RISK-ORIENTED STRUCTURAL OPTIMIZATION OF CIVIL DEFENSE PROTECTIVE STRUCTURES UNDER COMBINED EXTREME IMPACTS

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Abstract. The monograph provides a systematic investigation of a risk-oriented approach to the structural optimization of civil defense protective structures under combined extreme impacts, which is of particular relevance in the context of increasing intensity of military, technogenic, and natural threats, limited resources, and the necessity for rapid engineering decision-making. It is demonstrated that traditional deterministic methods of structural analysis and strengthening do not ensure a sufficient level of justification when predicting the behavior of structures under real operating conditions, as they fail to account for the probabilistic nature of loads, the variability of material properties, and the scenario-based character of structural failure.

The study substantiates the necessity of integrating the results of technical inspections, numerical modeling of the stress–strain state, and probabilistic reliability analysis methods into a unified engineering decision-making system. Particular attention is devoted to the strengthening of brick and masonry structures of protective facilities, especially columns, using steel jackets and spatial frames. The effectiveness of these strengthening solutions is assessed not only in terms of increased load-bearing capacity, but also through the reduction in the probability of reaching limit states.

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A key element of the proposed approach is the application of fragility models, which enable the quantitative assessment of the vulnerability of structural elements under different intensities of combined extreme impacts and serve as a basis for developing criteria for resource-efficient structural optimization. The research results provide a scientific foundation for substantiating reconstruction priorities, selecting strengthening technologies, and managing the risk of failure of civil defense protective structures throughout their life cycle.

The subject of the research comprises the processes of assessment, modeling, and optimization of the structural reliability of civil defense protective structures, taking into account the probabilistic nature of failures and the combined character of extreme impacts. Within the scope of the study, methods for determining the technical condition of structures and their compliance with the functional requirements of shelters are considered, as well as the behavior of masonry and brick structures under complex loading conditions and structural strengthening solutions, in particular those involving steel jackets and steel–reinforced concrete systems.

Special attention is devoted to the transformation of deterministic finite element analysis results into probabilistic indicators of reliability and vulnerability, which makes it possible to assess the risk of structural failure under various loading scenarios and to substantiate the expediency of resource expenditures for reconstruction and strengthening measures.

The research methodology is based on an integrated scientific approach that combines methods of technical diagnostics, numerical modeling, and probabilistic analysis. At the first stage, methods of inspection and assessment of the technical condition of civil defense protective structures are applied, including the identification of defects and damage and the evaluation of shelter compliance with regulatory requirements.

Subsequent analysis is performed using finite element modeling of the stress–strain state of strengthened and unstrengthened structural elements, which allows consideration of nonlinear material behavior, contact interaction, and damage localization under combined loading conditions. The obtained deterministic results are used as an initial basis for the development of probabilistic models, within which limit state analysis methods, stochastic approaches, and elements of risk management are applied in order to determine the probability of failure and to construct fragility curves.

The methodological framework of the study is further complemented by risk management principles, which ensure the systematic nature, reproducibility, and consistency of engineering decisions with safety requirements and resource efficiency throughout the life cycle of civil defense protective structures.

The aim of the research is to develop a scientifically substantiated risk-oriented system for the structural optimization of civil defense protective structures, which ensures a reduction in the probability of reaching limit states while accounting for operational damage to building structures and enabling the rational use of material and financial resources.

Achieving this aim involves the development of an engineering decision-making algorithm that integrates the results of technical inspections, finite element analysis, and probabilistic modeling of structural vulnerability, as well as substantiating the application of fragility models for evaluating the effectiveness of strengthening measures and ranking structures according to their risk level. The implementation of this approach is intended to enhance the safety, durability, and adaptability of civil defense protective structures under contemporary challenges and operational uncertainties.

1. Introduction

The current stage of development of construction science and civil defense engineering is characterized by a significant complication of the operating conditions of buildings and structures, which is associated with the intensification of military actions, an increase in technogenic risks, and a higher frequency of extreme natural events. Under these conditions, civil defense protective structures acquire critical importance as infrastructure elements intended to ensure the preservation of human life and the resilience of life-support systems even under combined loading effects [29, pp. 44–46; 13, pp. 29–31]. The reliability of such structures is determined not only by their load-bearing capacity but also by the ability of structural systems to maintain functionality under conditions of impact uncertainty, progressive damage, and limited resources available for recovery.

Traditional approaches to the design and reconstruction of protective structures, predominantly based on deterministic calculations and prescribed safety factors, prove insufficient for an adequate assessment of the actual safety level under combined extreme impacts. In particular, such approaches do not account for the probabilistic nature of loads, the statistical variability of material properties, and the scenario-based character of failure of structural elements [12, pp. 6–8; 30, pp. 330–332]. This necessitates a transition to risk-oriented analysis models that make it possible to evaluate not only the occurrence of a limit state but also the probability of its realization and the expected consequences for a civil defense facility.

The problem of optimizing the strengthening and rehabilitation of existing buildings incorporating civil defense protective structures *is of particular relevance*. A significant proportion of such facilities are constructed of brick and masonry elements that have undergone degradation during long-term operation or have been damaged as a result of military actions. Recent studies confirm the effectiveness of steel jackets, spatial reinforcement, and steel–reinforced concrete systems in increasing the load-bearing capacity and deformation capacity of such elements [12, pp. 9–14; 30, pp. 328–335]. At the same time, in most studies the effectiveness of strengthening is assessed using deterministic indicators, without a transition to a quantitative evaluation of the probability of structural failure.

