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STRUCTURAL DESIGN UNDER BLAST LOADING: FROM SIMPLIFIED MODELS TO ADVANCED DYNAMIC ANALYSIS

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The work summarizes and systematizes the main methods of calculating building structures for the effects of an blast-shock wave, the shock impulse method, and the method of direct integration of equations of motion, which allowed us to determine their areas of effective application. It was established that the quasi-static method is advisable to use at the initial stages of design to obtain engineering estimates, while the method of direct integration of equations of motion provides the most accurate results in a detailed analysis of the operation of structures under the action of a blast-shock wave. An improved approach to modeling the load from a blast-shock wave is proposed, which takes into account the spatio-temporal discretization of pressure and the sequence of the wave front passing over the surface of the structure. The results of the study are aimed at increasing the level of safety and stability of buildings and structures in the conditions of russian armed aggression against Ukraine, and can also be used to improve the regulatory framework in the field of designing structures for special impacts.

Keywords: engineering defense structures, fortification structures, critical infrastructure objects, damage factors, blast-shock wave, building structures.

Relevance. In the context of the full-scale war of russia against Ukraine, the issues of ensuring the reliability and survivability of buildings and structures under blast loading caused by aerial attack means, missile and artillery strikes, and other damaging factors are of particular relevance [1, 2, 12-14, 19]. The large-scale use of precision-guided weapons and strike unmanned systems necessitates the improvement of approaches to the analysis of structures subjected to blast waves (shock waves), taking into account realistic scenarios of damage to critical infrastructure facilities and protective structures [3, 4, 7].

Modern engineering practice provides the use of several principal methods for analyzing structures under blast wave effects, among which the most widely applied are the quasi-static method, the impulse (shock impulse) method, and the direct integration method of the equations of motion [5]. The quasi-static method is based on transforming dynamic loading into an equivalent static load using a dynamic amplification factor and is an effective tool for preliminary engineering assessments [6, 15]. The impulse method allows accounting for the integral effect of short-duration loading through impulse parameters, providing a more adequate representation of blast wave action [8, 9, 10]. At the same time, the most accurate approach is the direct integration of the equations of motion, which makes it possible to consider the actual time-dependent variation of loads, inertial characteristics of the system, damping, and the complex spatial behavior of structures.

Despite the availability of these methods, their practical application in the design of protective structures is complicated by the lack of generalized recommendations for selecting an appropriate calculation method depending on loading conditions, structural configuration, and the consequence class (importance level) of the facility. In addition, there is a need to improve the accuracy of modeling blast wave parameters, in particular by accounting for the spatial and temporal non-uniformity of shock wave effects on both enclosing and load-bearing structures.

The aim of this study is to systematize existing methods for analyzing building structures under the action of blast waves, to examine their advantages and limitations, and to improve approaches to

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modeling loads and the dynamic response of structures. The paper generalizes the algorithms for applying the quasi-static method and the direct integration method of the equations of motion, in particular with consideration of spatial and temporal discretization of loading, which allows for a more accurate representation of the interaction between the blast wave and structures.

The obtained results are of significant importance for enhancing the reliability of the design of critical infrastructure facilities, civil and military protective structures, as well as for the development of engineering measures aimed at minimizing the consequences of explosive effects under modern threats.

Summary of the main material

At present, several methods are used to design building structures subjected to blast shock wave effects, which are discussed in more detail below.

The quasi-static method is based on representing the building frame as a single-degree-of-freedom system and on the hypothesis that the maximum dynamic displacement is proportional to the static displacement under the action of the maximum load [5]. These assumptions make it possible to determine dynamic amplification factors and to perform the subsequent analysis using equivalent quasi-static loads. In this approach, the equivalent quasi-static loads are established based on practical experience in the design and analysis of structures subjected to shock waves from various types of attack means. The application of this method provides satisfactory results for the preliminary analysis of building and structural frames when followed by more accurate calculation methods.

