base materials, load-bearing walls, partitions and ceilings) corresponding to the maximum allowable values for their destruction. The article provides a consistent theoretical description of the formulas, which allows us to establish a relationship between the safety margin of a building (structure) and the probability of its destruction during realized impacts. An innovative approach is described that allows us to solve the problems of assessing the strength reliability of structural elements of buildings (structures), when it is important to be able to obtain guaranteed characteristics of a given safety factor, its resistance to possible realized impacts - explosions, fires, vibration processes. The use of the material, in order to determine reliability indicators based on risks, allows us to consider the calculated values of the safety margin of a building (structure), which meets the established requirements for evaluating effectiveness from the point of view of theory and practice of operations research.

1. Introduction
The issues of fire and explosion safety of objects of protection of the technosphere space are currently priority. Objects of protection of the technosphere - the whole tangible surrounding world around us created by mankind, and people themselves are also objects of protection from various kinds of technological hazards [1]. Safety from explosions and fires of the technosphere is one of the main tasks of the two subsystems (fire and industrial safety) included in the integrated safety system of a
production enterprise because the main share of all hazards (about 70%) falls on the system in question (figure 1).

![Figure 1. Integrated enterprise security system.](image)

The required level of safety of objects to be protected from various hazardous influences is achieved by maintaining the required safety coefficient in the considered subsystems, in the form of a ratio:

$$\varphi_{es} > \varphi_{edr}$$

where $\varphi_{es}$ is the calculated and maintained coefficient of the security level;

$\varphi_{edr}$ - the value of the maximum coefficient of the level of destructive impact on the subsystem [2,9].

In Russia, the situation related to fires and explosions at production facilities should be assessed as rather complicated, requiring constant attention not only from the authorities of the State Power, but also from owners (legal entities) of production enterprises, which, in accordance with the requirements of the Federal Law of the Russian Federation of 22.07.2008 No.123-FZ "The technical regulation about requirements of fire safety", they are personally responsible for maintaining the required level of fire protection at their property rights.

Every year in Russia, housing stock is destroyed with a total area equivalent to a city with a population of 10-20 thousand people from fires and explosions, where the main reason for their implementation is poor-quality compliance with the fire and explosion protection requirements of buildings (structures) specified in the requirements of documents [3-5].

With the transition of Russia to a new level of economic development (the period covered from the end of 1990 to the present), there have been events in the mass sale and lease of buildings, structures, their complexes, which are unprofitable and require significant investments.

Based on the analysis of statistics in the Russian Federation, reflecting the indicators of mass sales and leasing of buildings, structures, their complexes (for the period from the end of 1990 to the present), it is noted:

- at real estate, (about 70%), the class of functional fire hazard (FFH) was changed;
- real estate objects were demolished, in their place new objects were built or planned to be built (about 10-15%);
- only the remaining share of immovable objects began to be used in accordance with the established class of FFH prescribed in the project (about 10-15%) [6].

However, not all owners of buildings (premises) purchased or leased, fully complied with the requirements established by regulatory legal acts and regulatory documents on fire safety [4,5], for many unscrupulous legal entities the main goal is to make profit at the lowest cost and costs.

According to the results of statistics, the occurrence of fires and explosions over a period of 10 years (from 2007 to 2017), in buildings (rooms) operated under the conditions of a technological process associated with the effects of additional loads in the form of possible explosions, fires,
vibration processes, structures collapsed (about 50%) precisely at the objects acquired (leased), which needed to change the class of FFH [6].

The information presented required the development of a new scientific approach to assessing the readiness of buildings (structures) for changing the class of functional fire hazard, during their further operation in a process associated with the effects of additional loads in the form of possible explosions, fires, vibration processes.

2. Methodology

2.1. Characteristics of the materials to overcome the realized dangers

In fundamental research and development that has an applied aspect to increasing the stability of the functioning of physical objects, from the point of view of strength, reliability, survivability, and resource, determinate, statistical, and probabilistic approaches and their criteria characteristics are used, as a rule, to determine indicators of safe permissible states [7,8].

In the conducted studies, statistical data on the properties of materials used for the construction of buildings (structures) and indicators of their strength to overcome the realized dangers (explosion, fire, vibration, etc.) are usually considered from the point of view of the ratio of the magnitude of the implementation of hazardous effects - [σ] and the safety margin of a building (structure) - n.

The value [σ] is usually set according to the average or guaranteed values of the reliability of the building (structure), taking into account the characteristics of the materials calculated using yield strengths σT (for steel elements), strength σB, long-term strength σBT (for base materials, load-bearing walls, partitions and ceilings):

\[
[\sigma] = \frac{\sigma_T}{n_T}; \quad [\sigma] = \frac{\sigma_B}{n_B}; \quad [\sigma] = \frac{\sigma_{BT}}{n_{BT}}; \quad (1)
\]

2.2. The determination of the strength reliability of a building (structure)

For probabilistic calculations, the value [σ] and the calculated maximum value during operation of the building (structure) σn max were taken:

\[
\sigma_{n, max}^3 \leq \min \left\{ \frac{\sigma_C}{n} \right\}; \quad (2)
\]

where σn - the minimum value of the ratio of the destructive effect on the material used for the construction of the building (structure), i.e. its safety margin calculated by the formula (1). Using formula (2), it becomes possible to determine the strength reliability of a building (structure), characterized by an indicator of stability in calculating the likely implementation of a hazardous effect (explosion, fire, vibration, etc.).

