UDC 624.012.45:624.042.8
DOI: 10.15587/1729-4061.2026.360862

REVEALING THE EFFECT OF EXPLOSION ON THE PERFORMANCE OF REINFORCED CONCRETE STRUCTURES IN PROTECTIVE SHELTERS UNDER AIR ATTACKS

Serhii Pozdieiev
Doctor of Technical Sciences, Professor
Department of Fire Prevention in Populated Areas*
ORCID: https://orcid.org/0000-0002-9085-0513

Volodymyr Bashynskyi
Doctor of Engineering Science, Professor, Chief**
ORCID: https://orcid.org/0000-0003-0966-5714

Andrii Shvydenko
Corresponding author
Candidate of Technical Sciences, Associate Professor
Department of Information, Multimedia Technologies and Design
Cherkasy State Business College
Viacheslava Chornovola str., 243, Cherkasy, Ukraine, 18028
E-mail: andwell1980@gmail.com
ORCID: https://orcid.org/0000-0002-7708-8595

Serhii Bisyk
Doctor of Technical Sciences, Professor
Department of Scientific Research and Testing
National Defence University of Ukraine
Povitroflotskyi ave., 28, Kyiv, Ukraine, 03049
ORCID: https://orcid.org/0000-0002-5009-2113

Olga Nekora
Candidate of Technical Sciences, Senior Researcher
Department of Organization of Scientific Activities*
ORCID: https://orcid.org/0000-0002-5202-3285

Serhii Holets
Production Director
Limited Liability Company "Road and Energy Structures Reinforced Concrete Products Plant"
Mykola Mikhnovskyi str., 38, Kyiv, Ukraine, 02154
ORCID: https://orcid.org/0009-0008-2795-3318

Oleh Dmitriiev
Doctor of Technical Sciences, Professor, Leading Researcher
of the Scientific Information Department**
ORCID: https://orcid.org/0000-0003-1079-9744

Volodymyr Krivtsun
Doctor of Technical Sciences, Senior Research Associate,
Deputy Head of the Institute for Scientific Research**
ORCID: https://orcid.org/0000-0002-3907-5320

Viktor Nikitchenko
Candidate of Technical Sciences, Senior Researcher, Head of the Research
Department for Testing of Armament and Military (Special) Equipment**
ORCID: https://orcid.org/0000-0001-8973-8711

Ihor Chastokolenko
Candidate of Physical and Mathematical Sciences, Associate Professor
Department of Physics and Mathematics*
ORCID: https://orcid.org/0000-0001-9323-2684

*National University of Civil Protection of Ukraine
Onoprienko str., 8, Cherkasy, Ukraine, 18034
**State Scientific Research Institute
of Armament and Military Equipment Testing and Certification, Cherkasy, Ukraine

This study explores reinforced concrete structures at the UFS-1 and SHS VS-1-3 series block protective facilities under explosive conditions. The task addressed relates to the insufficiently studied patterns of their stressed-strained state taking into account contact interaction between structural elements and the soil base.

To solve the specified task, numerical modeling was performed using the finite element method. Calculations were carried out in the LS-DYNA software package (USA) taking into account physical and geometric nonlinearity and contact interaction of structural elements. The functional suitability of reinforced concrete structures at block protective facilities under explosive conditions was investigated.

The explosive impact scenarios provided for a TNT equivalent charge of 15 kg at distances to the structure of 0.55 m and 5 m. The calculation results showed that the maximum values of excess pressure reach $1.16 \cdot 10^6$ kPa and $1.01 \cdot 10^3$ kPa, respectively. It was found that the greatest stresses and displacements are localized in the junctions of blocks and near-surface areas of structures, which made it possible to identify the most vulnerable elements and justify directions for improving structural solutions.

It was found that at the assumed values of explosive effects, the facilities retain their functional suitability and stability while damage is localized in small areas and does not lead to progressive destruction of the shelter. This is explained by the spatial work of the structure and the redistribution of dynamic forces among individual blocks and the soil base.

The research results could prove useful for assessing explosion resistance and implementing engineering solutions in the design of civil defense structures with the aim of improving them

Keywords: explosive load, explosion resistance, protective shelters, reinforced concrete structures, stressed-strained state, LS-DYNA

Received 26.03.2026
Received in revised form 01.06.2026
Accepted 12.06.2026
Published 30.06.2026

How to Cite: *Pozdieiev, S., Bashynskyi, V., Shvydenko, A., Bisyk, S., Nekora, O., Holets, S., Dmitriiev, O., Krivtsun, V., Nikitchenko, V., Chastokolenko, I. (2026). Revealing the effect of explosion on the performance of reinforced concrete structures in protective shelters under air attacks. Eastern-European Journal of Enterprise Technologies, 3 (1 (141)), 6–18. https://doi.org/10.15587/1729-4061.2026.360862*

1. Introduction

Current conditions of armed conflicts are characterized by the widespread use of highly effective means of destruction, accompanied by intense explosive effects on civilian infrastructure. Under these conditions, providing reliable protection for people through the use of protective shelters that can effectively counteract the effects of shock waves and associated explosion factors is of particular importance. One of the key elements of such facilities is reinforced concrete structures, which must enable preservation of bearing capacity and integrity under dynamic loading conditions.

Analysis of related research reveals that conventional approaches to the design of protective structures are often based on simplified quasi-static models that do not fully take into account the complex nature of the interaction of the blast wave with structural elements. At the same time, the evolution of numerical methods, in particular the finite element method, allows for more accurate modeling of nonlinear processes of deformation and destruction of materials under impulse loads. This creates prerequisites for improving the validity of engineering solutions in the design of protective structures.

Of particular interest are block-type protective shelters whose structural systems are formed from individual reinforced concrete elements interconnected by mechanical links and installed directly on the soil base. Such solutions are characterized by manufacturability, mobility, and the possibility of rapid deployment, but require additional substantiation of their reliability under the action of explosive loads.

Thus, it is a relevant task to assess the stressed-strained state and functional suitability of reinforced concrete structures for protective block shelters under the action of explosive loads, taking into account deformation processes, contacts with structural elements, as well as the influence of soil base.

2. Literature review and problem statement

Study [1] considers the dynamic behavior of reinforced concrete elements under explosive loading, while showing the dependence of stresses and deformations on the parameters of the shock wave and the conditions of fastening the structures. At the same time, the work does not take into detailed account the spatial interaction of prefabricated systems with the soil base, which is explained by the complexity of building nonlinear spatial models and significant computational costs.

Paper [2] summarizes the results of experimental and numerical studies on reinforced concrete slabs under explosive loading and confirms the effectiveness of finite element modeling of local damage to structures. However, the issues of assessing the performance of prefabricated block-type shelters remain insufficiently studied due to the complexity of taking into account the contact interaction between the blocks and the limited experimental data for model verification.

Studies [3, 4] assess explosion resistance of reinforced concrete structures under internal and partially closed explosions, as a result of which regularities of damage localization and stress concentration were established. At the same time, most attention is paid to monolithic or large-sized structures, while the peculiarities of the behavior of prefabricated block-type shelters remain insufficiently studied due to the difficulty of taking into account the contact interaction of a large number of elements.

The influence of contact explosion and combined pulse-temperature loads on reinforced concrete structures is considered in [5, 6]; the determining influence of fastening conditions and nonlinear properties of materials is shown. However, the issues of assessing the functional suitability of prefabricated protective shelters after local damage to elements remain insufficiently studied due to the complexity of formalizing the criteria for the operability of structural systems.

In papers [7, 8] modern approaches to assessing the explosion resistance of civil defense structures and the use of additional structural elements to reduce the intensity of the explosive effect are considered. At the same time, the issues of spatial operation of prefabricated block-type shelters remain unresolved, which is associated with the complexity of simultaneously taking into account nonlinear deformation, contact interaction, and shock wave propagation.

Results from full-scale tests of the VS-1-3 and UFS-1 facilities are reported in work [9]; they confirm that the functional suitability of structures under certain parameters of the explosive effect is maintained. However, experimental methods do not make it possible to fully determine the internal stress distribution and damage localization mechanisms, which is due to the complexity of registering fast-moving dynamic processes during an explosion.

Our review of the literature [1–9] demonstrates that existing studies mostly consider individual elements or monolithic structures without detailed consideration of the spatial work of prefabricated shelters and their interaction with the soil base. This allows us to argue that it is advisable to conduct a study aimed at numerical modeling of the stressed-strained state and assessment of the functional suitability of prefabricated reinforced concrete shelters under the action of an explosive load.

