RESEARCH OF PARAMETERS OF SECURITY ROOMS' ENCLOSURE STRUCTURES IN RESIDENTIAL APARTMENT BUILDINGS

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Abstract: For the safe stay of people in the premises of residential multi-apartment buildings in the conditions of military operations, it is essential to strengthen measures against the effects of explosive weapons. Enabling of the presence of protected spaces during the design of new or reconstruction of residential construction objects meets the modern requirements for the protection of people in the event of the use of means of explosive damage. Study of the consequences of the use of explosive weapons in populated areas, establishing the relationship between the ability of the structures of protective buildings of civil defense to maintain their protective properties and the parameters of the effects of damage from explosive weapons, assessing the vulnerability of the enclosing structures of residential buildings to threats under explosive loads, conceptual principles regarding the organization of work and construction of such shelters for the civilian population is carried out by Ukrainian and foreign scientists. However, there is currently no substantiation of the requirements for the enclosing structures of security rooms in residential multi-apartment buildings in Ukraine. According to the results of the study, an analysis of statistical data on the death and injury of the civilian population in residential buildings from explosive weapons was carried out; foreign sources on the protection of the civilian population from explosive weapons are analyzed; a mathematical model was developed and verified to describe dynamic loads from explosive weapons; the characteristics of explosive weapons used on the territory of Ukraine were analyzed; calculations of the design parameters of protected spaces capable of withstanding falling fragments of this weapon were carried out. The research makes it possible to develop proposals for the design of protective security rooms in multi-apartment residential buildings.

Keywords: protective security room; explosive weapons; enclosing structures; loads on building structures.

1 Introduction

Since the beginning of the full-scale war against Ukraine, more than 8,300 civilians have died (including 500 children), and about 14,000 (including 900 children) have been injured in various degrees of severity. More than 40,500 shellings were recorded, which hit more than 152,000 residential buildings, mainly in Donetsk, Kharkiv, Kyiv, Mykolaiv, Zaporizhia, Kherson, Chernihiv, Luhansk, and Dnipropetrovsk regions. The reason for the death of a significant number of civilians was the use of explosive weapons. Statistical data indicate numerous cases of fragments of explosive weapons falling on the residential sector [13; 21].

It is worth noting that many of the shelters that Ukrainians use today for civil protection are mostly built in Soviet times, are located on industrial and social infrastructure facilities, and in terms of efficiency in modern realities do not have the proper functional capacity. Moreover, the existing shelters allow protection of approximately half of the country's population [9].

The problems of protecting civilian population from explosive phenomena all over the world are attracting increasingly more attention from the political, legal, socio-economic point of view [5]. Modern engineering solutions for the design of new ones or reconstruction of existing residential facilities complement the general strategy of the civilian population security. The experience of the USA, Germany, Switzerland, Singapore, Finland, and Israel regarding the protection of the civilian population involves the construction of fortified rooms in residential buildings and public buildings (mammaka, mammada, or protective capsule rooms, etc.). One can move there in a few seconds without leaving the building, which meets the requirements of today. As follows, the safe stay of the civilian population in the premises of residential buildings depends on the ability of their enclosing structures to retain their protective properties when being hit by an explosive weapon, taking into account the relevant volume-planning and structural solutions.

The use of enclosing structures in the premises of residential buildings, which can better resist shells fragments and the blast wave to reduce the destructive consequences and impact on people, is practically absent in Ukraine or has a very limited application. In domestic Ukrainian legal acts, there are not enough scientifically based requirements regarding the explosive load on building structures and provisions for their arrangement in residential multi-apartment buildings, capable of ensuring the safe stay of people during bombings and shelling.

This determines the relevance of the study regarding the establishment of conditions for the safe stay of the civilian population in the premises of multi-story residential buildings by equipping them with protective spaces, the enclosing structures of which are able to withstand the fall of fragments of explosive weapons.

The object of the study is the impact of the load on the enclosing structures of the security rooms of residential apartment buildings, which occur during the use of explosive weapons.

The subject of the study is the parameters of the enclosing structures of security rooms of residential apartment buildings depending on the characteristics of explosive weapons.

The purpose of the research is to establish the conditions for the safe stay of people in the living premises of apartment buildings by equipping them with security rooms, the enclosing structures of which are able to withstand falling fragments of explosive weapons. To achieve the set goal, the following scientific tasks are to be solved:

- To conduct an analysis of statistical data on the deaths and injuries of civilians in residential buildings from explosive weapons;
- To analyze foreign experience in protecting the civilian population from explosive weapons;
- To analyze the characteristics of explosive weapons used on the territory of Ukraine;
- To develop a mathematical model for describing dynamic loads from explosive weapons;
- To carry out calculations of the design parameters of the protective security room, which are able to withstand the fall of fragments of explosive weapons;
- To verify the developed mathematical model for describing dynamic loads from explosive weapons.