In a deterministic approach, the strength of a building (structure) is assessed using the average values P = Pav = 50%) calculated during the operation of the building (structure) (σ3) av and material properties characteristics (σ1) av and (σ2) av:

\[
(n_T)_{av} = \frac{(\sigma_T)_{av}}{(\sigma^3)_{av}}; \quad (n_B)_{av} = \frac{(\sigma_B)_{av}}{(\sigma^3)_{av}}; \quad (3)
\]

The statistical change in the current projected value for the operation of the building (structure) (σ3) p and the value of the limit (getting damaged) hazardous effect (explosion, fire, vibration, etc.) on the building (structure) (σC) p is described by the corresponding curves distribution density f.

When assessing the anthropogenic safety of buildings (structures), it is necessary to take into account that in the formulas (1), (2) presented for calculation, there is a probabilistic nature of the implementation of hazardous effects (explosion, fire, vibration, etc.). This condition makes it possible to determine the required safety margin of a building (structure) when conducting probabilistic studies and determining the level of integrated safety of an enterprise having sections (platforms) of safety and security measures, standardizing techno-safety, it is possible to calculate a given margin n by the established probability P.
\[ n_{cp} = \left( \frac{\sigma_c}{\sigma^p} \right)_p \]

where \((\sigma_c)_p\) - limit (receiving damage) hazardous effect (explosion, fire, vibration, etc.) on a building (structure) with a level of a given probability \(P\),
\((\sigma^p)_p\) is the projected value during the operation of the building (structure) with the same parameter \(P\) [11].

3. Results and discussion
To solve practical problems, we use a simplified assessment of the safety margin of a building (structure) \(n\) by yield strength \(\sigma_T\) (for steel elements) and strength \(\sigma_B\) (for base materials, load-bearing walls, partitions, and ceilings) corresponding to the given fracture probabilities \(P\):

\[ \left( n_T \right)_p = \left( \frac{n_T}{\sigma_T} \right)_p \quad \left( n_B \right)_p = \left( \frac{n_B}{\sigma_B} \right)_p \quad (4) \]

Figures 2, 3 show the distribution functions \(P\) of the operational characteristics of the building (structure) \(P\) \((\sigma^p)\), the properties of the materials according to the yield strengths \(P\) \((\sigma_T)\) (for steel elements), and the strength \(P\) \((\sigma_B)\) (for base materials, load-bearing walls, partitions and ceilings) (figure 1) and the distribution density function \(f(\sigma)\) for assessing the probability of destruction at the limit (receiving damage) of dangerous effects (explosion, fire, vibration, etc.) on the building (structure) with probability \(P(K)\) (figure 2) [9].

The operational characteristics of the building (structure) \(P\) \((\sigma^p)\) and the characteristics of the properties of materials according to yield strengths \(P\) \((\sigma_T)\) (for steel elements) and strength \(P\) \((\sigma_B)\) (for base materials, load-bearing walls, partitions and ceilings) correspond to the probability \(P(K)\) (figure 1) or the probability density of destruction \(P(K)\) at the point \(K\) (figure 2):

\[ P(K) = \left[ P(K_T), P(K_B) \right] \quad (5) \]

**Figure 2.** The scheme of the probabilistic assessment of strength in the calculation of the realized hazard.

The presented value of the hazardous exposure \(\sigma_C\) presented (figure 2) is characterized by the properties of materials with respect to yield strengths \(P\) \((\sigma_T)\) (for steel elements) and strength \(P\) \((\sigma_B)\) (for base materials, load-bearing walls, partitions, and ceilings). The ultimate stress \(\sigma_C\) characterizing the “strength” of materials \(\sigma_T\) and \(\sigma_B\) is also a random variable. If the distribution density functions \(f(\sigma^p)\) become known for the acting \(\sigma^p\) and \(f(\sigma_C)\), for the index of ultimate impacts on the “strength” of materials \(\sigma_T\) and \(\sigma_B\) (figure 2), then by considering the ratio of the segments \(\sigma_C\) and \(\sigma_{max}\) according to expression (3), the margin of safety of buildings (structures) will be calculated. At point \(K\), the curves intersect, which indicates the probability of possible destruction of buildings (structures), provided that two inequalities are satisfied:

\[ \sigma^3 > \sigma_K \land \sigma_C < \sigma_k \quad (6) \]
Figure 3. The impact of density and safety margin curves.

In this case, the probability of destruction, assuming that the events in expression (6) are independent under the indicated inequalities, will be represented by the formula:

$$P_{\text{destr}} = P(\sigma^3 > \sigma_K)P(\sigma_C < \sigma_K) = A_1 \times A_2,$$

(7)

where $\sigma_K$ is the stress at the intersection of the distribution density curves ($A_1$ and $A_2$), i.e. areas of shaded areas shown in the figure 2.