3. The aim and objectives of the study

The purpose of our study is to identify patterns of the stressed-strained state and assess the functional suitability of reinforced concrete structures of block protective facilities under conditions of explosive impact, taking into account the contact interaction between structural elements and the soil base. This will provide an opportunity to substantiate engineering solutions to increase the explosion resistance of civil defense structures.

To achieve the goal, the following tasks are set:

– to determine parameters of the explosive impact and devise calculation scenarios of the impulse load for block protective facilities;

– to construct a general calculation scheme and a finite element model of reinforced concrete structures at block protective facilities, taking into account physical and geometric nonlinearity and contact interaction with the soil base;

– to determine parameters of the stressed-strained state and assess the functional suitability and stability of reinforced concrete structures at block protective facilities under various scenarios of explosive impact.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of our study is reinforced concrete structures at block protective facilities of the SHS UFS-1 and SHS VS-1-3 series under conditions of explosive impact.

The principal hypothesis assumes that the use of numerical modeling taking into account nonlinearity, surface-contact interaction of structures and their elements with the influence of the soil base provides an opportunity to adequately describe the stressed-strained state (SSS) of protective shelters. This allows us to assess their functional suitability under conditions of explosive impacts.

It is assumed that the materials of the structures are homogeneous within the volume of individual elements, and the explosive load indicators are determined on the basis of the TNT equivalent of the charge and the empirical dependences of the Kingery-Bulmash model. It is assumed that the maximum impact on the structures is exerted by the reflection of the shock wave, and the load is applied by impulsive pressure that varies in time.

Simplifications of the study include neglecting the chemical and gas-dynamic nature of the explosion, as well as assuming that the deep layers of the soil structure are completely undeformed. In addition, secondary damaging factors such as the formation of fragments and the thermal effects of detonation products were not taken into account.

4. 2. Structural schemes of protective shelters

Two types of shelters are subject to a calculated assessment of their functional suitability under conditions of explosion impact, information about which is given in Table 1. These shelters have different purposes; however, increased requirements are imposed on their functioning as they can be used as fortifications.

During modeling, the impact of the explosion should be reproduced, as indicated in Table 1, by applying a simplified model using the curve of change in excess pressure at a point versus time, which is fitted with the well-known Friedlander formula.

The structural system of protective shelters consists of reinforced concrete blocks, which are fastened together by means of bolted joints. Fig. 1 shows the structural system of the SHS UFS-1 facility.

Fig. 2 demonstrates a visual image showing the structural system of the protective shelter in axonometric projection.

Fig. 3 shows a structural system of the SHS VS-1-3 facility.

According to the diagrams in Fig. 1–3, the structural system of the shelter consists of three types of reinforced concrete blocks: flat panels PShSS-1 and PShSS-2, as well as blocks of tubular rectangular shape LShSS-1 and LShSS-2.

The structural diagram of a reinforced concrete block of tubular rectangular shape with a doorway LShSS-2 is shown in Fig. 4.

Therefore, the structural schemes of the protective shelters SHS UFS-1 and SHS VS-1-3 are characterized by a spatial prefabricated structure and the presence of element joining nodes, which significantly affect generation of the stressed-strained state under the action of an explosive load.

Table 1

Types of shelters subject to calculated assessment of functional suitability

No. of entry	Type of shelter (designation)	Brief description	Features of explosive impact
1	SHS UFS-1	A deep shelter that can function as a fortification with increased requirements	It is intended to provide protection against 152 mm shells and 120 mm high-explosive fragmentation mines upon direct hit
2	SHS VS -1-3	Above-ground shelter that can function as a fortification with loopholes	It should provide protection against 152 mm shells and 120 mm high-explosive fragmentation mines when they are hit indirectly at a distance of 5 m from the side surface with a slot

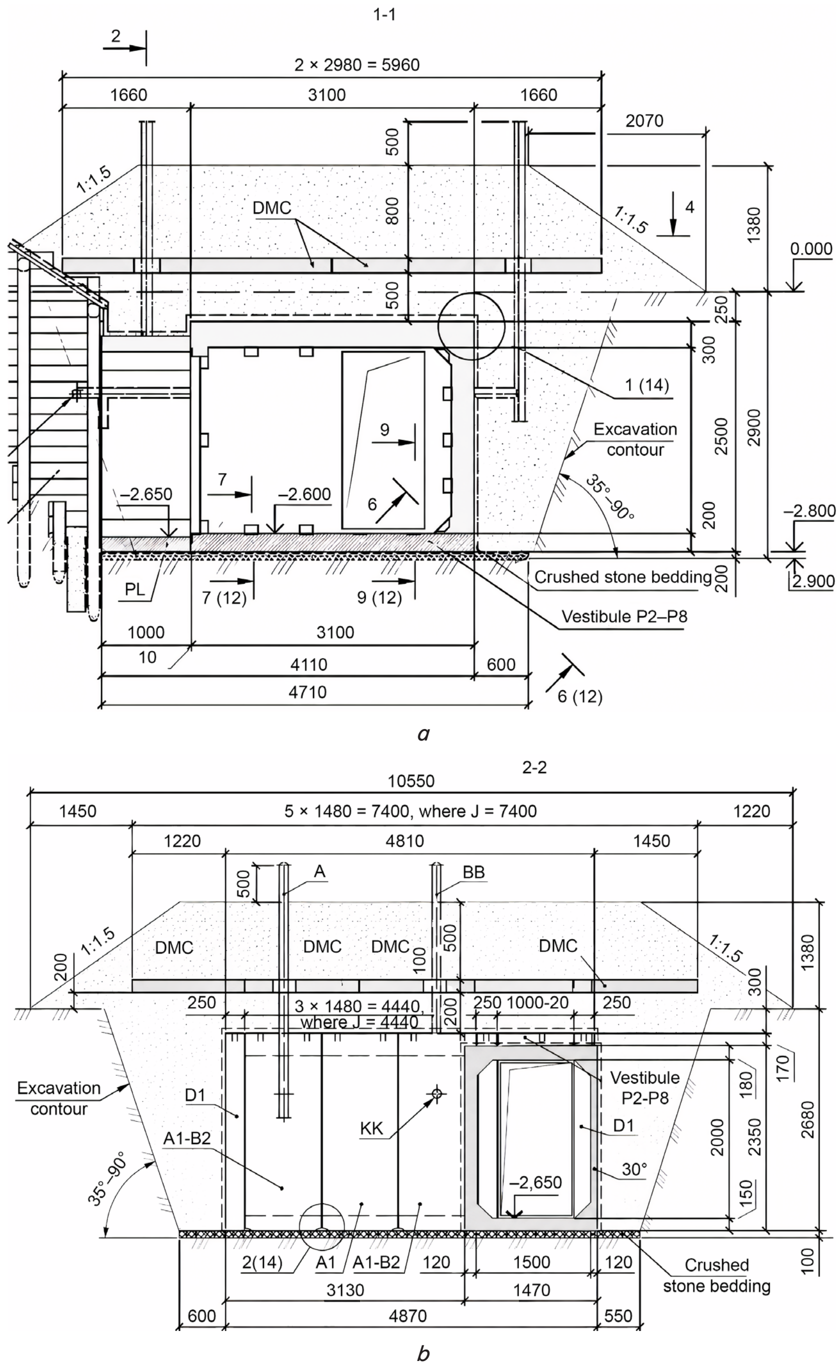
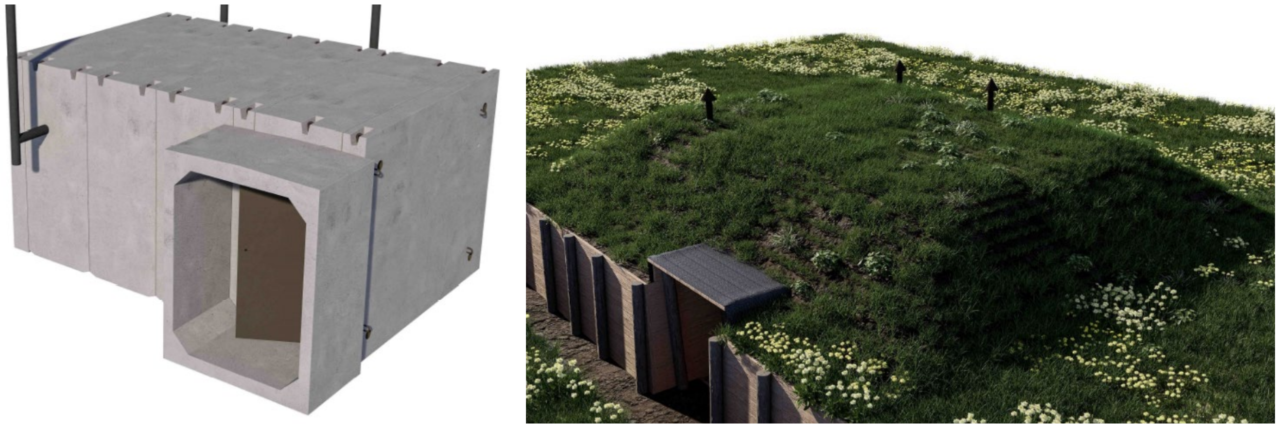