The development of modern numerical modeling methods, particularly finite element analysis, creates prerequisites for a detailed investigation of the stress–strain state of complexly loaded structures, taking into account nonlinear material behavior and damage localization. However, without integrating these results with probabilistic reliability models, such studies remain limited in terms of engineering decision-making at the level of civil defense systems [29, pp. 48–52; 15, pp. 2–4]. Therefore, *the application of fragility curves and scenario-based analysis is particularly relevant*, as they make it possible to establish a relationship between the intensity of extreme impacts and the probability of reaching structural limit states.

Under modern conditions, the principle of resource efficiency also becomes *especially significant*, as it implies the rational use of material, temporal, and financial resources throughout all stages of the life cycle of protective structures. Resource-efficient solutions should be based not only on cost minimization but also on reducing the overall probability of failure and the expected losses in the event of hazardous scenario realization [29, pp. 60–65]. This requires combining structural optimization methods with risk management tools and reliability assessment techniques.

Thus, the *key scientific problem* addressed in this monograph is the development of a unified risk-oriented system for the structural optimization of civil defense protective structures that integrates the results of technical inspections, finite element modeling, and probabilistic assessment of structural vulnerability. The proposed approach is aimed at eliminating the existing scientific gap between local evaluations of strengthening effectiveness and the systemic analysis of failure risks under combined extreme impacts [12, pp. 13–14; 13, pp. 34–36].

The purpose of this monograph is to substantiate the theoretical foundations and to develop applied methods for the risk-oriented optimization of civil defense protective structures, ensuring enhanced safety, durability, and adaptability while simultaneously complying with resource-efficiency requirements. Achieving this objective involves solving a set of interrelated scientific and applied tasks related to modeling combined extreme impacts, constructing fragility models for strengthened and unstrengthened structures, and developing engineering decision-making algorithms based on risk assessment.

2. Analysis of Contemporary Scientific Approaches to Risk-Oriented Optimization of Civil Defense Protective Structures with Consideration of Operational Damage

The analysis of existing scientific publications has confirmed that the problem of ensuring the reliability and safety of civil defense protective structures under combined extreme impacts is gradually shifting from local strengthening of individual structural elements toward the formation of systemic, risk-oriented approaches to engineering decision-making. Traditional methods for assessing the technical condition of structures, which are mainly based on deterministic calculations and regulatory checks, do not fully account under modern conditions for the uncertainty of loading effects, the variability of material properties, and the cumulative nature of damage, which is particularly characteristic of protective structures subjected to seismic, blast, vibrational, and technogenic impacts [13, pp. 31–33; 14, pp. 2–4].

Studies devoted to resource-saving technologies and structural optimization of protective structures emphasize that the effectiveness of structural solutions should be evaluated not only in terms of increased load-bearing capacity but also with regard to failure risks, service life, and the economic feasibility of strengthening measures [29, pp. 48–52]. In particular, monographic research highlights the necessity of comprehensively accounting for the stress–strain state, material degradation, and progressive collapse scenarios when reconstructing built-in civil defense protective structures [29, pp. 60–65].

A significant body of contemporary publications focuses on numerical modeling of the behavior of masonry and brick structures under complex loading conditions. The finite element method remains the primary tool for analyzing the stress–strain state of strengthened columns and walls, as it enables simulation of nonlinear material behavior, contact interaction between elements, and damage localization [12, pp. 7–10; 30, pp. 330–332]. Studies addressing the strengthening of brick columns using steel jackets and spatial frames demonstrate that this approach provides a substantial increase in load-bearing capacity and stiffness; however, the obtained results are predominantly deterministic and do not reflect the probabilistic nature of structural failure [12, pp. 11–13].

Research on the effectiveness of strengthening brick columns with steel jackets using mathematical modeling shows that the increase in load-bearing capacity can reach significant values depending on jacket geometry, steel properties, and the initial level of masonry damage [12, pp. 9–12]. At the same time, the authors emphasize that, to justify the feasibility of such solutions in civil defense systems, it is necessary to consider the probability of reaching limit states under various loading scenarios, particularly under repeated or combined impacts [12, pp. 13–14].

A separate line of research is related to the assessment of the technical condition of protective structures and the determination of their compliance with anti-radiation shelter requirements. These studies apply comprehensive inspection methodologies that combine visual diagnostics, instrumental measurements, and computational verification of load-bearing capacity [13, pp. 29–32]. However, it is noted that existing methods for technical condition assessment have limited capability to predict further structural degradation and do not allow for a quantitative evaluation of the probability of future structural failure [13, pp. 34–36].

In contemporary international standards and regulatory documents, probabilistic approaches to assessing the reliability of existing structures are gaining increasing importance. In particular, provisions for the assessment of existing structures are based on the limit state concept while accounting for uncertainties in loads and material properties [14, pp. 5–7; 8, pp. 21–24]. In the context of civil defense protective structures, this creates opportunities for transitioning to risk-oriented optimization methods, where decisions on strengthening or reconstruction are made based on a comparison of failure probability and expected consequences [15, pp. 2–3].

A promising direction actively developing in global research is the construction of fragility curves for building structures, which describe the relationship between the probability of reaching a specific limit state and the intensity of loading. Such approaches are widely used in seismic engineering and blast impact analysis and can be adapted to tasks related to evaluating the effectiveness of strengthening masonry and brick structures [17, pp. 1146–1148; 25, pp. 6–8]. The application of fragility curves to strengthened and unstrengthened columns enables a transition from comparing maximum stresses to a quantitative assessment of failure risk, which is fundamentally important for substantiating decisions in civil defense systems.

The literature review also indicates that modern research increasingly focuses on integrating numerical modeling with probabilistic risk analysis methods. Combining the results of finite element calculations with Monte Carlo methods, Latin hypercube sampling, or fault tree analysis makes it possible to account for parameter dispersion and identify the most vulnerable structural elements [15, pp. 4–6; 26, pp. 3–5]. This approach is particularly relevant for protective structures operating under conditions of heightened uncertainty and limited possibilities for rapid repair.