2 Method

The following research methods are used in the work: comprehensive analysis and generalization of previously performed works, mathematical modeling of the processes of construction and the effect of excessive explosion pressure on building structures, experimental method of elastic rebound, experimental method of researching the state of a building structure under the influence of excessive explosion pressure.

The method of the experiment on the dynamic behavior of the building structures of the protective security room is applied regarding the practice of protecting people in residential multi-apartment buildings due to the presence in them of building structures capable of maintaining protective functions against injuries from explosive weapons.

Guided by the strategic goal of increasing human security and possessing expert knowledge in the field of explosive objects, the Geneva International Center for Humanitarian Demining characterized explosive weapons and their impact on the consequences (primary, secondary, and tertiary ones) of their use in populated areas as an important humanitarian problem [4]. Taking into account the conclusions of this institution, our research is based on primary (caused by direct destructive effects, which include shell fragments, high-pressure blast wave and thermal energy released during the detonation of the explosive) and secondary (secondary fragmentation, fires, aftershocks as a result detonation of shell on the ground or above the ground, formation of craters, etc.) factors. Tertiary factors are associated with damage to human health, social and economic infrastructure in a longer time scale (lack of clean water caused by damage to water supply and sewage networks; disconnection of electricity and gas supply, etc.) [2; 4].

In our study, a room located in a common area on a floor or directly in an apartment of a multi-story residential building, where conditions are created to minimize the negative impact of dangerous factors from the impact of an explosive weapon on a person, will be called a protective security room.

According to the authors, the concepts of “shock wave” and “blast wave” existing in the scientific discourse and current legal acts of Ukraine are debatable; therefore, in the context of the study, they are taken into account in view of the relevant literature.

3 Literature Review

Research of the fundamental physical principles of explosive phenomena by scientists has led to an understanding of how explosive properties develop from the early stages of shell burst and the spread of fragments and the blast wave [12]. As a result of these studies, semi-empirical forecasting tools for blast wave action scenarios have been developed. Scientists have proven that a blast wave is a region of sharp, strong air compression that spreads from the epicenter of the explosion at supersonic speed. The excess pressure in the front of the shock wave of the explosion, which occurs right next to the building, is the difference between the pressure of this wave and the atmospheric pressure. Below, there is a quantitative determination of the action of the blast wave according to its peak pressure and duration, its consequences for protective structures and people (Table 1).

The interaction of blast and obstruction is a complex multifaceted problem. While there are engineering-grade tools for predicting blast parameters (such as peak pressure, impulse, and load duration) under geometrically simple conditions, a blast wave is fundamentally altered as it interacts with an object in its path, and thus affects the very load parameters. A comprehensive overview of key research in this field, which concerns the direct impact of the blast wave on the surface of the structure, the pressure of the blast wave in the wake of the obstacle, the description of methods for predicting load parameters in the conditions of the interaction of the explosion with the obstacle, was investigated by the scientist O. Isaak. The key conclusions of the study concern the mechanisms regulating the weakening of the blast wave [10].

Table 1: Impact of the blast wave on the enclosing structures and the human body in quantitative terms [1, 12, 14]

Peak overpressure	**Maximum wind speed**	**Impact on the structure**	**Effect on the human body**
7 kPa	17 m/s	The window glass breaks	Light shrapnel damage occurs
14 kPa	31 m/s	Moderate damage to buildings (broken windows and doors and significant damage to roofs)	People were injured by flying glass and debris
21 kPa	46 m/s	Destruction of residential buildings	Serious injuries are common, and fatalities are possible
34.5 kPa	73 m/s	Most of the buildings are collapsing	Injuries are ubiquitous, fatalities are common
69 kPa	131 m/s	Reinforced concrete buildings are heavily damaged or destroyed	Most people are fatally injured
138 kPa	224 m/s	Heavy concrete buildings are badly damaged or destroyed	Fatalities approach 100%

Prediction of structural response and damage due to loading, which is highly localized and inhomogeneous, requires a detailed understanding of both the magnitude and its distribution, which, in turn, depend on the properties and dimensions of the structure, the distance between the charge and the structure, and the composition of the explosive. Explosives are usually expressed in equivalent mass to facilitate the use of well-established semi-empirical methods. This requires the calculation of the explosive equivalence factor. In work [6], scientists derive the TNT equivalent for the three most common explosives, using the approach of the equivalent upper limit of kinetic energy. A series of numerical simulations, calculation of the magnitude and distribution of the specific momentum to obtain the theoretical upper limit of the kinetic energy are performed.