Fig. 1. Structural diagram of reinforced concrete structures for the SHS UFS-1 protective shelter: *a* — side view; *b* — front view



a *b*

Fig. 2. Axonometric projection of the structural scheme of the reinforced concrete structures for the SHS UFS-1 protective shelter: *a* — general view of shelter structures; *b* — assembled shelter suitable for use

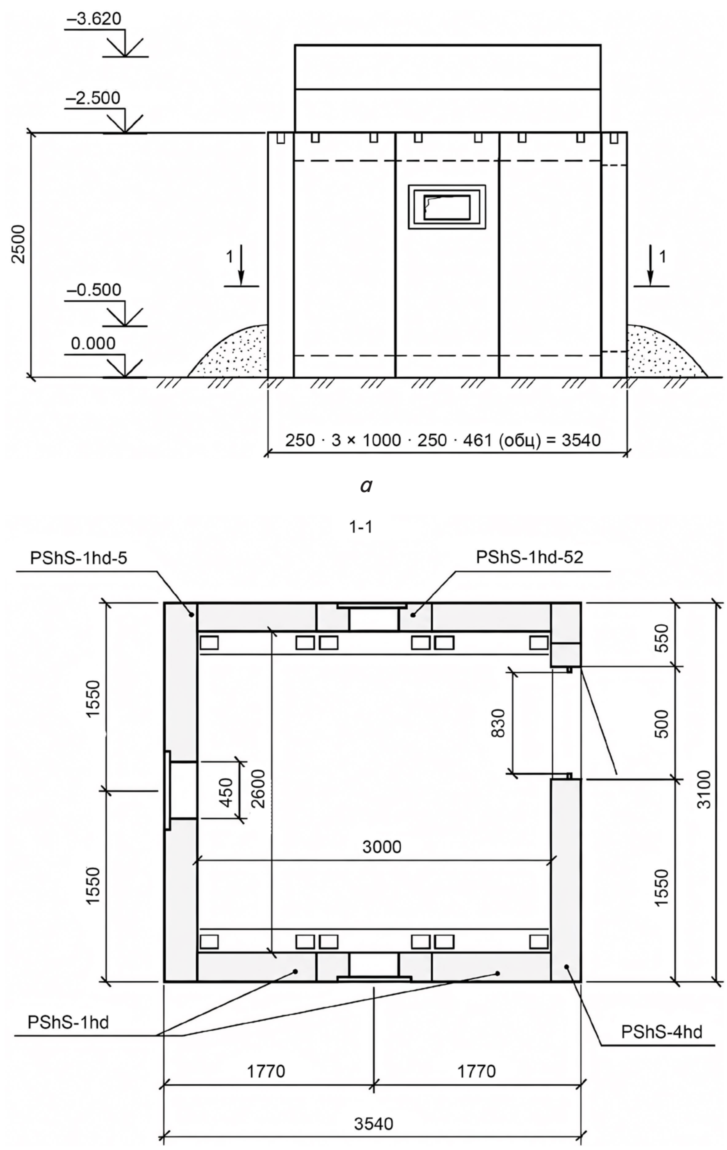


Fig. 3. Structural diagram of reinforced concrete structures for the SHS VS-1-3 protective shelter: *a* — general view of the shelter; *b* — cross section of the shelter 1-1

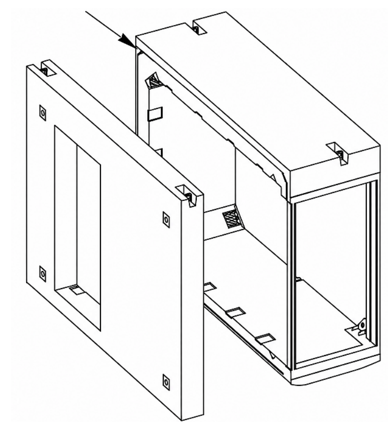


Fig. 4. Structural diagram of a reinforced concrete block of tubular rectangular shape with a doorway LSHSS-2

4. 3. Theoretical foundations of numerical modeling of dynamic interaction

To model the stressed-strained state (SSS) in reinforced concrete structures of shelters, a generalized engineering approach was applied, based on the following main provisions:

1. For mathematical modeling of the SSS of a deformed solid, a generalized theoretical approach is used, which is based on the initiation of movements of points of the mechanical system of rigid deformed bodies using a system of general dynamics equations and SSS equations caused by these movements. These equations are integrated using the finite element method (FEM).

2. To model the concrete base of the samples, three-dimensional massive finite elements of hexahedral shape with eight nodes are used.

3. To model steel reinforcement in the form of reinforcing bars, one-dimensional beam finite elements with a circular cross-section of the Hughes-Liu type are used [10].

For modeling steel embedded parts and steel parts of door systems, shell flat FEs of the Belichko-Tsay type [10] with four nodes and five integration points along the thickness are used.

4. To describe the nonlinear behavior of concrete material, a continuous failure surface model with a limiting dome is used [11,12], which is built on the basis of nonlinear deformation diagrams with descending branches.

5. As a model of the steel reinforcement material, a material with the possibility of plastic deformations is used, bilinear deformation diagrams of the Prandtl type, the shape of which includes only a growth section and a horizontal section with a limiting deformation of 15% [10, 13].

6. To describe the interaction between the components of structural systems, a contact interaction model is used. Explosion loads are applied in the form of excess pressure to the segments of the model together with the applied gravitational load. The application of the load has a dynamic history and occurs gradually over a certain time.

When investigating the process of testing the sample, the software package LS-DYNA (Livermore Software Dynamic) is used, developed by specialists from the National Livermore Laboratory named after Lawrence, University of California, USA (Lawrence Livermore National Laboratory, LLNL). Currently, the code of the software package LS-DYNA is part of the suite of computational engineering systems ANSYS Workbench (USA) and is also included as a module in a separate part of this ANSYS APDL (USA) package. At the same time, the pre/postprocessor of this system is provided as a free software application by developers, and the license for calculations of the constructed models is provided in the software ANSYS Workbench or ANSYS APDL.

We studied the performance of reinforced concrete structures for protective shelters under the action of an explosive load on the basis of equations from the mechanics of a deformable solid using the finite element method in a nonlinear statement. Time integration of the equations of motion is carried out by an explicit method, which allows us to correctly take into account the impulse nature of the explosive effect [10, 13].

The motion of a deformed solid as a dynamic system is described by the momentum conservation equation:

The fundamental equations that describe the state of a solid as a dynamic system are obtained by taking into account the laws of dynamics of a mechanical system and the conservation laws in accordance with ref. [10].

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

$$\sigma_{ij,i} + \rho \cdot f_i = \rho \cdot \ddot{x}_i, \quad (1)$$

where $\sigma_{ij,\,i}$ – Cauchy stress tensor at a given point belonging to the body; ρ – 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 finite element model of protective shelter structures is built by using three-dimensional volume elements for modeling concrete, one-dimensional beam elements for reinforcement, and two-dimensional shell elements for steel structural components [10]. This approach allows us to adequately reproduce the spatial operation of the system and the interaction among its elements.

To describe the nonlinear performance of concrete, a continuous failure surface model with a limiting dome is used, which takes into account both brittle and ductile material failure [11, 12]. Reinforcing steel is modeled using a bilinear deformation diagram taking into account plastic deformations [10, 13]. To describe performance of the soil base, the Drucker-Prager model is used [10].

The interaction among individual structural elements and between the structure and the soil base is described using contact algorithms employing the penalty function method, which makes it possible to take into account the possibility of joint opening, sliding, and local destruction of contact zones [10, 13].

We model explosive load on the basis of empirical dependences that determine the change in the excess pressure of the shock wave in time. For this purpose, the Friedlander fitting is used, and the explosion parameters are determined using the Kingery-Bulmash model taking into account the TNT equivalent of the charge and the distance to the object [14]. In this case, the effect of shock wave reflection from the soil surface and structures is taken into account [15, 16].

The numerical implementation of the constructed models was performed using the LS-DYNA software package, which enables modeling of the dynamic interaction of structural systems taking into account geometric and physical nonlinearity, contact interaction, and material destruction processes under the action of impulse loads [13, 17].

