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The Study of the Behavior of Reinforced Concrete Structures of Modular Shelter in Conditions of Explosion

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Abstract. The article presents the results of mathematical modeling of the impact of the explosion and the corresponding stress-strain state in reinforced concrete blocks of protective structures. The purpose of the work is to establish the safety of the developed protective shelters in the conditions of an explosion during aerial attacks. After conducting the calculations, the results were obtained, which allow to investigate the mechanisms of destruction or loss of integrity of shelter structures and to 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. The scientific novelty consists in the development of a new approach to calculations, based on the application of the warhead value of the corresponding projectile in TNT equivalent, the distance of the explosion and the position of the point where the explosion occurs. The determined pressure according to these parameters can be used to study its effect on structures. The practical significance of the research—on the basis of the conducted research, the results of mathematical modeling of the behavior of protective shelters in the conditions of an explosion were obtained, which allow to investigate the mechanisms of destruction or loss of integrity of the structures of the shelter and to establish the relationship of these aspects with ensuring the performance of its protective functions under the influence of an explosion.

Keywords: Reinforced concrete structures · Modular shelter · Stress-Strain state · Protective structures · Mathematical modeling · Impact of explosions

1 Introduction

Since the beginning of February 24, 2022, during the year of the war, Russia has launched almost 5000 missile strikes and about 1000 kamikaze drone attacks on the territory of Ukraine. Unfortunately, the greatest destruction of buildings and structures and a large

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number of victims are caused by S-200, S-300, X-22, “Iskander” missiles, which cannot be intercepted by the air defense of Ukraine. Therefore, today it remains an urgent issue to establish standardized ground shelters that, in the conditions of hostilities, can block the influence of impact factors (aircraft, missile and artillery fire) and protect people from damage by debris and fragments of building structures. An important aspect that determines the effectiveness of protective structures is the possibility of safe evacuation from them, after the destruction of the building structures of the objects from hitting them with combat shells. This determines the urgency of modernizing and improving existing or setting up new ground defense structures.

2 Purpose

The main goal is to determine the patterns of behavior of reinforced concrete structures of ground protective shelters, which are installed directly on the ground, under the conditions of an explosion during air strikes during hostilities on the territory of Ukraine. The obtained regularities can serve as a scientific basis for methods of establishing their compliance with the current norms of Ukraine [1, 2].

To fulfill this goal, the following research tasks were set:

- to analyze approaches to modeling the behavior of reinforced concrete structures under explosion conditions;
- to substantiate mathematical models of the behavior of reinforced concrete structures under explosion conditions;
- to develop a methodology and, in accordance with the methodology, conduct a numerical experiment on the effect of an explosion on reinforced concrete structures of a ground shelter;
- to establish the main regularities and peculiarities of the behavior of reinforced concrete structures of ground shelter in the conditions of an explosion.

3 Research Methods

To simulate the impact of the explosion and the corresponding stressed and deformed state (SDS) in reinforced concrete blocks under the conditions of the explosion, a generalized engineering approach was applied, which is based on the following basic methods. 1. For mathematical modeling of the SDS of a deformed solid, a generalized theoretical approach is used, which is based on the integration of equations using the finite element method (FEM) [3]. 2. To describe the nonlinear behavior of concrete under active loads, the plastic model of damaged concrete described in the works of Grassl and Jirasek [4] is used. 3. The Drucker-Prager model is used to model the nonlinear behavior of the soil [5]. 4. A model of contact interaction is used to describe the interaction between the support surfaces of reinforced concrete blocks of protective shelter on the ground. The bearing surfaces of the soil layer on the deep layers, according to the accepted assumptions, consist of absolutely undeformed material. 5. The combat charge of shells is assumed to be equivalent to 10 kg in TNT equivalent as the most common. To determine the change in pressure on the walls of reinforced concrete shelter blocks and on the surface of the soil, the Taylor model [6] is used. 6. When studying the behavior of ground protective shelters during an explosion, the LS-DYNA computer system is used, which is designed to simulate impulse effects on structural systems using the dynamics equations in finite-element implementation.

4 Results

The results of the work will become a prerequisite for further research in the part of substantiating the constructive parameters of ground shelters in the conditions of martial law. And the detection of regularities in the dependence of the degree and severity of damage of ground structures on the parameters of the effects caused by the action of combat shells, as well as the scattering of debris and fragments of building structures. The main results of the research consist in the development and improvement of the calculation base for the assessment of storage by the enclosing structures of ground protective structures in the conditions of explosions and impulse actions, as a scientific basis for the improvement of the existing regulatory framework of Ukraine.