Thus, the conducted review and synthesis of existing approaches within the framework of this study make it possible to form a consistent methodological framework for risk-oriented analysis and resource-efficient justification of decisions related to the strengthening and rehabilitation of civil defense protective structures. Within the monograph, *the emphasis shifts from maximizing strength reserves to achieving an acceptable* *level of risk with minimal resource expenditure*, which implies ranking structural elements according to risk level and concentrating strengthening measures on the most vulnerable zones. At the same time, a key direction for further development of the topic is the transition from conceptual integration of approaches to obtaining reproducible numerical results for specific types of elements and strengthening techniques (through parameterization of fragility curves and calibrated intensity measures), which is considered in this monograph as a methodologically prepared next step.

3. Main Part

3.1. Results of Inspection and Assessment of the Technical Condition of Protective Structures with Documentation of Defects and Damage

During the visual inspection of civil defense shelters, information is collected on the building and the technical condition of structural elements, as well as on the presence of visible defects, including:

– cracks;

– delamination of protective coatings and layers;

– spalling and loss of integrity in local zones of structures;

– stratification or weathering of materials and loss of adhesion between their components;

– corrosion wear of steel structures and embedded parts, as well as reinforcement of reinforced concrete structures;

– excessive deflections, tilts, settlements, bulging, and other defects caused by uneven settlement of load-bearing structures;

– efflorescence on surfaces, wetting of structural elements, and failure of waterproofing and water-protection layers;

– reduction of bearing areas of structural elements;

– loss of airtightness and waterproofing performance;

– detachment of anchors from plates;

– local (edge) concrete damage;

– freeze–thaw damage and weathering of concrete.

As a result of the visual inspection, a preliminary analysis of the collected data is performed to determine the overall pattern of defects and the expected trends of their development and influence on the technical condition of the building’s structural elements.

3.1.1. Damage to Reinforced Concrete Structures

During the inspection of reinforced concrete wall and floor structures in neglected shelters, typical damage includes corrosion deterioration over almost the entire concrete surface (up to 90%), peeling and delamination of the concrete finishing layer (Figure 3.1). Exposure and corrosion damage (up to 30%) of the load-bearing reinforcement of reinforced concrete structures are observed, particularly above door openings (Figures 3.2–3.4). Due to a malfunctioning ventilation system (Figure 3.5), increased humidity and moisture condensation on the surfaces of load-bearing structures are recorded within shelter premises, which significantly accelerates reinforced concrete corrosion processes (Figure 3.6). Steel elements of door frames exhibit corrosion damage of up to 50% (Figure 3.7).

Figure 3.1. Destruction of the protective concrete layer of walls and slabs

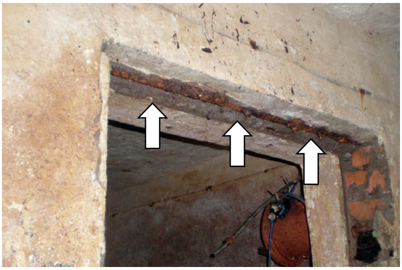

Figure 3.2. Exposure and corrosion of load-bearing reinforcement of reinforced concrete structures

Figure 3.3. Formation of cracks in load-bearing structures above door openings

Figure 3.4. Delamination of the reinforced concrete lintel above door openings

Figure 3.5. Partially dismantled ventilation system of the premises

Figure 3.6. Moisture condensation on the surfaces of reinforced concrete structures

a) **b)**

Figure 3.7. Corrosion damage of steel door frame elements

3.1.2. Damage to Utility Systems

Assessing the technical condition of engineering systems proves to be rather complicated, since in shelter premises the heating system has often been almost completely dismantled, and sanitary fixtures in utility rooms are partially broken and removed. Electrical power supply, electrical equipment, and lighting systems originally предусмотрені by the design are completely absent. Dismantling was not performed centrally. Communication and signaling equipment is also missing.

The supply-and-exhaust filtration ventilation system exhibits numerous damages in the form of breaks, dents, and loss of pipeline segments (Figures 3.5 and 3.8). The ventilation chamber and filter compartments are empty. There is a complete absence of ventilation and heating systems.

Internal water supply and sewerage systems are absent. The remaining sections of pipelines are in unsatisfactory technical condition, non-airtight, and covered with a layer of rust (Figure 3.9).

Entrance passages to the premises are cluttered with construction debris and corrosion products of reinforced concrete elements (Figure 3.10). Entrance doors were originally designed as protective airtight doors with a flat steel leaf framed by steel profiles. The door leaf and steel frame are severely corroded and poorly fitted. The remaining steel and wooden frames in the door openings are beyond restoration.

Thus, it can be stated that the structure is not equipped with protective airtight or hermetic devices, and the installation of new doors is not possible without destruction of the reinforced concrete edges of the openings and ensuring subsequent airtightness. Consequently, airtightness of the bomb shelter premises cannot be ensured. Any engineering measures aimed at restoring structural solutions in this case will be ineffective both from the standpoint of economic feasibility and in terms of compliance with modern requirements.

a) b)

Figure 3.8. Damage to the ventilation system of the bomb shelter premises: a) rupture of the ventilation duct; b) dents and corrosion of steel ventilation sleeves

Figure 3.9. General interior view of sanitary facilities

Figure 3.10. Obstruction of entrance passages with construction debris

3.1.3. Damage to External Enclosing Structures and Adjacent Territory

The territory surrounding shelter buildings is predominantly planned with a slope away from the building (Figure 3.11). However, during operation, non-draining platforms have formed near entrance passages (Figure 3.12), which leads to direct moisture penetration into the premises during atmospheric precipitation.