5. Results of modeling an explosive impact on reinforced concrete structures of block protective facilities

5. 1. Determining explosive impact parameters and calculation scenarios

The structural systems under study include all components of the protective structure at a facility given in Table 1.

According to the first scenario, a charge with an equivalent mass of explosives m(TNT) = 15 kg is detonated above the surface of the soil cushion at a distance of 0.55 m from its geometric center for a buried protective shelter SHS UFS-1. The second scenario assumes that a charge with an equivalent mass of explosives m(TNT) = 15 kg is detonated at a distance of 5 m from the side surface of the protective structure SHS VS-1-3. Table 2 gives parameters of the explosive impact scenarios used in the numerical modeling of protective shelters.

To determine the magnitude of the excess pressure of the shock wave using the model, data was obtained from special software that is publicly available [16].

Table 2

Types of shelters subject to calculated assessment of functional suitability

Scenario No.	Charge type	Brief description	TNT mass, kg	Distance to the surface during the experiment, m	Excess pressure of the reflected shock wave, kPa
1	OF-843	120 mm mortar shot	1.4	0.25	156506.35
2	OF-25	152 mm caliber artillery shell with enhanced power of heavy-duty action	10	5	678.94

To justify the position of the epicenter of the explosion, the following provisions were taken into account:

1) in both scenarios, the amplifying effect of the reflection of the shock wave from the surface is taken into account. In this case, it is assumed that the maximum pressure corresponds to the pressure of the reflected shock wave [14, 15];

2) to determine the excess pressure of the shock wave, taking into account the recommendations UFC 3-340-02 [15], the Kingery-Bulmash model [14, 16] is used, capable of taking into account the amplification of the excess pressure due to the superposition of the reflected and direct shock waves. As a provision that sets more stringent conditions for considering the explosive effect, the assumption of the location of the epicenter of the explosion near the surface in both scenarios is accepted. This makes it possible to verify applied loads using universal calculation dependences recommended by regulatory documents and reference sources [14, 15]. Calculation operations are implemented using the Conventional Weapons Effects Program (CONWEP) algorithm, integrated into the LS-DYNA software package [13].

The CONWEP calculation algorithm is based on the empirical dependences from the Kingery-Bulmash model and takes into account the attenuation of the shock wave during its indirect incidence, as well as the pressure gain due to reflection from the soil surface and the structure [14, 15]. The pressure applied to a fixed point on the surface where the shock wave propagates varies according to a law that generalizes empirical experience. The law of pressure change is shown in Fig. 5.

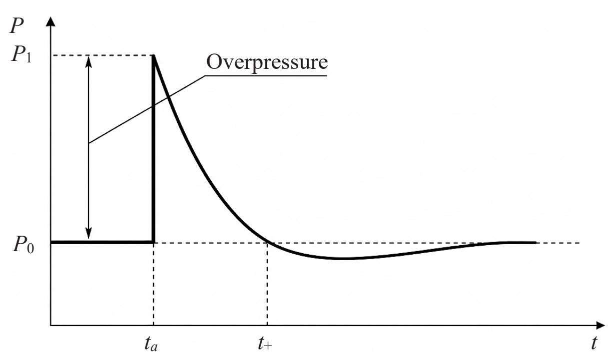


Fig. 5. Pressure curve on the surface of structures in a fragment of a protective shelter

This curve is constructed based on the scaled distance from the wall to the explosion center, which is calculated from the following formula [14, 15]

$$Z = R \cdot M^{-1/3}, \tag{2}$$

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

The parameters of the curve shown in Fig. 5 are determined using a special nomogram, which is obtained empirically and fitted with the Kingery-Bulmash model [14, 15].

When the blast wave front indirectly hits the surface of the wall of the shelter structure, the pressure is weakened. The weakened pressure is determined using the following formula

$$P_{eff} = P_{ref}\cos^2\theta + P_{inc}(1 + \cos^2\theta - 2\cos^2\theta), \tag{3}$$

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 caused by the incident shock wave, determined by using the following formula

$$P_{inc} = P_s\left(1-\tau\right)e^{-\alpha\tau},\ \tau = \frac{t-t_a}{t_+ - t_a}, \tag{4}$$

P_{ref} – pressure of the reflected shock wave, determined by using the following formula

$$P_{ref} = P_r\left(1-\tau\right)e^{-\beta\tau}. \tag{5}$$

The application of an explicit algorithm for integrating the dynamics equations makes it possible to take into account the spatial propagation of the shock wave front along the surfaces of the structure, taking into account the increase and decrease of pressure over time [10, 13]. In this case, two variants of the explosive effect are considered – an explosion at a considerable distance and an explosion near the surface. The second variant is adopted in the work as more conservative from the point of view of assessing the strength of the structure.

When setting the parameters of the position and power of the explosive charge, the limitations of the CONWEP algorithm were taken into account, which could lead to errors at small distances. In view of this, the minimum explosion distance was taken as not less than 0.55 m. To clarify the load parameters in the second scenario, the experimental data given in the test protocol [18] were used. According to these data, the maximum excess pressure was about 1000 kPa, which was taken into account when choosing the equivalent mass of the charge.

So, ultimately, it was established that for the first scenario, a charge m(TNT) = 15 kg is used at a distance from the surface of the soil cushion l = 0.55 m (Fig. 1) for the first scenario, and a charge m(TNT) = 15 kg at a distance from the surface of the soil cushion l = 5 m.

Using the provisions, hypotheses, and assumptions to build a mathematical model of protective structures, geometric diagrams and models were constructed, and segments to which the shock wave is applied were selected. That is, the surfaces of reinforced concrete structures that are located closest to the epicenter of the explosion are the segments to which the explosion effect is applied. Also, the explosion effect is applied to segments belonging to all external structures of buildings through which the shock wave can spread. Fig. 6, 7 show an image of the segments to which the explosion pressure is applied and the position of the explosion epicenter of the constructed mathematical model.

After calculations, results were obtained that allow us to study the dynamic loads of the explosion impact. The impact of the explosion was studied according to the first scenario, shown in Fig. 5, with a combination of explosion parameters with a TNT equivalent of the charge m(TNT) = 15 kg, and a minimum distance from the epicenter of the explosion to the surface in the middle of the soil cushion of the protective structure l = 0.5 m. In this case, the maximum pressure in the perpendicular direction to the segment of the covering slab should be 1157019.62 kPa according to preliminary calculations. The impact of the explosion was studied according to the scenario shown in Fig. 6. In this case, the maximum pressure in the perpendicular direction to the segment of the wall of the structure should be 1014.02 kPa according to preliminary calculations.

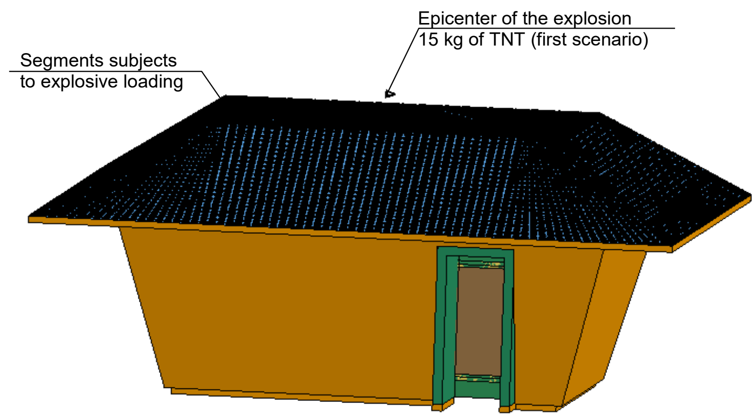


Fig. 6. Layout of segments in the SHS UFS-1 protective shelter that are exposed to the explosion according to the first scenario