There are numerical and experimental studies of impact and explosive effects on building construction elements, characterized by deformation rates. The research characterizes the idea of the impact of explosions, as a high nonlinearity of the behavior of the enclosing structures is observed. Scientist A. Remennikov developed an analytical model of the explosive destruction of protective objects, such as concrete and stone walls. Analytical models under study, based on the principles of explosion physics and the laws of conservation of the characteristics of contact charges, are necessary to detect a hole in the wall in terms of shape and size [18].

Scientists, led by M. Fouad [7], presented a study of reinforced concrete columns with different detailing of reinforcement undergoing explosions in the near zone. The researchers confirm that the main problem of the behavior of the enclosing structures during the explosion is the reduction of their strength due to the high rate of deformation. Numerical results of finite-element models of columns with seismic-resistant and conventional reinforcement, performed using the LS-DYNA program package, characterize their movements and the nature of damage.

Scientists J. Pereira and others experimentally investigated the dynamic behavior of stone wall fillings subjected to dynamic non-plane loading. Scientists prove that explosions caused by contact charges near buildings have a strong impact on internal and external structural elements [17]. This study presents a developed test rig for testing non-plane walls under dynamic loading using underwater blast wave generators. They make it possible to apply an extremely high rate of transformation of the energy of explosive detonation into the kinetic energy of the water column, which, in turn, enables its distribution over the surface area, avoiding the generation of high-speed fragments and reducing the atmospheric impact.

On the basis of analytical, numerical and experimental studies, the reaction and failure behavior of various types of reinforced concrete structures and their elements subjected to lateral shock loads were studied [22]. Field blast tests were conducted by H. Tian to investigate the effect of foamed concrete panels on response. He studied the influence of four key parameters, namely: explosion impulse, foam concrete density, foam concrete panel thickness, and aluminum alloy face sheet thickness on the structural response. The deformation of the back panel protected by foam concrete and the failure modes of the foam concrete sample under the impact load were obtained. Experimental results indicate that foam concrete can be used to reduce the explosive load and effectively reduce the deformation of the structure [20].

Jeon and Rigby [11] present the results of a study of the efficiency of an arched steel-concrete-steel structure made of profiled sheets under the load from the detonation of an explosive substance in the near field. It was noticed that with an increase in the thickness of the arch (the depth of the concrete filling), most of the energy is absorbed by crushing the concrete and a large mass of concrete is mobilized. It is shown that the thickness of the arch of 240 mm is sufficient to withstand the explosive load of TNT charge weighing 5.76 kg, which confirms the suitability of the proposed protective structure.

Experimental and analytical results of the dynamic reaction of a reinforced concrete one-sided slab to an explosive load are given in by Park and others their works [16]. The types of measured data related to the response of 1500×2350×150 mm reinforced concrete slabs to surface blasts of 50 kg of TNT and 100 kg of TNT at a distance of 20 m include deformations of the longitudinal reinforcement at mid-span and longitudinal mid-span. All measured data were compared with the results of the AUTODYN interactive nonlinear dynamic analysis program. Research has proven that the numerical approach can model the behavior of a reinforced concrete slab during an explosion with sufficient accuracy.

Thus, scientists proved that a significant danger characteristic of the urban environment is the risk of an inevitable violation of the structural integrity of the enclosing structures of residential buildings (supporting columns, building facades, walls, etc.), exfoliation of debris due to the action of a blast wave, etc. Scientists state that one of the important factors affecting the safety of the premises of residential buildings is their construction. Various measures can be taken to reduce the risk of damage to the building structure and to protect people from the effects of explosive weapons, including the installation of protective structures capable of providing high blast resistance. For this purpose, special materials, double-glazed doors and windows, etc., can also be used to reduce the consequences of an explosion, absorb the impact of energy and disperse it in other directions.

4 Results and Discussion

Development of a mathematical model for describing dynamic loads from explosive weapons

For the design of protective structures, which are recommended by the normative and legal acts in force in Ukraine [3], the excess pressure of the shock wave is determined as the main influence. To simulate the pressure under the influence of an explosion, the corresponding empirical curve [1; 4; 8], shown in Figure 1, is used.