Figure 3.11. General condition of the territory adjacent to the bomb shelter

a) b)

Figure 3.12. General view of entrances to shelter premises

3.2. Conceptual Foundations of the Risk-Oriented Approach in the Engineering of Protective Structures

The risk-oriented approach to the design and optimization of protective structures implies a shift in emphasis from the absolute "strength" of structures toward a quantitative assessment of the probability of failure and the potential consequences of such failure. In the context of civil defense, risk is considered an integral characteristic that combines the probability of reaching a certain limit state with the level of hazard posed to people and infrastructure. This approach is particularly relevant for protective structures that must ensure an acceptable level of safety even under conditions of partial damage and material degradation [13, pp. 33–35; 15, pp. 2–3].

Scientific studies devoted to the assessment of the technical condition of protective structures indicate that the actual operational characteristics of structures significantly differ from their design values due to the presence of hidden defects, load nonuniformity, and the influence of external factors [13, pp. 29–32]. This determines the necessity of using probabilistic models that make it possible to account for the dispersion of material strength characteristics, geometric parameters, and load intensities. Within the risk-oriented approach, each of these parameters is treated as a random variable that collectively determines the overall level of reliability or vulnerability of the structure.

Conceptually, the risk-oriented approach is based on the integration of three interrelated components: *numerical modeling of the stress–strain* *state of structures, probabilistic assessment of limit states, and analysis of scenarios of combined extreme impacts*. Numerical models constructed using the finite element method make it possible to reproduce in detail the behavior of strengthened and unstrengthened masonry elements under various loading schemes [12, pp. 7–10; 30, pp. 331–333]. At the same time, the results of such calculations acquire practical significance only when they are integrated with probabilistic analysis methods that explicitly account for uncertainties in the input parameters [15, pp. 4–6].

Combined extreme impacts, which are characteristic of modern operating conditions of protective structures, play a particularly important role in the formation of a risk-oriented system. Seismic loads, blast waves, impact and vibrational actions, as well as secondary technogenic factors, may act sequentially or simultaneously, forming complex scenarios of structural damage [25, pp. 6–8; 28, pp. 3–5]. A deterministic consideration of such impacts does not allow the probability of progressive collapse to be assessed, whereas a risk-oriented approach enables a quantitative description of the spectrum of possible scenarios, ranging from local damage to the loss of load-bearing capacity of the entire structure.

Within the framework of the resource-efficiency concept, the risk-oriented approach gains additional importance, as it allows optimization not only of structural solutions but also of material volumes and labor costs. Instead of maximizing the safety margin, the objective is to achieve an acceptable level of risk with minimal resource expenditures, which is critically important for the rehabilitation of protective structures in the post-emergency period [29, pp. 52–55]. This approach involves ranking structural elements according to their risk level and concentrating strengthening measures on the most vulnerable zones.

The concept of risk-oriented optimization is also closely related to the assessment of the residual service life of structures. Based on the results of probabilistic analysis and numerical modeling, a range of possible safe service periods for strengthened and unstrengthened elements can be determined. Such an approach creates prerequisites for predictive management of the technical condition of protective structures rather than emergency-driven elimination of damage consequences.

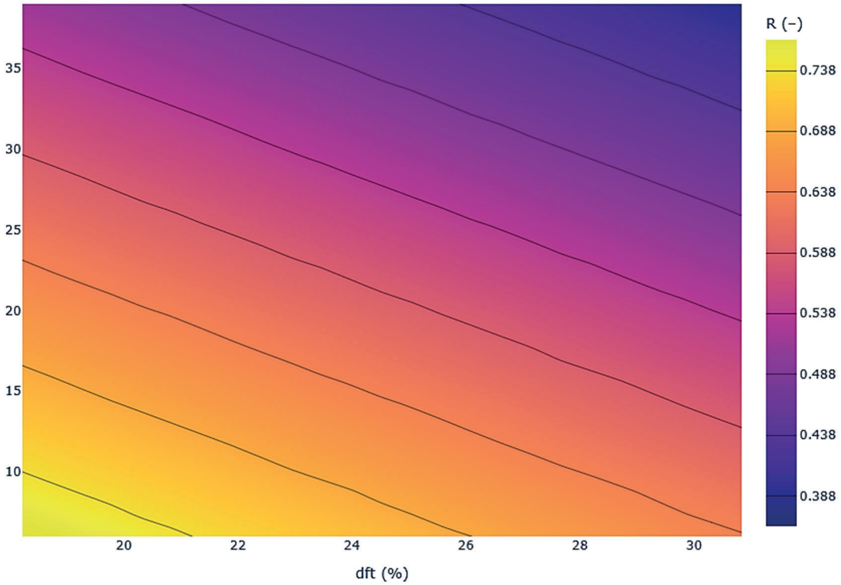

Figure 3.13. Contour map of the residual load-bearing capacity of an unstrengthened element $R_0\left(d_m, d_{ft}\right)$

The constructed map represents a deterministic visualization of the residual capacity ratio as a dimensionless coefficient characterizing the fraction of the initial load-bearing capacity of an element after the combined action of two independently interpreted degradation mechanisms: moisture exposure/increased humidity (parameter $\mathrm{d_m}$) and freeze–thaw damage (parameter d_{ft}). To ensure correct physical interpretation, the percentage degradation indicators are converted into unit fractions: $\delta_m = \frac{d_m}{100}$, $\delta_{ft} = \frac{d_{ft}}{100}$. The basic model for the unstrengthened state is then expressed in multiplicative form:

$$R_0\left(d_m, d_{ft}\right) = \left(1-\delta_m\right)\left(1-\delta_{ft}\right).$$