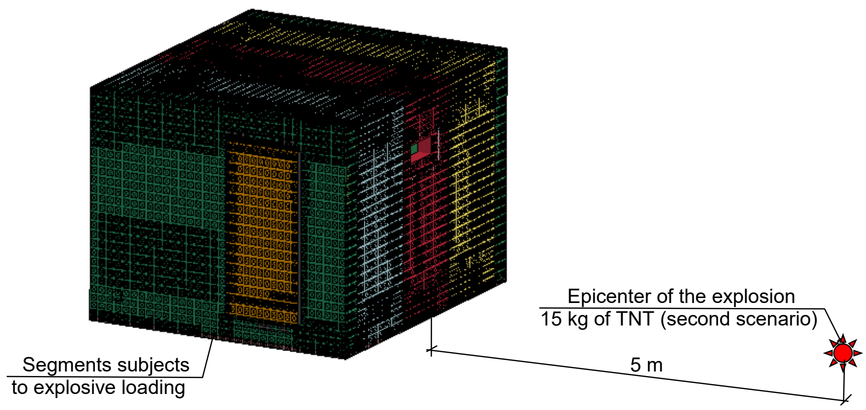
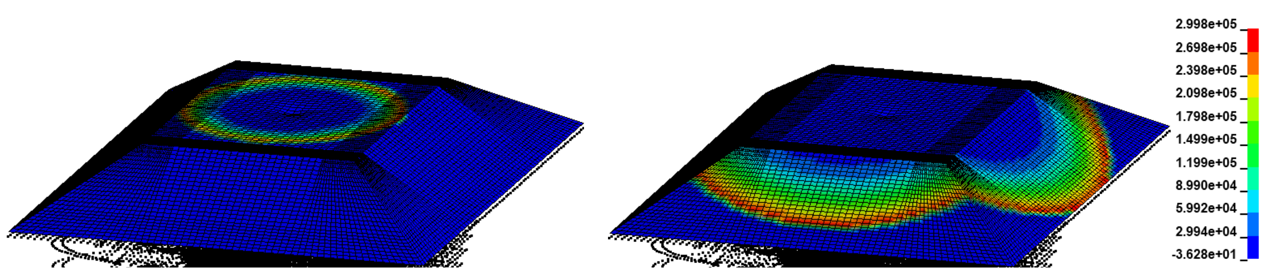


Fig. 7. Layout of segments in the SHS VS-1-3 protective shelter that are exposed to the explosion according to the second scenario

Under the conditions of this calculation scheme, the distribution of excess pressure was obtained over the segments of surfaces exposed to the explosion. The resulting distribution for the first scenario is shown in Fig. 7.

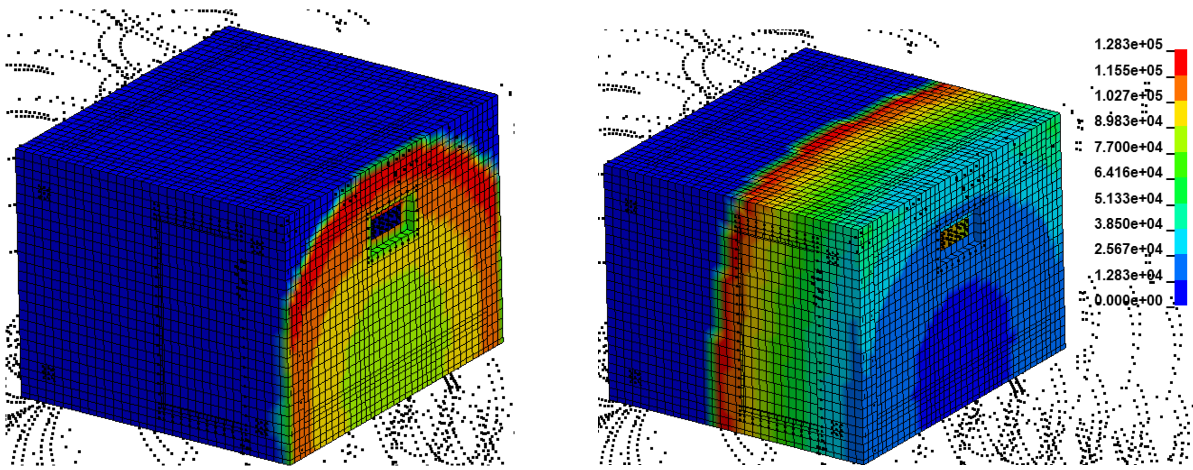
The resulting distribution for the second scenario is shown in Fig. 8.

Analyzing the pressure distribution from the shock wave, shown in Fig. 7–9, we can see that they take the form of a ring spot that spreads over the surface where the FE segments are located, to which this pressure is applied. This pattern corresponds to the applied pressure from the shock wave, which is determined by the plot in Fig. 5 and the CONWEP algorithm. That is, a time-dependent pressure is applied to each FE segment located near the surface. The beginning of the initiation of pressure on a given segment corresponds to the time of its achievement by the shock wave. And thus, in the spot, one can observe zones of peak pressure that decrease and pass to a rarefied zone. This can be illustrated by plots of pressure changes on individual segments. The excess explosion pressure is determined in the segment of the surface of the protective structure located opposite the epicenter of the explosion according to the first scenario, shown in Fig. 9, *a* in the form of a plot of explosion pressure changes for a certain distance from the plate to the epicenter of the explosion. Similarly, the excess explosion pressure determined in the segment of the surface of the protective structure located opposite the epicenter of the explosion according to the second scenario is shown in Fig. 9, *b* in the form of a plot of change in explosion pressure for a certain distance from the plate to the epicenter of the explosion. The plots (Fig. 9) show the values of the maximum excess pressure.



a *b*

Fig. 8. Distribution of excess pressure across segments of surfaces exposed to the explosion for the SHS UFS-1 protective facility according to the first scenario: *a* – after 1 s; *b* – after 4 s



a *b*

Fig. 9. Distribution of excess pressure across segments of surfaces exposed to the explosion for the SHS VS-1-3 protective facility according to the second scenario: *a* — after 5 ms; *b* — after 8 ms

By analyzing the data in Fig. 6, it was determined that the excess pressure applied to the structures corresponds to the set value. Given this, it can be noted that this pressure was calculated and applied to the segments correctly.

5. 2. Construction of the calculation scheme and a finite element model of the protective structure

Fig. 10 shows a general calculation scheme of structures at the SHS UFS-1 protective facility. The individual components-parts of the protective shelter depicted in the diagram have different colors so that they can be separated from each other. In this model, each individual component is a separate part that perceives the impact of the explosion and interacts with other components-parts of the model.

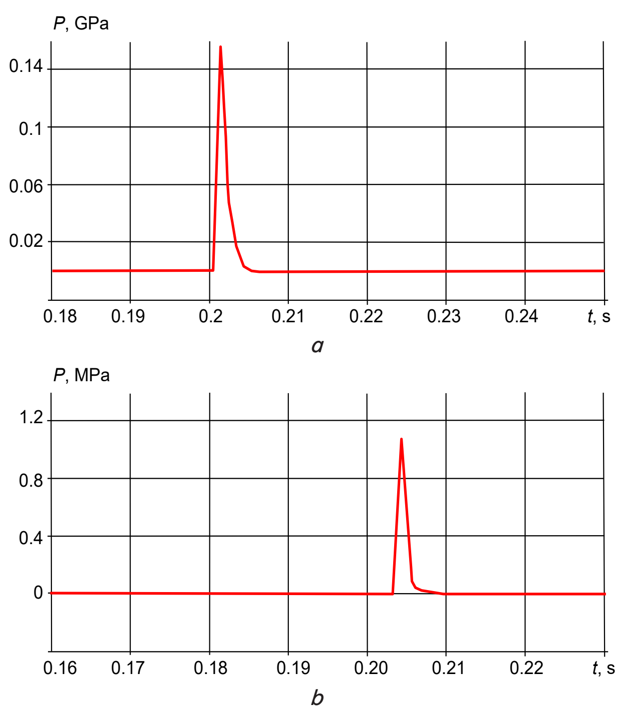


Fig. 10. Maximum excess pressure on the surface of the plate at the set explosion parameters: *a* — *m*(TNT) = 15 kg; *l* = 0.5 m; maximum pressure on the plot Pref = 1157020 kPa; *b* — *m*(TNT) = 15 kg; *l* = 5 m; maximum pressure on the plot Pref = 1016 kPa

A feature of this model is the presence of a special component that is the basis for the soil, limiting its global movement and the movement of its points. In this case, this component of the model is represented by an absolutely rigid body. Also, the anchoring system of reinforced concrete blocks and reinforcement are considered as separate components of the model.

Fig. 11 shows a general calculation scheme of structures at the SHS VS-1-3 protective facility.

To numerically model the performance of reinforced concrete structures for protective shelters, generalized nonlinear material models were used that take into account their operation under dynamic loading conditions. Concrete is described using a continuous failure surface model with a limiting dome, which allows for brittle and ductile fracture in a complex stress state [11, 12]. Reinforcing steel is modeled using a bilinear deformation diagram taking into account plastic deformations [10, 13]. For the soil base, the Drucker-Prager model was used, which provides an adequate reproduction of its performance in compression and shear [13].