Assuming that the operational and ultimate stresses are distributed according to the normal law, taking into account inequality (7), the probability of failure will be equal to:

$$P_{\text{destr}} = \left[\frac{1}{2} - f\left(\frac{\sigma_K - \sigma^3}{S_3}\right)\right] \times \left[\frac{1}{2} + f\left(\frac{\sigma_K - \sigma_C}{S_C}\right)\right],

(8)

where $\sigma^3$ and $\sigma_C$ are the average values of the designed (operational) and probabilistic (ultimate for hazardous effects) on the building (structure) and ultimate stresses $\sigma_K$ on the materials according to yield strength (for steel elements) and strength (for base materials, load-bearing walls, partitions and ceilings). $S_3$ and $S_C$ mean square deviations in the distributions.

Then the reliability (probability of non-destruction) $P(H)$ of the bearing element will be equal to:

$$P(H) = 1 - P_{\text{destr}}.

(9)

The calculation of $\sigma_K$ can be implemented on the basis of distribution functions analytically in the presence of known, or in the absence of known on the basis of experiments.

When considering the cases when the stresses $\sigma^3$ and $\sigma_T = \sigma_C$ will be considered in the form of random variables $\sigma_0 = \beta$ and $\sigma^3 = \alpha$ with parameters known for the normal distribution law, we obtain a function for the random variable $\psi$ (figure 4), which will be look like:

$$F(\psi) = \frac{1}{2} + F\left(\frac{\psi - \Psi}{S_\psi}\right),

(10)

where $\psi = \sigma_B - \sigma^3 = \beta - \alpha$, then

$$F(x) = \frac{1}{\sqrt{2\pi}} \int_0^x \exp\left(-\frac{t^2}{2}\right) dt

(11)
If in this case the random strength values of the characteristics $\sigma_B$ or $\sigma_T$ and the loading characteristics $\sigma^2$ are considered to be practically independent random variables (i.e. there is no correlation between them), then the parameters of the non-destructive function will be defined as $\psi = \sigma_B - \sigma^2 = \bar{\beta} - \bar{\alpha}$ (average):

$$S_\psi = \sqrt{S_\beta^2 + S_\alpha^2}$$  \hspace{1cm} (12)

$\psi$ - mean value, $S_\psi$ - standard deviation. Then the coefficient of variation:

$$V_\psi = \frac{S_\psi}{\psi} = \frac{\sqrt{S_\beta^2 + S_\alpha^2}}{\bar{\beta} - \bar{\alpha}}$$  \hspace{1cm} (13)

With such a consideration of the problem, the probability of destruction will correspond to the condition: $\psi = \sigma_B - \sigma^2 < 0$ (shaded area, figure 3), and the formula for determining the probability of destruction will take the formula:

$$P_{destr} = P(\psi < 0) = F(0)$$  \hspace{1cm} (14)

Given equalities (10) and (12), the probability of destruction will be expressed by the formula:

$$P_{destr} = \frac{1}{2} - F\left(\frac{\psi}{S_\psi}\right) = \frac{1}{2} - F\left(\frac{1}{V_\psi}\right)$$  \hspace{1cm} (15)

Thus, the presented formulas in expressions (2-13) allow us to establish a relationship between the margin $n$ and the probability of destruction $P_{destr}$, while dividing the numerator and denominator of the ratio for the coefficient of variation $V_\psi$ by $\alpha^-$, we obtain the expression:

$$V_\psi = \frac{\sqrt{S_\beta^2 + S_\alpha^2}}{n_\alpha}$$  \hspace{1cm} (16)

where $V_\alpha = \frac{S_\alpha}{\bar{\alpha}}$, $V_\beta = \frac{S_\beta}{\bar{\beta}}$ - the variation coefficients of the operating and breaking stresses; $n_\alpha$ - margin of stress according to their average values: $n = \frac{\bar{n}}{\bar{\bar{\alpha}}}$

The final formula will be presented as follows:
It follows from the relation presented in formula (17) that the probability of fracture decreases with increasing margin of safety \( \bar{n} \) in terms of average values of destructive and effective stresses. As a result, having adopted, as a first approximation, the assumption of a normal law of the distribution of the operating load and the bearing capacity of the structural element and knowing the actual (or given) values of the variation coefficients \( V_\alpha \) and \( V_\beta \), it becomes possible to determine the relationship between the fracture probability \( P_{\text{destr}} \) and reserves \( n \) for various buildings (structures) when assessing decisions in technological safety based on risks [10, 11].

4. Conclusions
The presented approach allows us to solve the problems of assessing the strength reliability of structural elements of buildings (structures), when it is important to be able to obtain guaranteed characteristics of a given margin of safety, its resistance to possible realized effects (explosions, fires, vibration processes). Using the material in order to determine reliability indicators on the basis of risks allows us to consider the calculated values of the safety margin of a building (structure), which meets the established requirements for evaluating effectiveness from the point of view of theory and practice of operations research. The described approach is innovative and representative, correctly reflects the essence and target function of security, allows you to take into account the features of the functioning of each of the indicators, taking into account the characteristics of the relationship between them.

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