The theoretical base of the main approach to calculating the dynamic interaction of mechanical systems, implemented in the code of the software complex LS-DYNA.

4.1 Peculiarities of Mathematical Modeling of the Stress-Strain State

For mathematical modeling of the SDS of a deformed solid body, a generalized theoretical approach is used, which is based on the initiation of movements of the points of the mechanical system of rigid deformed bodies using a system of general dynamics equations and equations of the SDS caused by these movements. The main methods of calculating the dynamic interaction of mechanical systems for ground protective structures are detailed in the Table 1 [7–15].

4.2 Mathematical Model of the Behavior of Reinforcing Steel Under Mechanical Load Conditions

The mathematical description of the phenomenology of the behavior of reinforced steel corresponds to the material model, which describes a simple isotropic material with a deformation diagram that is symmetrical for compression and for tension [7]. When describing concrete, a model of a continuous failure surface with a limiting dome was used, which is described in works Murray, Abu-Odeh i Bligh [8].

The main feature of this model is that the combinations of stresses that the material can withstand are limited by a special surface, which is composed of a yield surface and a brittle failure surface. So this surface covers all cases of destruction of concrete in a complex way and thereby establishes the conditions for either brittle or viscous destruction Fig. 1 shows the general view of the geometry of this surface.

At the same time, parts of the destruction surface are unequal, and therefore this surface is divided into zones—a zone of destruction due to shear deformations and a zone of strengthening during compaction of concrete due to compression, which are interconnected and form a smooth and continuous surface. Figure 2 shows the meridional section of this surface.

To determine the nature of deformation, deformation diagrams are used. They are presented in Fig. 3.

Table 1. A generalized engineering approach to calculation

№	Peculiarities of mechanical processes	Mathematical model or methods
1	The stressed-deformed state of a solid body	Integration of dynamics equations and stress-deformed state equations using the finite element method
2	Modeling of concrete base and soil layer of shelter blocks	Application of three-dimensional massive finite elements of hexahedral shape with eight nodes
3	Modeling of steel plate elements of the anchoring system and door elements	Using two-dimensional shell finite elements of a rectangular shape of the Belychko-Tsai type with four nodes and five integration points
4	Modeling of steel reinforcement in the form of reinforcing bars	The use of one-dimensional linear elements with a defined cross-sectional shape, known as Hughes-Liu rod-beam elements
5	Description of non-linear behavior of concrete under active loads	Application of the plastic model of damaged concrete according to the works of Grassl and Jirasek, which is built on the basis of nonlinear deformation diagrams with descending branches
6	Modeling of nonlinear soil behavior	Application of the Drucker-Prager model
7	Interaction between the support surfaces of reinforced concrete blocks of protective shelter on the ground	Using the model of contact interaction
8	Modeling the explosion and determining the change in pressure on the walls of reinforced concrete shelter blocks	Application of the Taylor model
9	Program code for the sample testing process	The use of the LS-DYNA computer system is part of the complex of engineering calculation systems ANSYS Workbench and is also included as a block in a separate part of this complex ANSYS APDL

4.3 Modeling the Effect of the Explosion on the Structures of Protective Structures

The guidelines for the design of protective structures, recommended in the norms [5] in force in Ukraine, determine the excess pressure of the shock wave as the main influence. This pressure is defined as a reference value and is a force factor applied to the surfaces of the building structures of the bomb shelter. At the same time, appropriate coefficients are used to take into account the dynamics of load application. This approach is somewhat outdated, as it uses a quasi-static approach for calculation. For a more accurate description, it is proposed to use a more physically based approach, which is based on the application of the warhead value of the corresponding projectile in TNT equivalent,

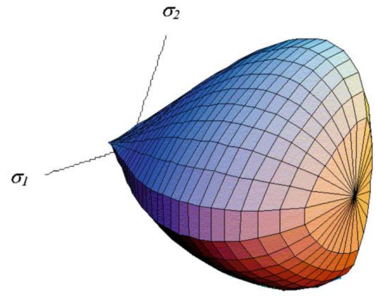

Fig. 1. General view of the geometric configuration of the surface of concrete destruction.