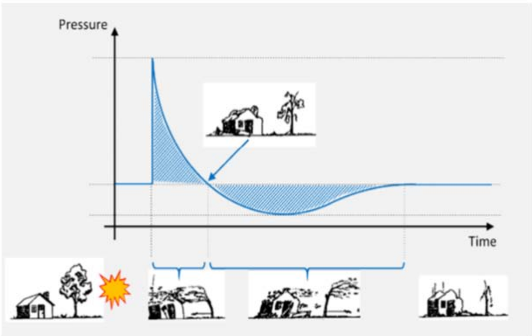

Figure 1. The impact of an air blast wave on building structures from conventional means of destruction [1; 4; 8]

The parameters of this curve depend on the scaled distance from the wall to the center of the explosion, which is determined by the formula:

$$Z = R \cdot M^{-\frac{1}{3}} \quad (1)$$

where: R is the distance of the wall to the center of the explosion; M is TNT mass equivalent.

The parameters of the curve shown in the figure are determined using a special nomogram obtained empirically.

When the blast wave front hits the surface of the wall of the shelter structure indirectly, the pressure weakens. The reduced pressure is determined by the formula:

$$P_{eff} = P_{ref}\cos^2\theta + P_{inc}\,(1 + \cos\theta - 2\cos^2\theta) \quad (2)$$

where: θ is the angle between the facet of the surface finite element and the line drawn from the point of the explosion center at a right angle and the shortest distance from the explosion center to the center of the facet.

P_{inc} is the pressure causing the incident shock wave, determined by the formula:

$$P_{inc} = P_s(1 - \tau)e^{-\alpha\tau} \text{ where: } \tau = \frac{t - t_a}{t_+ - t_a} \quad (3)$$

P_{ref} is the pressure of the reflected shock wave, determined by the formula:

$$P_{ref} = P_r(1 - \tau)e^{-\beta\tau} \quad (4)$$

The parameters included in these formulas are determined by empirical nomograms.

The described model makes it possible to formalize the impact of the explosion, taking into account the attenuation of the shock wave depending on the distance and angle of the surface of the shelter structures. For this, one can use the nomogram below (Figure 2).

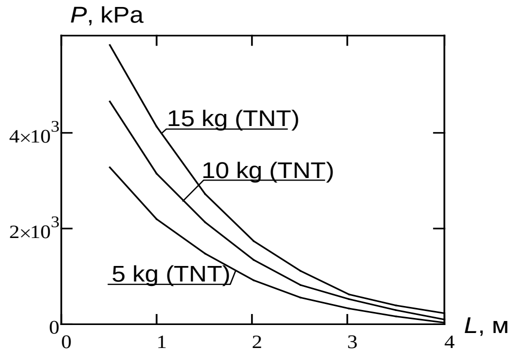

Figure 2. The curve of pressure change depending on the distance and the TNT equivalent of the warhead charge of the shell

When creating this model, taking into account the arguments of J. Hallqvist [8], the following assumptions were made:

- The combat charge of an explosive weapon is assumed to be equivalent to 10 kg in TNT equivalent as the most common;
- When modeling an explosion, its chemical and gas-dynamic nature is not taken into account, but its result is considered in the form of a corresponding pressure curve on the walls of the product;
- Material with averaged mechanical characteristics is accepted as the material of structures and soil;
- The material of the shelter and soil structures is homogeneous, isotropic, and solid without cavities and cracks;
- To model the process of deformation of shelter structures and the soil on which it is installed, the finite element method is used in the implementation of calculations by the explicit method;

- Planar end elements according to the Belychko-Tsai scheme, which includes integration by thickness at 5 internal points, are used to calculate the fixing elements of the shelter and door structures;
- For the implementation of calculations of the concrete base of structures and soil, volumetric finite elements of the Lagrangian type are used;
- Hughes-Liu type rod beam elements are used for calculations;
- To describe the nonlinear behavior of the concrete material, a model of a continuous failure surface with a limiting dome is used, which is built on the basis of nonlinear deformation diagrams with descending branches;
- As a model of material of steel reinforcement and steel surveying, a material with the possibility of plastic deformations, bilinear deformation diagrams of the Prandtl type, the shape of which includes only the growth section and the horizontal section with a limit deformation of 15%, is used;
- A contact interaction model is used to describe the interaction between the surface of shelter structures and the soil, as well as the ends of concrete blocks.