The mechanical load on the structures is given in the form of excess pressure of the shock wave, which varies in time according to the impulse dependence. The load parameters are determined based on the TNT equivalent of the charge and the distance to the object using the empirical dependences from the Kingery-Bulmash model [14, 15] taking into account the recommendations of the regulatory document UFC 3-340-02 [15]. In this case, the effect of the reflection of the shock wave from the soil surface is taken into account, which leads to an increase in pressure on the structure. The boundary conditions of the model take into account the interaction of the structure with the soil base, as well as restrictions on movements in the deep layers of the soil.

The finite element model of protective shelters was built using three-dimensional volume elements for concrete, one-dimensional beam elements for modeling reinforcement, and two-dimensional shell elements for steel components [10]. This scheme makes it possible to take into account the spatial work of the structure and the interaction of its components. The contact interaction between the elements is implemented using penalty function algorithms, which ensures the correct reproduction of load transfer, sliding, and local opening of joints [10, 13]. The numerical implementation of the model was performed using the LS-DYNA software package [13], which makes it possible to take into account geometric and physical nonlinearity, contact effects, and material destruction processes under the action of impulse loads.

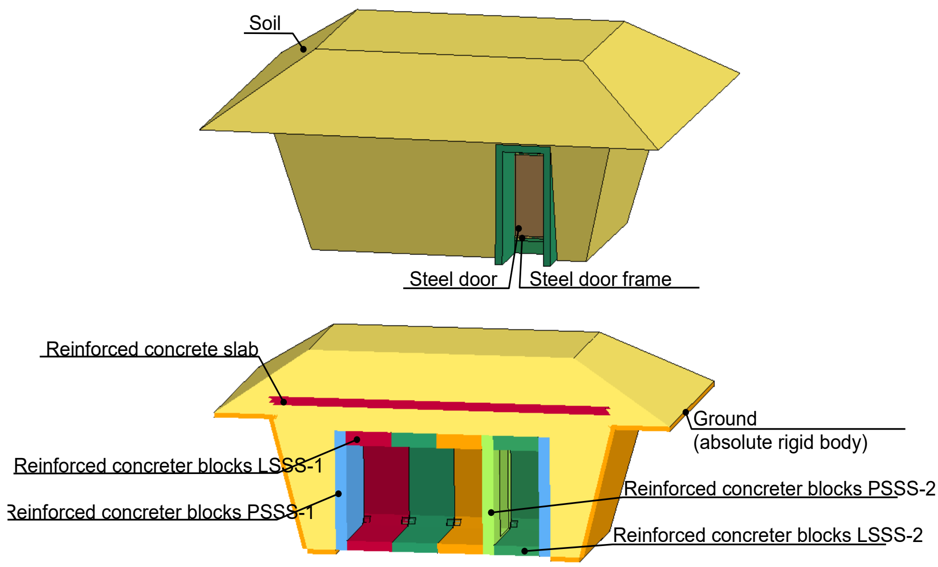


Fig. 11. General calculation scheme of the SHS UFS-1 protective facility

Following the calculations, we obtained results that make it possible to investigate the mechanisms of destruction or loss of integrity of shelter structures and establish the relationship of these aspects with ensuring the performance of its protective functions under the influence of an explosion. To study the mechanisms of destruction or loss of integrity, the impact of the explosion was investigated under two scenarios with the most dangerous combination of explosion parameters with a TNT equivalent of the charge $m(\text{TNT}) = 15$ kg, and a minimum distance from the epicenter of the explosion to the surface of the shelter fence $l = 0.55$ m for the first scenario and a charge $m(\text{TNT}) = 15$ kg, and a minimum distance from the epicenter of the explosion to the surface of the shelter fence $l = 5$ m for the second scenario.

As described above, the system was loaded in two stages: in the first stage, the load of the initiated prestress in the connecting bolts was applied due to the tightening force and the gravitational load due to the own weight of the system elements.

5. 3. Assessing the stressed-strained state and functional suitability of structures

To analyze the stressed-strained state, a diagram of the distribution of plastic deformations after applying pressure from the blast wave to the surface of the shelter structures was constructed for the scenario when the epicenter of the explosion is located on the side of the shelter. The constructed distribution of plastic deformations for both shelters is shown in Fig. 12, 13.

The plastic strain distribution shown in Fig. 13, 14 demonstrates the locations of defects in the structural elements where crack growth in their concrete base is possible. However, one can see that fragmentation and separation of the structural elements into separate parts does not occur.

Fig. 15 shows the distribution of displacements in the soil cushion.

When analyzing the above distribution of displacements in the soil cushion, shown in Fig. 15, on can see that they do not have large values, that is, the soil during the calculated time moves no more than 0.08 m (80 mm). These deformations are not significant, and when they stabilize near this value, it can be assumed that the destruction of structures does not occur and the shelter retains its protective capabilities.

To assess the consequences of the explosion on reinforced concrete structures of shelters, a field of displacements of structural elements after applying a load from a shock wave according to the first scenario was constructed. The corresponding distribution of displacements for the SHS UFS-1 protective facility is shown in Fig. 16.

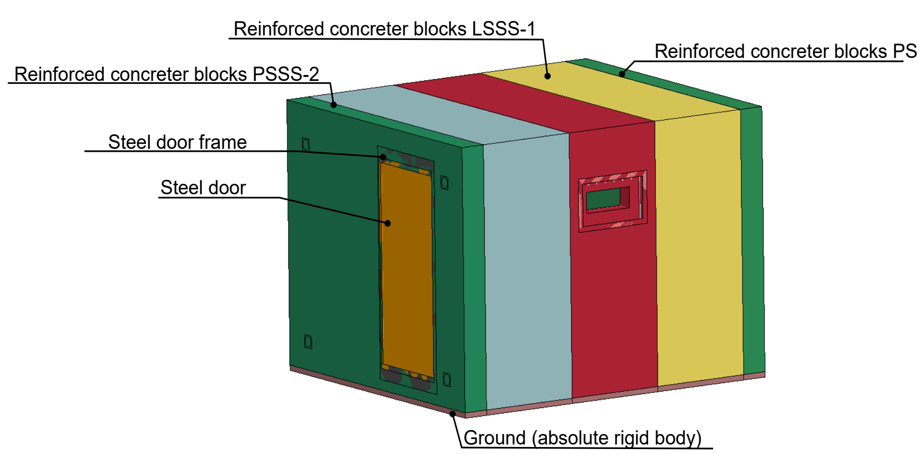


Fig. 12. General calculation scheme of the SHS VS-1-3 protective facility

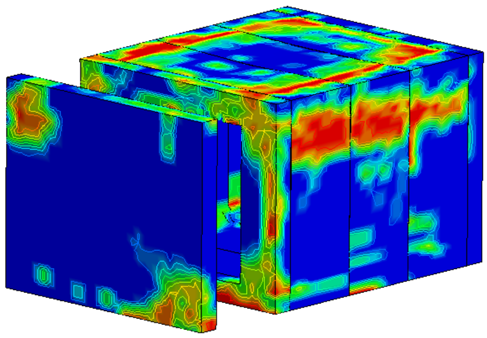


Fig. 13. Distribution of plastic deformations after applying pressure from the blast wave (m(TNT) = 5 kg, l = 0.55 m) to the surface of the SHS UFS-1 protective facility for the first scenario

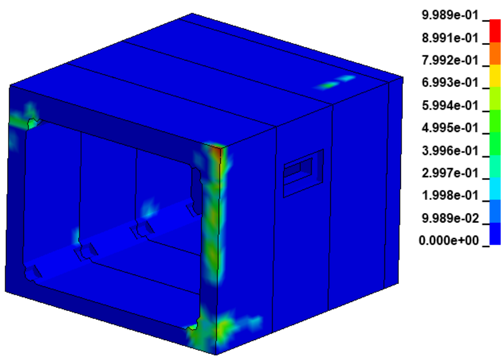


Fig. 14. Distribution of plastic deformations after applying pressure from the blast wave (m(TNT) = 5 kg, l = 5 m) to the surface of the SHS VS-1-3 protective facility for the second scenario

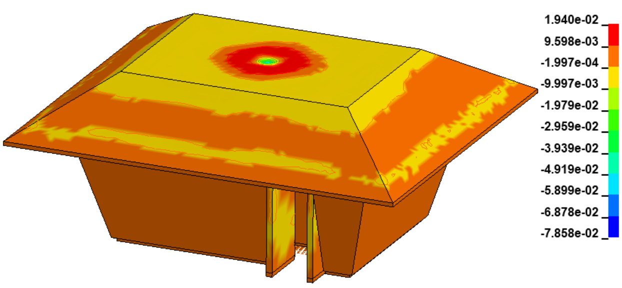


Fig. 15. Distribution of displacements (m) of elements in the soil cushion of the SHS UFS-1 protective facility after applying pressure from the blast wave

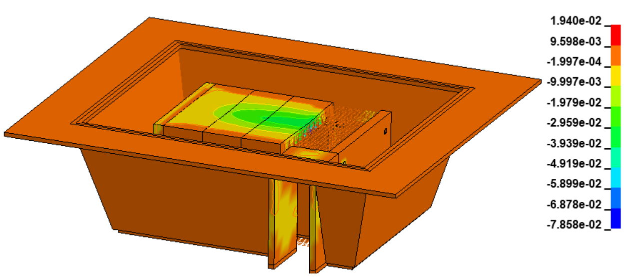


Fig. 16. Distribution of displacements (m) of elements in a fragment of the SHS UFS-1 protective facility after applying pressure from the blast wave

The above distribution of displacements clearly demonstrates that the largest values of displacements are localized in the near-surface areas of the structure, which are directly exposed to the shock wave. With distance from the load application zone, a gradual decrease in displacements is observed, which indicates their attenuation in the thickness of the structure. The distribution has a pronounced uneven nature, which is due to the geometry of the structure and the conditions of its interaction with the soil base. At the same time, maximum displacements do not lead to a loss of the overall stability of the structure. The visualization for the SHS VS-1-3 protective facility is shown in Fig. 17.