The multiplicative character directly corresponds to the concept of “sequential resource reduction” due to two degradation mechanisms: the first mechanism reduces the available load-bearing capacity to $1-\delta_m$, while the second further scales it by $1-\delta_{ft}$. On the contour map (isolines $R_0=\text{const}$) zones of higher R_0 values correspond to low levels of degradation, whereas a shift toward higher values of d_m and d_{ft} reflects a systematic decrease in residual load-bearing capacity. The practical interpretation of Figure 3.13 lies in the fact that it serves as a "baseline hazard map" in the material state space: each pair d_m, d_{ft} uniquely defines a deterministic state of structural capacity. In the subsequent risk-oriented framework, this map acts as the core for constructing a limit state function, for example in the form:

$$g\left(d_m, d_{ft}\right)=R_0\left(d_m, d_{ft}\right)\cdot N_{ref}-N_{demand},$$

where N_{ref} – is the reference (initial or code-based) load-bearing capacity, and N_{demand} is the design demand/load (accounting for a specific extreme-impact scenario). The transition to a probabilistic formulation is achieved by treating d_m and d_{ft} as random variables (or random processes over time), which enables the evaluation of the failure probability $P\left(g\leq 0\right)$ and the formulation of risk-oriented prioritization criteria.

To represent the strengthening effect, a strengthening coefficient k_{steel}, is introduced, which scales the residual load-bearing capacity relative to the unstrengthened state. Within the adopted conceptual scheme (where degradation mechanisms reduce the "base" resource and strengthening restores/increases the load-bearing capacity within the admissible part of the range), the following relationship is used:

$$R_{steel}\left(d_m, d_{ft}\right)=k_{steel}, R_0\left(d_m, d_{ft}\right).$$

In the calculations, $k_{steel}=\dfrac{36}{28}=1.285714\ldots$, is applied, which is interpreted as the relative increase in the "effective" load-bearing capacity/strength for the given strengthening scheme. The contour map in Figure 3.14 demonstrates a systematic shift of isolines toward higher values of R for the same levels of d_m, d_{ft}. This has an important methodological implication for risk-oriented optimization: strengthening does not merely "improve" the structure qualitatively, but quantitatively reduces the region of degradation parameters that leads to crossing a limit state. In terms of the limit state function,

$$g_{steel}\left(d_m, d_{ft}\right)=R_{steel}\left(d_m, d_{ft}\right)\cdot N_{ref}-N_{demand},$$

trengthening increases the safety margin g and thereby reduces $P(g \leq 0)$ for the same distribution of degradation parameters. Precisely this type of maps constitutes a convenient tool for ranking objects and selecting strengthening technologies: by fixing an admissible level of residual load-bearing capacity R_{lim} (for example, as a serviceability threshold), it becomes possible to immediately identify the regions $\left(d_m, d_{ft}\right),:, R \geq R_{lim})$ and to compare their area/geometry before and after strengthening. In the context of this subsection, this represents a direct transition from "local strengthening efficiency" to a systemic formulation, where the decision is chosen not only by the average strength gain but by how the domain of safe operation changes within the space of possible degradation states.

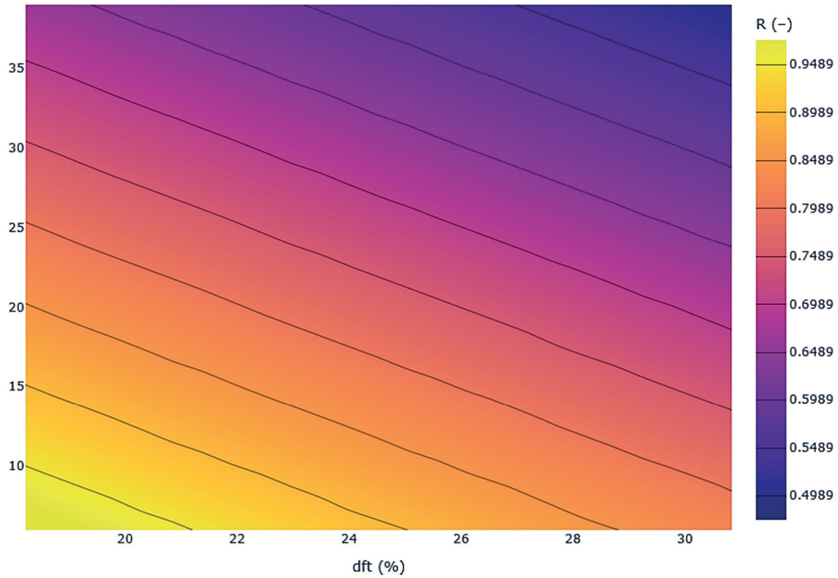

Figure 3.14. Contour map of the residual load-bearing capacity of an element after strengthening with a steel jacket $R_{steel}\left(d_m, d_{ft}\right)$

The three-dimensional representation is a geometric interpretation of the same function R_0, as in Figure 3.15, but it allows a more illustrative assessment of "degradation gradients," i.e., the sensitivity of the resource to changes in each parameter. Since the model has the form of a product of two linear-in-δ factors, the surface is smooth and without discontinuities:

$$\frac{\partial R_0}{\partial \delta_m} = -\left(1-\delta_{ft}\right), \qquad \frac{\partial R_0}{\partial \delta_{ft}} = -\left(1-\delta_m\right).$$