The basis for calculations is the solution of the problem of sample deformation in the setting of the movement of a deformed body as a dynamic system. In this formulation, the diagram of a single rigid deformed body in the initial state at the initial time t = 0 is shown in Figure 3. A single rigid deformed body has an initial volume Ω_0, which is limited by the surface Γ_0. In the current position of the body at the given time t, the volume acquired by the body is denoted as Ω, with the boundary surface Γ. During the movement of the body from the position Ω_0 to the position Ω, an arbitrary point with coordinates X, which in the initial position belongs to the body with volume Ω_0, will belong to the same body when it acquires the volume Ω in the current position with coordinates x.

The fundamental equations that describe the state of a solid body as a dynamic system are obtained by taking into account the laws of dynamics of a mechanical system and the laws of conservation in accordance with work [8].

In this case, the generalized momentum conservation equation is written in the form:

$$\sigma_{ij,i} + \rho \cdot f_i = \rho \cdot \ddot{x}_i \tag{5}$$

where:

$\sigma_{ij,i}$ - the Cauchy stress tensor at a given point belonging to the body

ρ - the density of the material at a given point belonging to the body

$\rho \cdot f_i$ - external forces acting on the body through a given point

$\ddot{x}_i$ - acceleration of a given point belonging to the body

The initial undeformed state and the current deformed state of a rigid body during its movement are shown on Figure 3.

Figure 3. The initial undeformed state and the current deformed state of a rigid body during its movement [19]

The mass conservation equation is written in the form of the following formula:

$$\rho \cdot det(\mathbf{J}) = \rho_0 \tag{6}$$

where: ρ_0 - the density of the material of the body in the undeformed initial state; $det(\mathbf{J})$ - determinant of the tangential stiffness matrix (Jacobian)

The equation that expresses the law of conservation of energy is the sum of kinetic and internal energies, which must be equal to the total sum of work done by external forces:

$$P^{int} + P^{kin} = P^{ext} + P^{heat} \tag{7}$$

The total kinetic energy of the body is determined by the following expression:

$$P^{kin} = 0.5 \frac{d}{dt} \int_{\Omega} \rho \mathbf{v} \cdot \mathbf{v} d\Omega \tag{8}$$

The total internal energy of a deformed body is determined by the equation:

$$P^{ext} = \int_{\Omega} \mathbf{v} \cdot \rho \mathbf{b} d\Omega + \int_{\Gamma} \mathbf{v} \cdot \mathbf{t} d\Gamma \tag{9}$$

In the absence of internal and external sources of thermal energy, the energy conservation equation in accordance with work [8] takes the form:

$$\frac{d}{dt} \int_{\Omega} \rho w^{int} + (0.5 \rho \mathbf{v} \cdot \mathbf{v}) d\Omega = \int_{\Omega} \mathbf{v} \cdot \rho \mathbf{b} d\Omega + \int_{\Gamma} \mathbf{v} \cdot \mathbf{t} d\Gamma \tag{10}$$

The energy balance equation in a modified form for a deformed solid body in the current position can be given in the following form:

$$\rho \dot{w}^{int} = 0.5 \sigma_{ij} \left[\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right] \tag{11}$$

Boundary conditions limiting the movement of a rigid deformed body Γ_f are written in the form of the formula:

$$\sigma_{ij} n_j = t_i(t) \tag{12}$$

where n_j is the vector of normal to the boundary surface of the rigid deformed body directed outward.

Regarding the boundary conditions that set the deformation parameters on the boundary surface of a rigid deformed body, the following formula can be written:

$$x_i(\mathbf{X}, t) = \bar{x}_i(t) \tag{13}$$

Under the condition of initiation of contact interaction between deformed bodies, compatible boundary conditions take the following form:

$$\left(\sigma_{ij}^{+} - \sigma_{ij}^{-}\right) n_j = 0 \tag{14}$$

When applying the principle of possible displacements δx_i, the movement of rigid deformed bodies experiencing contact interaction with each other can be written through the equation of conservation of virtual work:

$$\int_{\Omega} \left[\rho \ddot{x}_i + \sigma_{ij,j} - \rho f_i \right] \delta x_i d\Omega + \int_{\Gamma_f} \left[\sigma_{ij} n_j - t_i \right] \delta x_i d\Gamma + \int_{\Gamma_c} \left(\sigma_{ij}^{+} - \sigma_{ij}^{-} \right) n_j \delta x_i d\Gamma = 0 \tag{15}$$