The value of the equivalent quasi-static load can be determined by the formula:

$$q_e = q_{\max} k_d \, , \tag{1}$$

where q_e is the maximum value of the dynamic load, kN/m^2; k_d – dynamic coefficient, which is equal to the maximum value of the dynamic function. The adequacy of replacing the dynamic load with a static one is determined by the correctness of determining the dynamic coefficient for each specific case [3, 6].

It is recommended to perform the calculation using the quasi-static method in six stages.

At the *first stage*, we collect the initial data and determine the explosion scenarios. This stage is the foundation for all further calculations. It includes:

1. Definition of explosion scenarios and parameters: The type of explosion (air, ground or underground) and the spatial location of the explosion center relative to the building (frontal, side or corner impact) are established. The number of scenarios should take into account all possible cases of emergency impact on the structures of the protective structure [17, 18].

2. Establishing the exact distance from the explosion source to the object (or its individual structures), which is key to assessing the intensity of the wave.

3. Definition of TNT equivalent: Converting the energy of a real explosive to the mass of TNT to standardize the calculation.

At the *second stage*, we determine the parameters of the explosive shock wave.

Based on the established scenario, indicators that directly affect the obstacle are calculated in accordance with existing methods described in detail in the works [1-5]:

1. Determination of excess pressure: calculation of the maximum pressure at the front of a shock wave propagating in free air [11, 16].

2. Determination of reflected pressure: calculation of the pressure that occurs when a wave collides with the surface of a building facade.

3. Determining the duration of the compression phase: calculating the time during

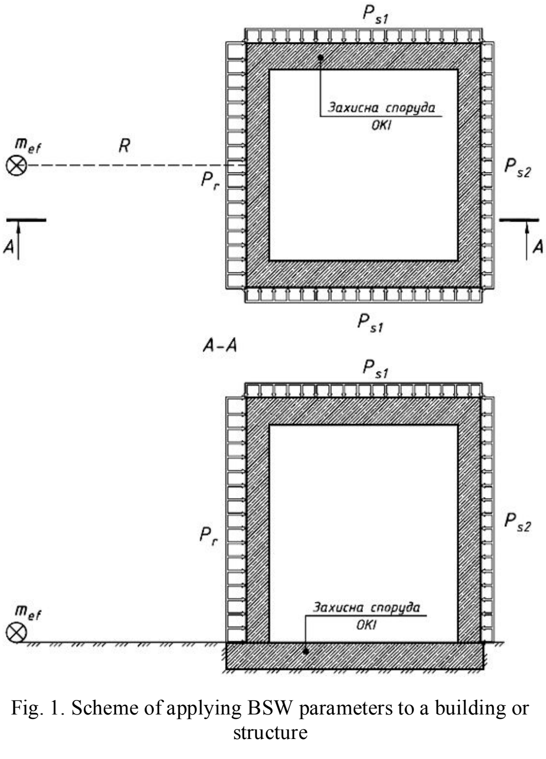

Fig. 1. Scheme of applying BSW parameters to a building or structure

which excess pressure acts on the structure until it is completely extinguished (*t*).

At the *third stage*, we determine the period of the building's natural oscillations. (*T*).

The building is considered as a dynamic system taking into account permanent and temporary long-term loads and the calculation of the natural oscillation period for the main (first) form is performed. This stage makes it clear how exactly the structure is able to "react" to a short-term external impulse.

At the *fourth stage*, we determine the dynamic coefficient (k_d).

The calculation of the dynamic coefficient within the elastic work of the protective structure structures can be determined through the ratio of the duration of the explosion to the period of oscillations according to the graph in Fig. 2.

Also, the dynamic coefficient can be determined according to the relevant nomograms or technical manuals for the relevant structures [3].

At the *fifth stage*, we determine the equivalent static load.

The determination of the equivalent static load is performed according to formula (1). The obtained value is used as a uniformly distributed static load (t/m² or other pressure units) to check the strength of structures.