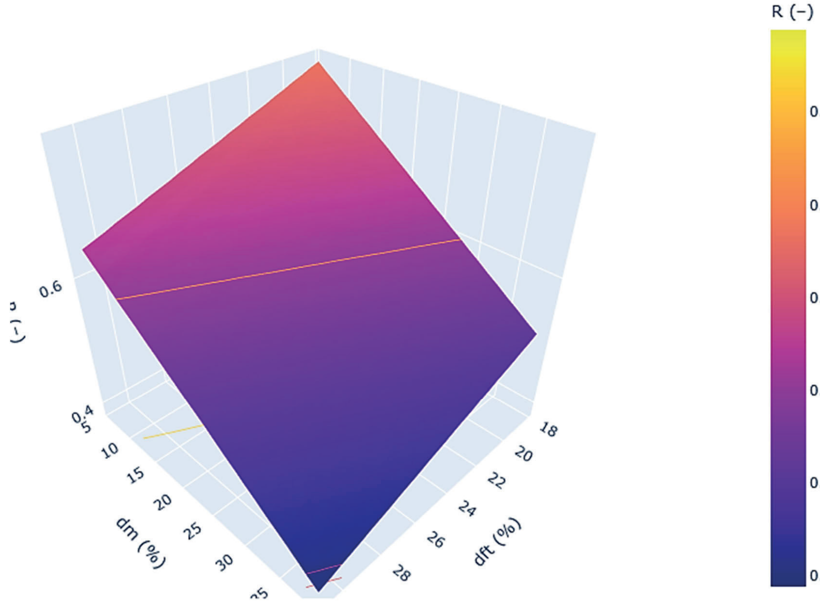

Figure 3.15. Spatial model of the residual load-bearing capacity surface of an unstrengthened element $R_0\left(d_m, d_{ft}\right)$

Thus, at low degradation levels, one mechanism "amplifies" sensitivity to the other (because the factor 1 – δ is close to 1), whereas at significant degradation by one parameter, the contribution of the other becomes less "visible" in absolute values of *R* (the factor is already substantially smaller). This conclusion is important for risk-oriented logic: in zones of severe damage by one mechanism, an additional influence of the second mechanism may rapidly drive the system to a limit state even with a relatively small increase in degradation. Therefore, in practical scenarios of technical condition management, it is advisable to use not only thresholds of d_m or d_{ft} separately, but the integral indicator R_0 as an "aggregated resource" that directly enters the limit state function and subsequent risk assessment. Within the concept of monitoring and forecasting, $d_m(t)$ and $d_{ft}(t)$ can also be interpreted as functions of time (or accumulated indicators), then $R_0(t) = (1 - \delta_m - (t))\ (1 - \delta_{ft}\ (t))$ and the surface in Figure 3.16 becomes a basic "transition map" from the current state to the forecasted one, providing a foundation for moving from emergency repairs to predictive resource management.

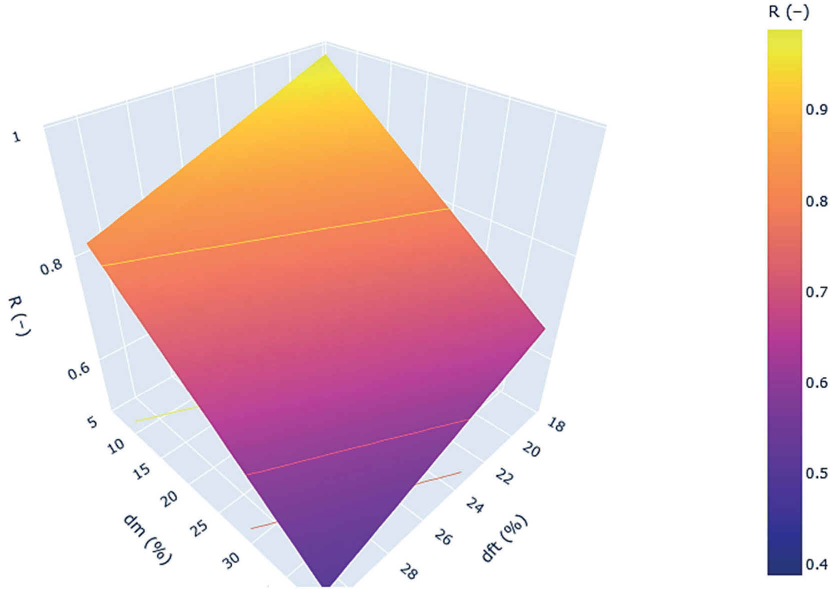

Figure 3.16. Spatial model of the residual load-bearing capacity surface of an element after strengthening with a steel jacket $R_{steel}(d_m, d_{ft})$

Unlike the unstrengthened case, where the surface directly reflects only degradation mechanisms, the strengthened state includes a "compensatory" factor k_{steel}, that scales the entire surface:

$R_{steel}\left(d_m, d_{ft}\right) = k_{steel}\left(1 - \ddot{a}_m\right)\left(1 - \ddot{a}_{ft}\right)$. Geometrically, this means lifting the surface upward without changing its topology (the shape is preserved, the level changes). This is an important feature for engineering optimization: for a given degradation model, strengthening with a steel jacket acts as a global “resource amplifier,” increasing the safety margin for a wide range of states d_m, d_{ft}. In terms of risk, this is equivalent to reducing the probability of reaching a limit state for the same statistical characteristics of degradation and loading. At the same time, the 3D surface allows correct interpretation of an important applicability boundary: if, in subsequent formulations, an upper constraint appears (for example, due to regulatory limits on deformations/stability or other failure mechanisms), then for large k_{steel} the model should be supplemented with “strengthening effect saturation” mechanisms or additional limit states. This is precisely the value of the risk-oriented approach: it does not reduce the decision to a single strengthening coefficient but forces consideration of the full set of failure scenarios. However, within this subsection, these surfaces perform a key function–they create a mathematically transparent basis for the subsequent transition to a fragility description: by setting a serviceability threshold R_{lim}, one can define the failure domain

$$\Omega_f = \left(d_m, d_{ft}\right) : R < R_{lim}$$

and evaluate its probability for given distributions of d_m and d_{ft}. This is the necessary link between the assessment of residual load-bearing capacity and risk-oriented optimization of strengthening/reconstruction decisions.