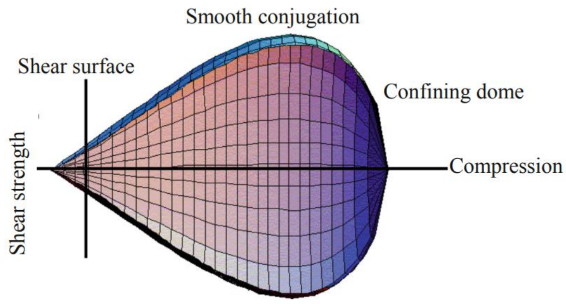

Fig. 2. Meridional section of the surface of concrete destruction

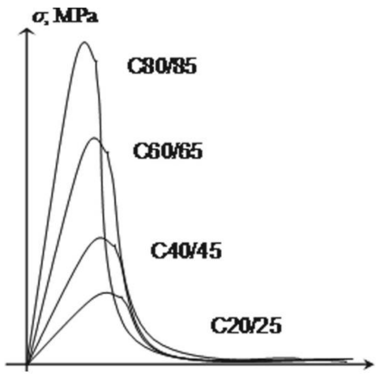

Fig. 3. Diagrams of concrete deformation depending on the strength class.

the distance of the explosion and the position of the point where the explosion occurs. The determined pressure according to these parameters can be used to study its effect on structures.

A special empirical curve according to [9] is used to simulate pressure under the influence of an explosion. This curve is shown in Fig. 4.

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:

$$Z = R \cdot M^{-\frac{1}{3}} \tag{1}$$

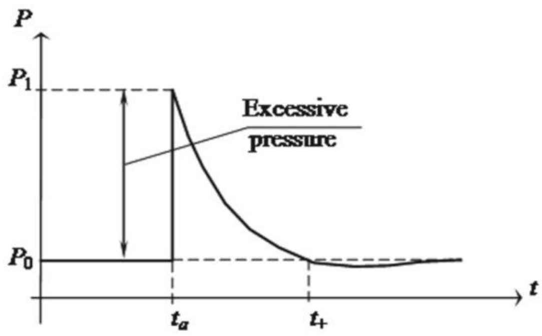

Fig. 4. The curve of pressure on the surface of the walls of shelter structures.

where

R—the distance of the wall to the center of the explosion;
M—TNT mass equivalent.

4.4 Modeling the Impact of the Explosion on the Ground Protective Structures

Two types of load are used to study the impact of an explosion on shelter structures: the load from the structures' own weight and the load from the explosion. The load from its own weight is applied to all components of the model and has a constant effect, however, at the moment of its application, when using the explicit method, unwanted kinetic energy appears, which is manifested, as a rule, in an oscillatory process of a certain duration of its damping. When applying the load from the explosion, the Taylor model [9] and the calculation scheme shown in Fig. 6 are used. According to the diagram in Fig. 5 to simulate the explosion two main parameters—the minimum distance from the epicenter to the surface of the shelter and the equivalent mass of the TNT charge are used.

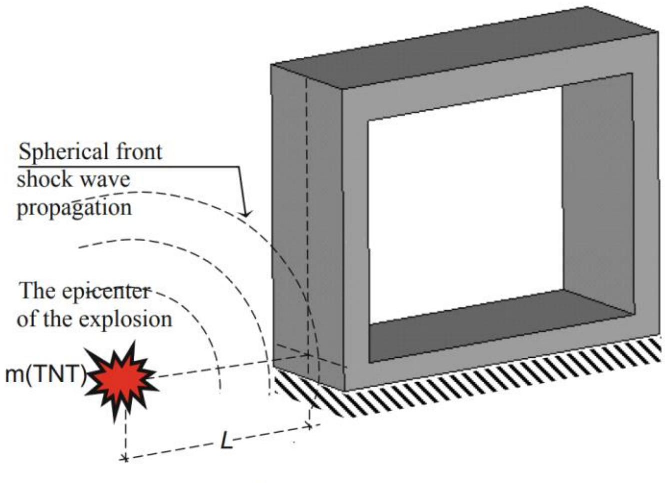

Fig. 5. The scheme of applying the load from the explosion.

In Table 2 sets of such parameters and the corresponding maximum overpressure of the explosion are given.

Table 2. Parameters of the explosion impact model

A variant of the impact of the explosion	Distance, L, m	TNT equivalent, m(TNT), kg	Maximum excess pressure, kPa
1	1	10	4000
2	1	20	8450
3	1	30	13640

Figure 6 shows several options for the location of the epicenter of the explosion: in the middle of the side surface of the shelter, on the side of the entrance to the shelter and above the upper slab of the shelter.