At the *sixth stage*, we perform a structural inspection in accordance with regulatory requirements (after quasi-static calculation).

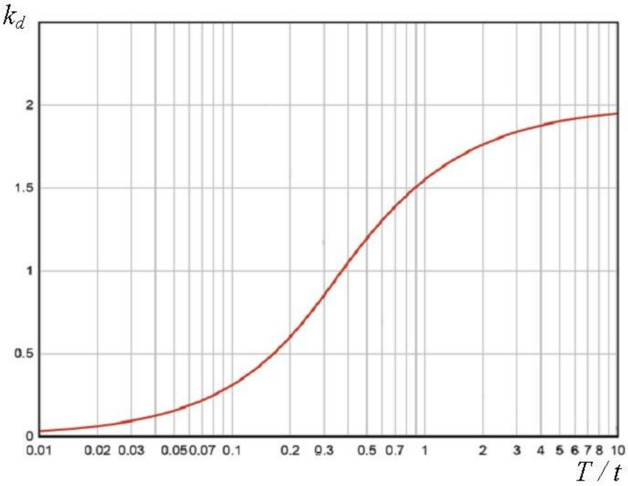

Fig. 2. Graph for determining the dynamic coefficient of the structure taking into account the elastic work of the protective structure structures

Shock impulse method. The essence of this method is to use the momentum conservation theorem to determine the strength and vibrations of the supporting frame of a building or structure [14]. The main parameters for which the calculation is performed using the shock impulse method include excess pressure and the time of action of the load from the BSW. In the BSW front, the reflected pressure should be taken, the values of which can significantly exceed the values of the excess pressure. For individual specific scenarios and cases, they can be determined depending on the main parameters, or taken as constant, for example, for buildings of a certain structural scheme with given parameters of load-bearing structures. In this case, the pressure of both signs can be taken into account. In simplified terms, for most calculation schemes, the load is taken as a shock pulse of the compression phase with a triangular distribution.

The shock impulse method can be used both for calculating the frame of the entire building or structure and for its individual structural elements.

It is recommended to apply the shock impulse of the compression phase of the reflected pressure of the BSW along the front according to the constant patterns of the change in the pressure of the BSW. On the side and rear surfaces of the structure, it is allowed to apply

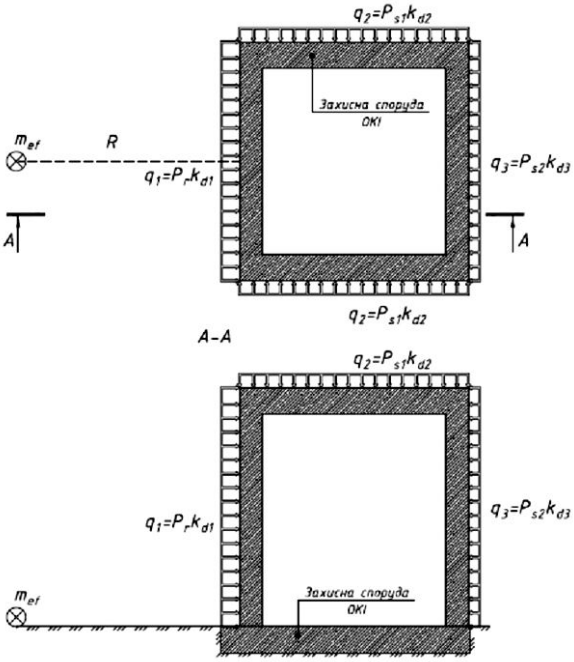

Fig. 3. Scheme of applying quasi-static loads to the protective structure of the CIF

the averaged values of the shock impulse of the compression phase of the excess pressure of the BSW in the form of evenly distributed loads.

The method of direct integration of equations of motion. This method consists in the dynamic calculation of the structure on the actual laws of load changes over time. This method is the most accurate. This method can be used to take into account the operation of reinforced concrete structures of buildings and structures with cracks.