Considering the above, the maps $R_0\left(d_m, d_{ft}\right)$ and $R_{steel}\left(d_m, d_{ft}\right)$ are not merely illustrations of degradation but instruments that directly support the argument for transitioning to predictive management of the technical condition. The concept of risk-oriented optimization is closely linked to the assessment of residual resource: if the initial load-bearing capacity of an element is N_{ref}, then the current load-bearing capacity is evaluated as $N_{res}\left(d_m, d_{ft}\right) = R\left(d_m, d_{ft}\right) \cdot N_{ref}$, where $R = R_0$ or R_{steel} depending on the type of strengthening. Further, by linking degradation parameters to service time (through damage accumulation models or monitoring data), it is possible to transition to a time-dependent resource function $N_{res}\left(t\right)$ and to estimate the range of safe service periods as the time to reach the threshold R_{lim} or to satisfy $g\left(t\right) = 0$ in the adopted limit state function.

Table 3.1

Residual resource of structural elements of operating shelters

n_{cycles}	*R(n)*	*%Loss*
0	1	0
5	0,97	3
10	0,941	5,9
15	0,914	8,6
20	0,888	11,2
25	0,863	13,7
30	0,84	16
35	0,817	18,3
40	0,795	20,5
45	0,774	22,6
50	0,754	24,6
60	0,717	28,3
70	0,683	31,7
80	0,652	34,8
90	0,623	37,7
100	0,597	40,3
120	0,551	44,9
140	0,51	49
160	0,473	52,7
180	0,441	55,9
200	0,411	58,9
250	0,358	64,2
300	0,313	68,7
350	0,274	72,6
400	0,24	76
450	0,211	78,9
500	0,186	81,4
600	0,147	85,3
700	0,116	88,4
800	0,091	90,9

The presented table of residual resource of structural elements completes the formation of the conceptual foundations of the risk-oriented approach to the assessment and management of the technical condition of civil defense protective structures. Its key methodological value lies in the fact that the structural resource is not treated as a fixed normative value, but as a random function of time or the number of loading cycles, directly associated with damage accumulation in the material.

Within the proposed concept, the state of a column at an arbitrary moment of service is described by a set of dimensionless damage parameters $d_m(t)$ and $d_{ft}(t)$, which characterize, respectively, mechanical degradation (deformation and cracking damage, stiffness reduction) and degradation due to cyclic or physicochemical effects (freeze–thaw, moisture, microcrack formation). In generalized form, the residual load-bearing capacity can be represented as

$$R(t) = R\left(d_m(t), d_{ft}(t)\right),$$

where $R(t)$ is a relative indicator of load-bearing capacity normalized to the initial state of the structure.

The proposed approach fundamentally differs from traditional deterministic schemes in that the moment of resource exhaustion is not specified a priori but is determined by the condition of reaching a limit state. Formally, this can be written as $R(t) = R_{\lim}$, or equivalently through the safety margin function $g(t) = R(t) - R_{\lim} = 0$, where $R_{\lim}$ corresponds to the minimum admissible level of load-bearing capacity at which further operation becomes unacceptable from a safety standpoint.

The constructed residual resource table effectively implements a discrete representation of this condition for different damage accumulation scenarios. If one of the parameters is fixed (for example, $d_{ft} = \text{const}$), the table allows direct construction of curves of the type $R(d_m)$, which reflect degradation of load-bearing capacity with increasing mechanical damage. This approach is appropriate for analyzing local defects associated with overloads, localized failures, or repeated seismic or blast impacts.

Conversely, when a trajectory of joint damage growth $R(t)$ is specified, the table becomes the basis for constructing the function $R(t)$, which is directly interpreted as the degradation of load-bearing capacity over time or by the number of operational load cycles. This variant is the most representative for resource forecasting tasks, as it accounts for the real interaction of different damage mechanisms that, under the operating conditions of protective structures, are typically realized simultaneously.

It is important to emphasize that the presented accumulation law does not require the introduction of conditional or hypothetical time parameters. The transition from cycles to years of service can be performed at a subsequent stage by incorporating climatic, operational, or monitoring data (for example, the average number of freeze–thaw cycles per year or the intensity of repeated dynamic loads). Thus, the model retains universality and can be adapted to specific site conditions and operating regimes.

In the context of risk-oriented optimization, a crucial point is that the residual resource table can be directly integrated into probabilistic failure models. Since the parameters d_m and d_{ft} are stochastic in real conditions, the function $R(t)$ also acquires a random nature. This creates the possibility of constructing fragility curves for strengthened and unstrengthened columns and of evaluating the probability of reaching a limit state at a given time.

Therefore, a logically coherent concept is obtained: from the description of damage mechanisms and material degradation to a formalized definition of residual resource and a transition to predictive management of the technical condition of civil defense protective structures. The proposed approach establishes a methodological basis for moving from reactive decisions aimed at eliminating damage consequences to a proactive risk management strategy, in which structural strengthening, selection of rehabilitation technologies, and prioritization of interventions are determined based on a quantitative assessment of resource and failure probability.

The proposed logic creates prerequisites for predictive management of the technical condition of protective structures, since the integration of inspection and modeling domains makes it possible to interpret residual load-bearing capacity as a function of the current damage level, strengthening parameters, and combinations of impacts, and to orient decisions on reconstruction/strengthening/operational restriction toward the forecasted probability of transition to limit states and the expected residual load-bearing capacity. In this formulation, risk becomes not a declarative criterion but a variable that links the results of numerical analysis, limit state criteria, and resource constraints. The conceptual foundations of the risk-oriented approach in the engineering of civil defense protective structures thus consist in abandoning purely deterministic safety criteria in favor of an integrated system for assessing failure probability, consequences of damage, and resource efficiency of structural solutions. The methodological basis for quantitative vulnerability forecasting in this study is defined through the introduction of the fragility approach: for each limit state, a vulnerability curve is determined as the conditional probability of exceeding the limit state for a given intensity measure, with a lognormal fragility model adopted as the basic form and its parameters estimated using the maximum likelihood method. In this way, the monograph formulates a toolkit for transitioning from qualitative conclusions to formalized probabilistic assessments suitable for further scaling to multiple scenarios and strengthening options.