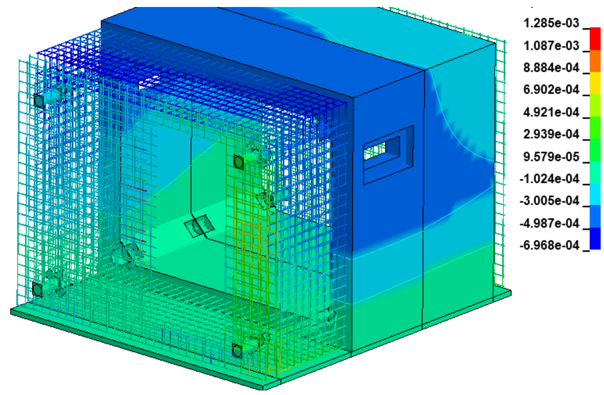


Fig. 17. Distribution of displacements (m) of elements in a fragment of the SHS VS-1-3 protective facility after applying pressure from the blast wave

When analyzing the above distribution of displacements in the elements of shelter modules, shown in Fig. 16, 17, one can see that they do not take large values, that is, these elements move no more than 0.04 m (40 mm) during the calculated time. These deformations are not significant, and when they stabilize near this value, it can be assumed that the destruction of the structures does not occur and the shelter retains its protective capabilities.

For a detailed analysis, plots of displacements of the most dangerous points on the upper surface of the SHS UFS-1 protective facility were constructed. The positions of these points are shown in Fig. 18, the plot for which is shown in Fig. 19.

The plots in Fig. 19 show that the displacements of structural elements increase rapidly at the moment when the shock wave pressure is maximum, and then, after fluctuations associated with oscillatory processes, quickly decay and stabilize at deformations of no more than 25 mm. This indicates that no avalanche-like build-up of deformations is observed and the shelter structures retain their protective capacity.

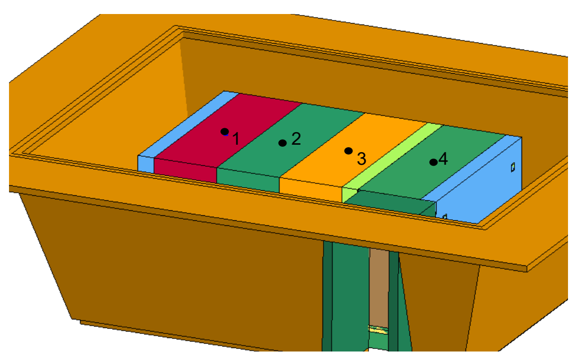


Fig. 18. Position of the most dangerous points of the side wall of the SHS UFS-1 protective facility during an explosion

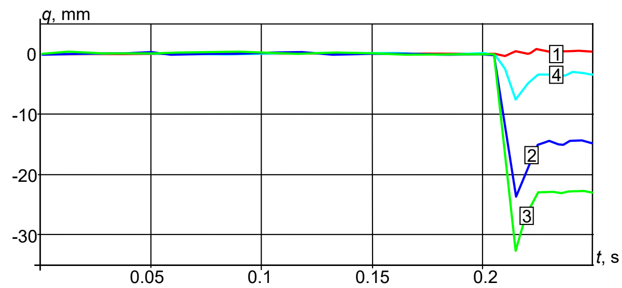


Fig. 19. Plots of point displacements in the structures of the SHS UFS-1 protective facility that undergo the greatest displacements during an explosion according to the second scenario

Plots of displacements of the most dangerous points on the upper surface of the protective structure were also constructed. The positions of these points and the corresponding plot are shown in Fig. 20, 21, respectively.

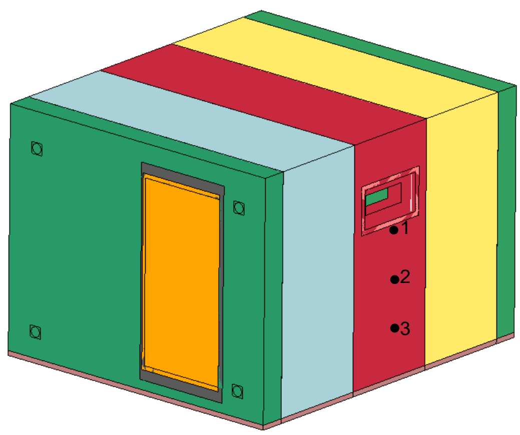


Fig. 20. Position of the most dangerous points on the side wall of the SHS VS-1-3 protective facility during an explosion

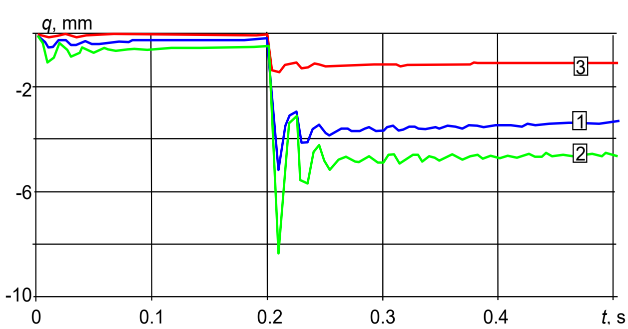


Fig. 21. Plots of movements of the most dangerous points on the structures of the SHS VS-1-3 protective facility, which undergo the greatest movements during an explosion according to the second scenario

The plots in Fig. 21 show that the displacements of structural elements increase rapidly at the moment when the shock wave pressure is maximum, and then, after fluctuations associated with oscillatory processes, quickly decay and stabilize at deformations of no more than 5.5 mm. These deformations are insignificant and our results indicate that the structures at a protective facility retain their functional suitability and protective properties under the action of an explosive load with the adopted parameters for both scenarios considered.

6. Discussion of results based on modeling the explosive impact on protective shelters

Our numerical modeling results showed that the nature of the stressed-strained state of protective shelter structures significantly depends on the indicators of the explosive load, the geometry of the structure, and the conditions of contact interaction between individual elements of the structure and the soil surface. According to the results shown in Fig. 7–9, the maximum values of excess pressure are formed in areas localized closest to the epicenter of the explosion, which is justified by the influence of the reflected shock wave and the factors of spatial propagation of the explosion pulse. It was established that for the first variant of the explosive impact, the maximum excess pressure reaches $P_{ref} = 1.16 \cdot 10^6$ kPa, while for the second variant – about $P_{ref} \approx 1.01 \cdot 10^3$ kPa. This difference is explained by the smaller distance to the explosion center and the more intense influence of the reflected wave in the first scenario.

Analysis of the distribution of plastic deformations and displacements, shown in Fig. 12–16, revealed that the largest local deformations occur in the near-surface areas of structures and in the nodes of block connections. This is due to the uneven transmission of the impulse load between individual elements of the system and the stress structure in the contact zones. At the same time, our results confirm the absence of progressive destruction of the structural system even under the most unfavorable loading conditions, which indicates reliable rigidity and stability of the structural design of the shelters.

A feature of the proposed approach is the consideration of the simultaneous influence of physical and geometric nonlinearity, contact interaction between structural elements and the soil surface, as well as the impulse nature of the explosion action. Unlike studies [1–6], which mainly consider individual reinforced concrete elements or monolithic structures, our study focuses on the spatial deformation of prefabricated block shelters. This allows us to establish local patterns of stress concentration and distribution features between structural blocks.