When using this method, it is necessary to determine all parameters of the dynamic actions (time histories of overpressure from blast shock waves) and to approximate them. Such an approach makes it possible to obtain all required load variation parameters at discrete time intervals.

The method of direct integration of the equations of motion also allows taking into account various combinations of graphs of changes in excess pressure along the front of explosive shock waves. The results of the calculation are set at the corresponding moments that coincide with the integration points.

The method of direct integration of equations of motion is based on a system of differential equations of motion obtained from the general equations of mechanics by discretization in spatial variables:

$$Mu''(t)+Cu'(t)+Ku(t)+q(t)=0, \tag{2}$$

where M, C, K – respectively the mass, damping and stiffness matrix of the system; $u(t)$, $u'(t)$, $u''(t)$, $q(t)$ – vectors of nodal displacements, velocities, accelerations and nodal loads at a given time t.

The solution of equation (2) is possible by two main methods: expansion by the forms of natural oscillations and difference schemes, which are also called direct integration of the equations of motion. The method of expansion by the forms of natural oscillations can be used only for linear calculation, since the principle of superposition is not used in nonlinear theory. The method of direct integration of the equations of motion is of a general nature and can be applied to all problems of dynamic calculation of structures.

Methods for dynamic calculation of elastic systems are based on the decomposition of the solution into the forms of natural oscillations:

$$u(t)=\Phi y(t). \tag{3}$$

Forms φ_i , $i = 1, 2, \ldots, m$, $\Phi = [\varphi_1 , \varphi_2 , \ldots, \varphi_m]$ and frequencies ω_i of natural oscillations is the solution to the eigenvalue problem

$$K\varphi_i=\omega_i^2 M\varphi_i. \tag{4}$$

The forms satisfy boundary conditions and orthogonality conditions:

$$\varphi_i^T M\varphi_j=0,\ \ \varphi_i^T M\varphi_j=0 \ \text{ при } \ i\neq j \tag{5}$$

and are normalized by the mass matrix:

$$\varphi_i^T M\varphi_i=1,\ \ \varphi_i^T M\varphi_i=\omega_i^2 . \tag{6}$$

If the orthogonality conditions are also satisfied for the damping matrix C:

$$\varphi_i^T C\varphi_i=2\xi\omega_i,\ \ 0\leq\xi<1, \tag{7}$$

then system (2) breaks down into separate equations:

$$y_i''+2\xi\omega_i y_i'+\omega_i^2 y_i=-q_i(t),\ q_i(t)=\varphi_i^T q(t),\ i=1,2,\ldots,m . \tag{8}$$

The accuracy of the results using this method depends on the number m of calculated shapes, and the error is inversely proportional to the square of the largest frequency.

When constructing a difference scheme for the system of differential equations (2), acceleration, velocity, and displacement are approximated by difference relations. External load $q(t)$ in the equation of motion (2) is a piecewise linear function in time that can approximate any impulse, including the BSW.

If we denote the time step by θ,

$$\begin{aligned}
&t_n=n\theta,\ u_n=u(t_n),\\
&\delta_n u=(u_{n+1}-u_n)/\theta,\ \beta_n u=(u_{n+1}-u_{n-1})/(2\theta)=(\delta_n u+\delta_{n-1}u)/2,\\
&\gamma_n u=(u_{n+1}-2u_n+u_{n-1})/\theta^2,\ \alpha_n u=(u_{n+1}+u_{n-1})/2.
\end{aligned} \tag{9}$$

Replacing the acceleration, velocity and displacement at time tn by the difference relations (2), we obtain:

$$
\begin{aligned}
u_n'' &= \gamma_n u = (u_{n+1} - 2u_n + u_{n-1})/\theta^2, \\
u_n' &= \beta_n u = (u_{n+1} - u_{n-1})/(2\theta), \\
u_n &= \alpha_n u = (u_{n+1} + u_{n-1})/2.
\end{aligned}
\tag{10}
$$