Conclusions

As a result of the conducted research aimed at forming a risk-oriented system for the structural optimization of civil defense protective structures with consideration of operational damage, it has been established that modern requirements for the functioning of shelters during wartime and post-accident periods necessitate a transition from local solutions for strengthening individual elements to a comprehensive algorithm for engineering decision-making. This algorithm integrates the results of numerical analysis, technical inspection, and probabilistic assessment of failures. Such an approach makes it possible to ensure not only an increase in the load-bearing capacity of structures but also substantiated management of risks, resources, and recovery priorities, taking into account real scenarios of combined impacts and the accumulation of damage over time [29, p. 48–52; 29, p. 60–65].

The expediency of a risk-oriented formulation of the structural optimization problem for civil defense protective structures *has been substantiated*. Within this framework, the main efficiency criterion is not merely the increase in strength or stiffness, but the reduction in the probability of reaching limit states under fixed resource constraints and with consideration of the possible consequences of failure. Such a formulation ensures methodological unity between technical inspection, computational models, and managerial decisions regarding reconstruction and strengthening, which is consistent with modern approaches to resource saving and optimization in the field of civil defense [29, p. 52–55; 29, p. 60–65].

It has been shown that the most practically significant basis for risk-oriented decisions is the combination of the results of technical diagnostics and verification of compliance of a structure with the functional requirements of an anti-radiation shelter, followed by the identification of critical elements that form dominant failure scenarios. It has been proven that a comprehensive assessment of the technical condition, with formalization of defects and damage, creates the initial information base for parameterization of computational models, ranking of vulnerable zones, and formulation of the strengthening optimization problem according to the risk criterion [13, p. 29–32; 13, p. 34–36].

It has been established that numerical modeling of the stress–strain state of strengthened masonry/brick structural elements, particularly columns, is a key tool for the quantitative assessment of strengthening efficiency and for forming the initial relationships for subsequent probabilistic analysis. Finite element models make it possible to reproduce real conditions of complex loading and localization of damage in deformed brick columns, which is fundamental for design and reconstruction tasks of built-in civil defense structures made of steel–reinforced concrete. At the same time, the deterministic result of a FEM analysis by itself is insufficient for decision-making within the civil defense system, since it does not account for the dispersion of material properties and load uncertainties, which directly affect the risk of reaching a limit state in real operation [29, p. 60–65].

It has been confirmed that strengthening brick columns with steel jackets (steel frames/cages) *is an effective structural solution* for increasing load-bearing capacity and stabilizing the behavior of elements within built-in protective structures. Mathematical modeling of strengthening efficiency has demonstrated a significant influence of the parameters of the strengthening system (geometry, steel properties, interaction conditions with masonry) on the resulting performance indicators, which opens the possibility of formulating an optimization problem for strengthening parameters within given resource constraints [12, p. 9–12; 12, p. 11–13]. At the same time, it has been established that in order to move from “strengthening efficiency” to “failure risk management,” it is necessary to transform the results of deterministic models into probabilistic reliability characteristics that directly reflect uncertainty and variability of the initial parameters [12, p. 13–14; 29, p. 48–52].

The necessity of developing fragility models for strengthened and unstrengthened elements as a central tool for integrating the results of experimental and numerical studies into a risk-oriented decision-making system *has been formulated and methodologically justified*. Fragility curves make it possible to move from comparing limit stresses or deformations to a quantitative assessment of the probability of reaching specified damage levels at a given intensity of combined loads, which is critically important for ranking civil defense facilities, determining recovery priorities, and substantiating the choice of strengthening technology [29, p. 60–65; 12, p. 13–14].

It has been shown that the methodological basis of risk-oriented optimization *should be linked* to modern risk management principles, which provide for systematization, traceability of decision-making, and alignment of risk criteria with safety objectives and available resources. Within the scope of the study, it has been determined that the application of risk management principles makes it possible to formalize the stages of the algorithm (hazard identification, analysis, assessment, selection of risk treatment measures) and to align technical strengthening solutions with safety and resource-saving requirements [15, p. 2–3; 15, p. 4–6].

It has been established that the integration of three components – (a) a diagnostic block for assessing the technical condition and compliance of the structure with shelter requirements, (b) numerical modeling of the behavior of key elements under complex loading, and (c) probabilistic interpretation of results through reliability indicators and fragility – ensures elimination of the scientific gap associated with the absence of a unified risk-oriented optimization system for civil defense protective structures. Such integration transforms a “set of separate engineering methods” into a technologically and scientifically consistent decision-making system capable of accounting for the probabilistic nature of failures, the combined character of extreme impacts, and resource-saving requirements [13, p. 34–36; 29, p. 60–65; 12, p. 13–14].

Prospects for further research within the selected topic should be directed toward: (1) expanding the calibration database for fragility models for different types of masonry and strengthening schemes; (2) forming scenarios of combined extreme impacts for multi-hazard analysis with reference to real operating conditions of shelters; (3) developing optimization formulations with explicit consideration of resource constraints and recovery efficiency criteria; (4) refining procedures for combining technical inspection results with parameterization of numerical models to improve the reliability of risk-oriented decisions [29, p. 44–81; 13, p. 29–40].

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