The limitation of our research is the use of a simplified description of the explosive effect without detailed consideration of the gas-dynamic processes of detonation and secondary impact factors. In addition, the results are adequate for the considered structural schemes of shelters and the range of parameters of the explosive load adopted in the work. The reliability of the results also depends on the accepted material models, contact interaction parameters, and conditions of fastening the structure.

The disadvantage of the study is the limited number of considered schemes of the blast wave action and the absence of analysis of long-term damage accumulation in structures under repeated loads. These shortcomings could be eliminated by conducting a series of full-scale experiments, expanding the range of structural schemes of shelters, and using more detailed models and soil base.

Further studies should consider the construction of models for combined explosive and thermal effects, the investigation of progressive destruction of structures, and the improvement of contact interaction. Difficulties may include significant computational and experimental costs, the complexity of test verification of fast-moving dynamic processes, as well as the need to refine the parameters of nonlinear material models for different types of building structures.

7. Conclusions

1. We have established that the SHS UFS-1 and SHS VS-1-3 protective facilities have significant sensitivity to explosive effects at the joints of the blocks and near-surface areas of contact with the soil. This is explained by the concentration of local stresses with uneven distribution of the impulse load between the nodes of the structural elements.

2. A calculation scheme and a finite element model of a protective structure have been constructed, which take into account physical and geometric nonlinearity, the impulse nature of the explosive impact, as well as the contact interaction of structures with the soil base. Unlike simplified calculation schemes, the proposed model makes it possible to reproduce the spatial work of the structure and the localization of plastic deformations in critical zones, which increases reliability of the assessment of its stressed-strained state.

3. The maximum values of excess pressure were calculated based on the results of numerical modeling of the explosive effect for a charge of $m(\text{TNT}) = 15$ kg at distances of 0.55 m and 5 m, which are $P_{ref} = 1.16 \cdot 10^6$ and $P_{ref} \approx 1.01 \cdot 10^3$ kPa, respectively. It was found that under the considered loading schemes, the shelter structures retain their functional suitability and stability; our results correlate with the data on field tests No. 366-B/2024, which confirms reasonable reliability of the proposed approach.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

Funding

The study was conducted without financial support.

Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

When preparing the manuscript, the authors used the ChatGPT artificial intelligence model (OpenAI, GPT-5.5) as an auxiliary tool for improving the structure and language design of the paper.

Artificial intelligence tools were used in chapters "Literature review and problem statement", "Bibliography", as well as partially in the preparation of the abstract and Authors' contributions (translation).

Specifically, artificial intelligence was used for:

– search and preliminary selection of scientific publications indexed in Scopus;

– improvement of the academic style of presentation of the material;

– structuring of individual text fragments;

– linguistic editing and translation of individual parts of the manuscript into English.

All results generated using artificial intelligence tools were verified by the authors on the basis of scientific publications, engineering reports, and experimental data obtained within the framework of the study. All numerical results, calculation models, engineering assumptions, interpretations, and conclusions were generated, verified, and confirmed directly by the authors.

The use of artificial intelligence tools did not affect the scientific conclusions of the study and was limited to supporting editorial, linguistic, and bibliographic tasks during manuscript preparation.

Authors' contributions

Serhii Pozdieiev: Conceptualization, Methodology, Supervision, Validation; **Volodymyr Bashynskyi**: Project administration, Supervision, Methodology; **Andrii Shvydenko**: Writing – Original Draft, Writing – Review & Editing, Visualization, Project administration; **Serhii Bisyk**: Conceptualization, Methodology, Formal analysis, Validation, Writing – Review & Editing, Supervision.; **Olga Nekora**: Investigation, Data curation, Validation; **Serhii Holets**: Methodology, Investigation, Resources, Project administration; **Oleh Dmitriiev**: Investigation, Resources, Validation; **Volodymyr Krivtsun**: Methodology, Investigation, Data curation; **Viktor Nikitchenko**: Formal analysis, Validation, Visualization; **Ihor Chastokolenko**: Resources, Investigation, Supervision.

References

1. Zhang, C., Gholipour, G., Mousavi, A. A. (2020). Blast loads induced responses of RC structural members: State-of-the-art review. Composites Part B: Engineering, 195, 108066. https://doi.org/10.1016/j.compositesb.2020.108066
2. Anas, S. M., Alam, M., Umair, M. (2021). Experimental and numerical investigations on performance of reinforced concrete slabs under explosive-induced air-blast loading: A state-of-the-art review. Structures, 31, 428–461. https://doi.org/10.1016/j.istruc.2021.01.102
3. Park, Y., Kim, K., Park, S.-w., Yum, S.-G., Baek, J.-W. (2024). Experimental Evaluation on Blast Resistance of Reinforced Concrete Structures under Partially Confined Explosion. International Journal of Concrete Structures and Materials, 18 (1). https://doi.org/10.1186/s40069-024-00663-2
4. Guo, X., Li, Y., McCrum, D. P., Hu, Y., Bai, Z., Zhang, H., Li, Z., Wang, X. (2024). A reinforced concrete shear wall building structure subjected to internal TNT explosions: Test results and numerical validation. International Journal of Impact Engineering, 190, 104950. https://doi.org/10.1016/j.ijimpeng.2024.104950
5. Draganić, H., Jeleč, M., Gazić, G., Lukić, S. (2025). Numerical Investigations of Reinforced Concrete Slabs Subjected to Contact Explosions. Buildings, 15 (7), 1063. https://doi.org/10.3390/buildings15071063
6. Li, H., Chen, W., Hao, H. (2024). Performance of reinforced concrete slabs subjected to simultaneous fire and blast loads. Engineering Structures, 311, 118133. https://doi.org/10.1016/j.engstruct.2024.118133

7. Ivanchenko, G., Getun, G., Bezklubenko, I., Solomin, A., Posternak, O. (2023). Influence of explosive loads on buildings and structures of the population civil protection. Strength of Materials and Theory of Structures, 111, 39–48. https://doi.org/10.32347/2410-2547.2023.111.39-48
8. Kostopoulos, V., Kalimeris, G. D., Giannaros, E. (2022). Blast protection of steel reinforced concrete structures using composite foam-core sacrificial cladding. Composites Science and Technology, 230, 109330. https://doi.org/10.1016/j.compscitech.2022.109330
9. Fatima, A., Sangi, A. J., Mohammad, A. F., Joohi, M. (2023). Global response of reinforced concrete framed building under varying blast load pulse shapes. Structures, 50, 482–493. https://doi.org/10.1016/j.istruc.2023.02.001
10. Belytschko, T., Liu, W. K., Moran, B. (2013). Nonlinear finite elements for continua and structures. John Wiley & Sons. Available at: https://scispace.com/pdf/nonlinear-finite-elements-for-continua-and-structures-1qwp4eb2pg.pdf
11. Grassl, P., Jirásek, M. (2006). Damage-plastic model for concrete failure. International Journal of Solids and Structures, 43 (22-23), 7166–7196. https://doi.org/10.1016/j.ijsolstr.2006.06.032
12. Murray, Y. D., Abu-Odeh, A., Bligh, R. (2007). Evaluation of LS-DYNA Concrete Material Model 159 (2007). FHWA-HRT-05-063. Available at: https://www.fhwa.dot.gov/publications/research/infrastructure/structures/05063/
13. Hallquist, J. O. (2006). LS-DYNA® Theory Manual. Livermore Software Technology Corporation, 680. Available at: https://ftp.lstc.com/anonymous/outgoing/jday/manuals/ls-dyna_theory_manual_2006.pdf
14. Kingery, C. N., Bulmash, G. (1984). Airblast Parameters from TNT Spherical Air Burst and Hemispherical Surface Burst. Aberdeen Proving Ground. Available at: https://erdclibrary.on.worldcat.org/search?databaseList=&queryString=867650613
15. Structures to resist the effects of accidental explosions (UFC 3-340-02) (2008). Unified Facilities Criteria (UFC). Available at: https://nibs-s3-wbdg3-production.s3.us-east-1.amazonaws.com/FFC/DOD/UFC/ufc_3_340_02_2008_c2.pdf
16. Kingery-Bulmash blast parameter calculator. UN SaferGuard. Available at: https://unsaferguard.org/un-saferguard/kingery-bulmash
17. Index of /~gyebro/files/ans_help_v182/ans_thry. Available at: https://www.mm.bme.hu/~gyebro/files/ans_help_v182/ans_thry/ans_thry.html
18. Protokol naturnykh vyprobuvan No. 366-V/2024 vid 18.07.2024 r. Shvydkosporudzhuvani zakhysni sporudy typiv "ShS VS-1-3" ta "ShS UFS-1".