Substituting relation (7) into (2), we obtain a system of equations:

$$M\gamma_n u + C\beta_n u + K\alpha_n u + q_n = 0,\ n = 0, 1, ... \tag{11}$$

The value of displacements u_0 and u_{-1} are determined from the initial conditions, in most cases $u_0 = 0$, $u_{-1} = 0$. Such difference schemes are called implicit, because the unknown displacements u_{n+1} are determined by previously found u_n, u_{n-1} from a system of linear equations whose matrix includes the stiffness matrix K

$$
\begin{aligned}
&u_{n+1} = u_n + \theta u_n' + \theta^2((1/2 - \vartheta)u_n'' + \vartheta u_{n+1}''),\ 0 \le \vartheta \le 1/2, \\
&u_{n+1}' = u_n' + \theta((1-\tau)u_n'' + \tau u_{n+1}''),\ 0 \le \tau \le 1, \\
&Mu_{n+1}'' + Cu_{n+1}' + Ku_{n+1} = f_{n+1}.
\end{aligned}
\tag{12}
$$

It is recommended to perform the calculation using the ***direct integration method of the equations of motion*** in the following six stages.

Stage 1. Collecting initial data and defining explosion scenarios.

This stage is the foundation for all further calculations. It includes:

1. Definition of explosion scenarios and parameters: The type of explosion (air, ground or underground) and the spatial location of the detonation center relative to the building (frontal, side or corner impact) are established.
2. Comprehensive scenario coverage: The number of scenarios should consider all possible cases and combinations of explosive loads that may arise from an emergency impact. Both the most probable and the most critical detonation variants should be analyzed for each individual structural element of the protective structure.
3. Establishing precise distance: Determining the distance from the detonation source to each characteristic point of the object, which is key to estimating the intensity of the wave.
4. Definition of TNT equivalent: Converting the energy of a real explosive to the mass of TNT to standardize the calculation.

Stage 2. Spatial and temporal discretization of the BSW parameters

At this stage, the physical impact is converted into a mathematical load function. $P(t)$, which takes into account the unevenness of the impact.

Spatial discretization: The surfaces of the building are divided into a grid with a step of no more than 1.0–1.5 m for the reflected pressure zone, for the incident pressure zone it is allowed to increase the grid step to 2.5–3 m. For each point, the individual distance R and the corresponding reflected or incident pressure are calculated. This allows taking into account the nonlinear attenuation of the wave along the facade.

Front dynamics: It is imperative to record the time of wave arrival for each grid point to simulate the sequential "run" of the wave front through the building.

Stage 3. Creating a dynamic model, accounting for masses and damping

Formation of a linear mathematical

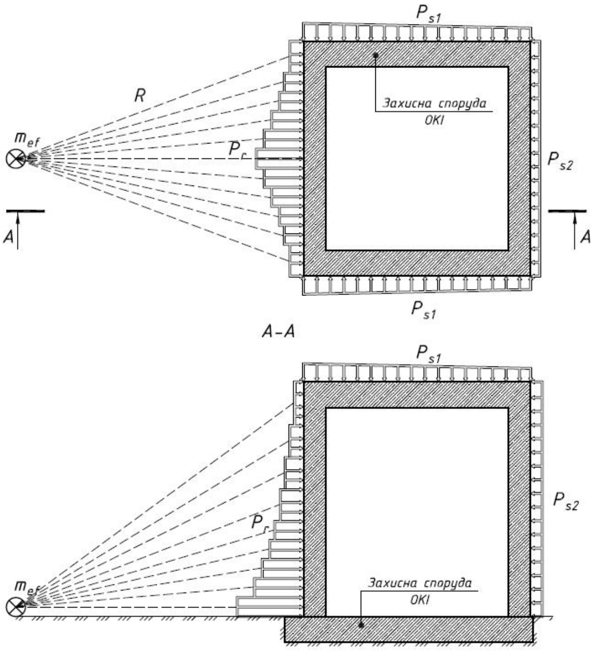

Fig. 4. Scheme of applying loads for the method of direct integration of equations of motion on the protective structure of the CIF

model (matrix [*M*], [*C*], [*K*]):

1. Inertial masses: The dead weight of structures and permanent loads are taken into account 100% as inertial masses.

2. Damping: The system's ability to dissipate energy is specified (Rayleigh method). For reinforced concrete, a damping coefficient of 5% of the critical value is assumed.