Assuming that the sum of possible works should be equal to zero, performing certain transformations of equation (11), the latter can be written in the form of a modified expression [8]:

$$\int_{\Omega} \rho \ddot{x}_i \delta x_i d\Omega + \int_{\Omega} \sigma_{ij,j} \delta x_i d\Omega - \int_{\Omega} \rho f_i \delta x_i d\Omega - \int_{\Gamma_f} t_i \delta x_i d\Gamma - \int_{\Gamma_c} t_i^c \delta x_i d\Gamma = 0 \quad (16)$$

Analysis of the characteristics of explosive weapons used on the territory of Ukraine

Results of the analysis of explosive weapons used on the territory of Ukraine

On the territory of Ukraine, the troops of the Russian Federation use explosive weapons of Soviet origin, some of which have been modernized [15]. Lancet, Cube, Geranium, etc. drones are used to attack objects of various purposes. Unmanned aerial vehicles of the Shahed type are widely used. According to the results of the analysis of such weapons, the following characteristics were established (Tables 2, 3).

Table 2: Main characteristics of UAVs of the Russian Federation, which are used for strikes in Ukraine

Type of unmanned aerial vehicle	Length/width, m	Average speed, m/s	Starting mass/mass at the moment of impact, kg	Weight of the explosive substance, kg	Meeting angle, gr.	Speed at the moment of impact, m/s
Type-1	2.6/2.2	27.8	135/100-125	10	60	27.8
Type-2	3.5/2.5	45	200/150-180	15-40	60	50-60

Table 3: Main characteristics of the missiles of the Russian Federation, which are used for strikes in Ukraine

Type of missile	Length / diameter, m	Maximum speed, m/s	Starting mass/ mass at the moment of impact, kg	Weight of the explosive substance, kg	Meeting angle, gr.	Speed at the moment of impact, m/s
X-59	5.7/0.4	291.67	900	201.5*	80*	95.2*
X-22	11.7/0.94	1111,11	5780	630	80*	362.8*
9M723 “Iskander”	7.3/0.92	2450.00	3800	312*	90	800
X-55/X-555	6.04/0.77	260.00	1500	292.5*	80*	84.9*
3M-14K/T “Caliber”	8.2/0.514	240	1320	292.5*	80*	78.37*
Kh-47 “Dagger” (“*Kindjal*”)	7.7/0.9	4080	4615	325*	80*	741.82*
X-101	7.5/0.74	200.00	2400	279.5*	80*	65.3*
P-800 “Onyx”	8.9/0.67	884	3900	195*	80*	288.65*
X-35	4.4/0.42	280	670	94.25*	80*	91.43*

Note: * the value is assumed based on analogues.

Selective calculation results

The value of excess pressure that occurs when using an explosive weapon can vary significantly depending on its type, the size of the charge, as well as the distance to the object affected by the explosion and other factors. The pressure of the explosion is usually the highest directly near the source of the explosion and weakens with increasing distance from it (Fig. 4).

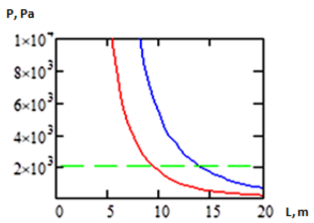

Figure 4. Dependence of the distance over which the excess pressure spreads, on the mass of the explosive substance of the explosive weapon

According to the results of calculations, it was determined that when using an explosive weapon with an explosive mass of 220 kg, the static load to all wall and ceiling structures will be 20 kPa at a distance of up to 10 m. When using an explosive weapon with an explosive mass of 718 kg, with a static load to wall and floor structures at 20 kPa, the distance will be up to 15 m.

This means that increasing the distance from the source of the explosion to the object leads to a significant decrease in excess pressure. The above may cause in the further normalization, in addition to the operational load during the design of the enclosing building structures of the protected spaces of residential apartment buildings, an additional load from excess pressure in the amount of at least 20 kPa.

The ability of an explosive weapon to penetrate a target is primarily influenced by the mass of the explosive substance. Generally, other things being equal, a weapon with a greater mass of explosive has a greater potential for penetration. This is due to the fact that a larger mass of explosive contains more energy, which can be released in the process of explosion and create greater overpressure and negative consequences. Other factors such as the type of explosive, the shape and design of the explosive weapon, the properties of the target, and other factors also play an important role. In general, the depth of penetration of explosive weapons depends on a combination of the above-mentioned factors.

The results of the calculations of the penetration of explosive weapons into the building structure are shown in Table 4.

Table 4: Characteristics of penetration of missiles of the Russian Federation, which are used for strikes in Ukraine, into a concrete wall

Type of missile	Penetration into a concrete wall
X-59	450
X-22	1643
9M723 “Iskander”	2864
X-55/X-555	788
3M-14K/T “Caliber”	546
Kh-47 “Dagger” (“Kindjal”)	3089
X-101	761
P-800 “Onyx”	1286
X-35	451

Figure 5 shows the dependence of the depth of penetration of an explosive weapon on the mass of its explosive substance.