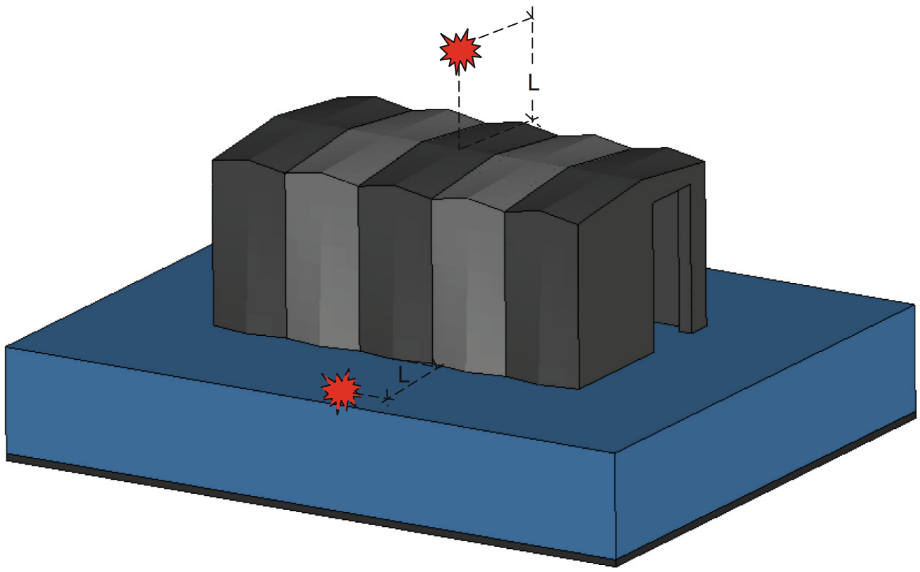

Fig. 6. Schemes of different options for the location of the epicenter of the explosion.

4.5 Finite Element Scheme of the Ground Protective Shelter

After carrying out the above calculations, according to the developed methods, the finite-element scheme of the shelter was obtained, shown in Fig. 7. This diagram shows the finite-element discretization of all components-parts of the mathematical shelter model [8–15].

Thus, the results that will allow in the future to investigate the mechanisms of destruction or loss of integrity of shelter structures and to establish the relationship of these

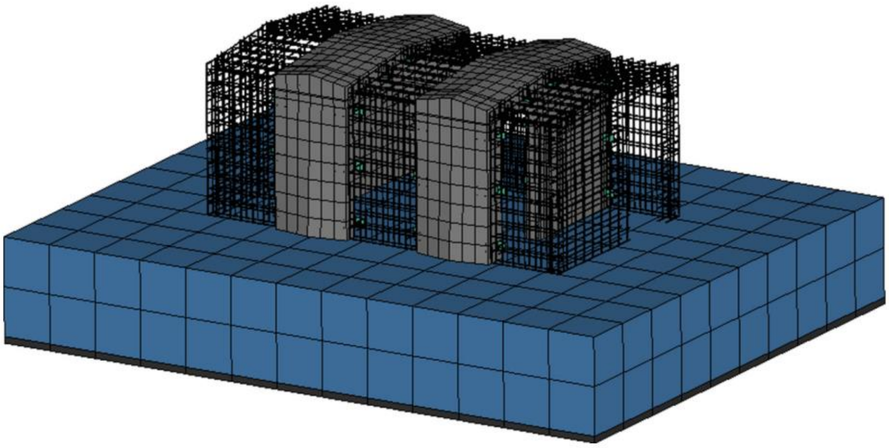

Fig. 7. Finite element diagram of shelter components.

aspects with ensuring the performance of its protective functions under the influence of an explosion were obtained.

Scientific novelty and practical significance

The results of the work will become a prerequisite for further research in the part of substantiating the structural parameters of ground reinforced concrete shelters during shelling in martial law conditions. They will also be useful for project organizations during the design and evaluation of the effectiveness of the functioning and protective properties of ground defense structures. The above determines the urgency of developing and improving the relevant regulatory framework, taking into account the generalized practical experience gained during Russia's war against Ukraine.

5 Conclusions

So, in the work, scientific results were obtained regarding the determination of the regularities of the behavior of reinforced concrete structures of ground protective shelters, which are installed directly on the ground, under the conditions of an explosion during air strikes during hostilities on the territory of Ukraine. It is worth noting that in the current regulatory documents, the calculation method is expressed by the following criteria: overpressure of the explosion and the protection factor (reduction of ionizing radiation), and such criteria as mechanical impact from military weapons are not defined. Therefore, the developed mathematical models and methods provide a solution to the current problem—this is the improvement of the methodological and regulatory framework for determining the structural parameters of ground protective structures in Ukraine.

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