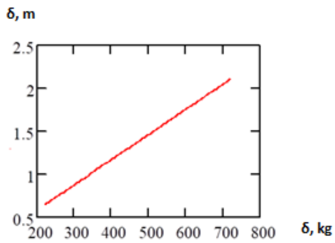

Figure 5. Dependence of the depth of penetration on the mass of the explosive substance of the explosive weapon

From Table 4, the following can be seen: in order for the enclosing structures of the protective security room to be able to withstand a direct hit by means of fire damage, the wall thickness should be from 0.45 to 3.0 m, which seems contradictory and is an unacceptable economic solution for residential apartment buildings. At the same time, the authors did not take into account calculations for increasing the strength of concrete under load, which involves reducing the thickness of the enclosing structures surrounding the protective space of an apartment building [1].

Thus, the criterion for evaluating the enclosing structures of the protective security room can be:

- The level of protection against fragments and blast waves in case of indirect hits at a distance of at least 15 m when using explosive weapons with an explosive weight of up to 718 kg;
- The level of protection against falling fragments of explosive weapons.

Figure 6 shows the dependence of the change in the thickness of a reinforced concrete wall on the value of the excess pressure of the explosion, which such a wall must withstand.

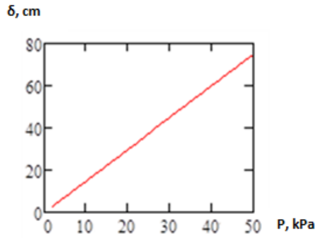

Figure 6. The dependence of the change in the thickness of a reinforced concrete wall on the value of the excess pressure of the explosion, which such a wall must withstand

From Figure 6, it can be concluded that a reinforced concrete wall with a thickness of at least 300 mm is expected to withstand an excess explosion pressure of 20 kPa.

Let us carry out calculations according to the designed mathematical model for a reinforced concrete shelter with a thickness of 300 mm. The reinforcement of the concrete-steel walls is made with 3 grids for the spatial framework of the reinforcement with a diameter of 16 mm and a step of 150 mm, for the transverse reinforcement, a diameter of 10 mm and a step of 50 mm. Concrete class is C25/30. The thickness of the concrete protective layer is 30 mm.

Based on the results of the calculations, the distribution of plastic deformations after applying pressure from the blast wave to the surface of the structures was determined (Figure 7).

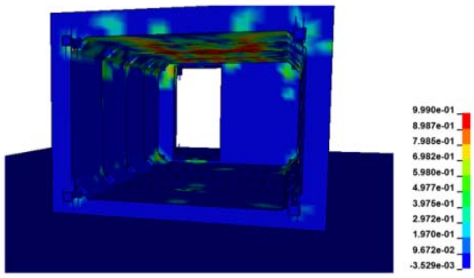

Figure 7. Distribution of plastic deformations after applying pressure from the blast wave to the surface of the structure

Experimental studies of the adequacy of the mathematical model

In order to check the adequacy of the proposed mathematical model, experimental studies of a reinforced concrete wall with a thickness of 300 mm were carried out.

A fragment of the experimental study is shown in Figure 8.

Figure 8. A fragment of an experimental study of a reinforced concrete wall

The actual results of experimental studies of concrete on compression, determined by the method of elastic rebound, are shown in Table 5.

Table 5: Results of experimental studies of concrete on compression

Normative document	Name of tests and (or) characteristics (parameters) to be determined	Normative (nominal) value	Unit	Actual indicators – evaluation results (measurements, tests) rebound value in the direction of impact α=0°										Designation of normative documents on test methods
				1	2	3	4	5	6	7	8	9	10	
clause 4.4.1 DSTU Б В.2.6-2:2009	Requirements for concrete	The nominal values of the characteristics of concrete properties, which are set in the work documentation, must comply with DSTU Б В.2.7-43	kgf/cm 2 MPa	Identification number of the tested sample 0808-23/3										DSTU Б В.2.6-2:2009 DSTU Б В.2.7-220:2009 DSTU-Н Б EN 13369:2013 (EN 13369:2004 + A1:2006, IDT)
				51	53	51	52	53	52	51	52	52	52	
				The average value of the rebound criteria Rm=51.9										
clause 6.3 TU У 23.6-43409145-002:2023		Products should be made of heavy concrete in accordance with DSTU Б В.2.7-43 class for compressive strength B40 523.9 kg/cm2 (51.4 MPa)		The average compressive strength of concrete is 541.4 kgf/cm2 (53.1 MPa)										

The actual results of experimental studies on checking the condition of structures under the influence of excess pressure are given below (see Tables 6, 7).

Table 6: Results of experimental studies of checking the condition of structures under the influence of excess pressure

Normative document	Name of tests and (or) characteristics (parameters) to be determined	Control (test) load, tc		Crack opening width, mm		Designation of normative documents on test methods
		Normative value (total)	Actual value	Normative value	Actual value	
Clause 4.3.1.3 DSTU Б В.2.6-2:2009	The products must meet the requirements for their strength and crack resistance specified in the design and specified in the work documentation					DSTU Б В.2.6-7-95 (DSTU 8829-94)
Clause 7.3 TU У 23.6-43409145-002:2023	According to strength and crack resistance indices, the links of NUTSZ MSSS must meet the established requirements and withstand the control loads according to the support and loading schemes given in Appendix B of TU U 23.6-43409145-002:2023					DSTU Б В.2.6-2:2009 DSTU EN

Appendix B TU У 23.6-43409145-002:2023	Load testing of structures to verify strength for shelters class	A-IV	77.6	77.6	0.4	No cracks	13018:2017 (EN 13018:2016, IDT)
		A-III	156	156	0.4	0.15	
		A-II	234	234	0,4	0.3	DSTU-Н Б EN 13369:2013 (EN 13369:2004 + A1:2006, IDT)

Table 7: Data on the applied test load

Class of the shelter (according to DBN B.2.2-5-97)	Excessive pressure of the shock wave ΔP, kgf/cm^2 (kPa)	Test load P when testing the element for strength, ms
A-IV	1.0 (100)	38.8
A-III	2.0 (200)	78
A-II	3.0 (300)	117

Thus, the results of experimental studies confirm the acceptable reliability of the calculation results.

5 Conclusions

In today's conditions, it is extremely important for Ukraine to ensure the safe stay of people in residential buildings, taking into account the requirements for building structures. During the design and construction of Ukrainian domestic residential buildings, the possibility of damage from explosive weapons and the provision of structures capable of maintaining protective functions against such damage are not taken into account.

The analysis of statistical data shows a constant increase in the number of deaths and injuries of the civilian population in residential buildings from explosive weapons since the beginning of the full-scale war against Ukraine. It has been established that foreign and domestic Ukrainian scientists are increasingly paying attention to the problems of protecting the civilian population from explosive phenomena. They proved the risk of an inevitable violation of the structural integrity of the enclosing structures of residential buildings, which affects the safety of the premises and the people who are in them during the impact of explosive weapons. However, there are not enough scientifically based requirements regarding the explosive load on building structures and provisions for the arrangement of protective security rooms in residential multi-apartment buildings in domestic legal acts.

To describe dynamic loads from explosive weapons, a mathematical model has been developed that enables the formalization of the effects of the explosion, taking into account the attenuation of the blast wave depending on distance and angle of the shelter structures surface. The mathematical model for describing the dynamic loads from explosive weapons has been verified, which satisfies its reliability.

The results of the calculations, taking into account the characteristics of explosive weapons, show that when the distance from the source of the explosion to the object increases, the excess pressure significantly decreases. Therefore, when using an explosive weapon with an explosive mass of 220 kg, the static load to all wall and ceiling structures will be 20 kPa at a distance of up to 10 m. When using an explosive weapon with an explosive mass of 718 kg, with a static load to wall and ceiling structures of 20 kPa, the distance will be up to 15 m. The conducted experimental studies confirmed the acceptable reliability of the adequacy of the proposed mathematical model.

This level of protection can be provided by monolithic reinforced concrete structures with a thickness of 300 mm. The reinforcement of the concrete walls is made with 3 grids for the spatial framework of the reinforcement with a diameter of 16 mm and a step of 150 mm; for the transverse reinforcement, a diameter is 10 mm and a step is 50 mm. Concrete class is C25/30. The thickness of the concrete protective layer is 30 mm.

The criterion for evaluating the enclosing structures of the protective security room can be: the level of protection against fragments and blast waves in case of indirect hits at a distance of at least 15 m when using explosive weapons with an explosive weight of up to 718 kg; level of protection against falling fragments of explosive weapons.

Further scientific research, based on the obtained results, will be directed to the development of proposals for the design of a protective security room in multi-apartment residential buildings.

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