3. Temporary loads: Wind and snow loads can be ignored due to their incommensurability with the pressure of the BSW.

4. Work of material: Materials (concrete and reinforcement) are described within linear elasticity (Hooke's law) using dynamic elastic modul.

Stage 4. Direct integration method of equations of motion.

Direct solution of the dynamic equilibrium equation according to formula (2).

It is recommended to take the integration step no more than 1/10 of the smallest period of the system's natural oscillations.

Integration time is set in such a way as to capture the full cycle of the structure's response, including the phase of maximum amplitudes after the shock wave passes. As a rule, the calculation is performed over an interval that is 3–5 times the duration of the compression phase of the BSW.

Stage 5. Verification of structures in accordance with the requirements of regulatory documents of Ukraine.

According to the design standards for protective structures, the calculation for the second serviceability limit state under special influences is not performed. The main criterion is to ensure the load-bearing capacity and overall stability of the structure.

Conclusions. Scientific novelty and practical significance of the results.

The main methods of calculating building structures under the action of an blast-shock wave are generalized and systematized, in particular the quasi-static method, the shock impulse method, and the method of direct integration of equations of motion, which allowed us to determine their areas of effective application.

It was established that the quasi-static method is advisable to use at the initial stages of design to obtain engineering estimates, while the method of direct integration of equations of motion provides the most accurate results in a detailed analysis of the operation of structures under the action of a blast-shock wave.

An improved approach to modeling the load from a blast-shock wave is proposed, which takes into account the spatio-temporal discretization of pressure and the sequence of the wave front passing over the surface of the structure.

The scientific novelty of the obtained results lies in:

- systematization of calculation methods in a single methodological structure;
- development of detailed algorithms for applying the quasi-static method and the method of direct integration of equations of motion;
- improvement of approaches to taking into account the unevenness of dynamic loading;
- expanding the possibilities of applying dynamic methods for analyzing the real operation of structures.

The practical significance of the work lies in the possibility of using the proposed approaches in the design and testing of buildings and structures exposed to blast loads, in particular:

- critical infrastructure facilities;
- civil defense protective structures;
- military engineering structures.

The results of the study are aimed at increasing the level of safety and stability of buildings and structures in the conditions of russian armed aggression against Ukraine, and can also be used to improve the regulatory framework in the field of designing structures for special impacts.

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РОЗРАХУНОК КОНСТРУКЦІЙ НА ДІЮ ВИБУХОВИХ НАВАНТАЖЕНЬ: ВІД СПРОЩЕНИХ МОДЕЛЕЙ ДО РОЗШИРЕНОГО ДИНАМІЧНОГО АНАЛІЗУ

Актуальність. В умовах повномасштабної війни росії проти України особливої актуальності набувають питання забезпечення надійності та живучості будівель і споруд при дії вибухових навантажень, спричинених засобами повітряного нападу, ракетно-артилерійськими ударами та іншими уражаючими факторами.

Сучасна інженерна практика передбачає використання кількох основних методів розрахунку конструкцій на дію ВУХ, серед яких найбільш поширеними є квазістатичний метод, метод ударного імпульсу та метод прямого інтегрування рівнянь руху.

Попри наявність зазначених методів, їх практичне застосування у проєктуванні захисних споруд ускладнюється відсутністю узагальнених рекомендацій щодо вибору методу розрахунку залежно від умов навантаження, конструктивної схеми та рівня відповідальності об'єкта. Крім того, існує потреба у підвищенні точності моделювання параметрів ВУХ, зокрема шляхом врахування просторово-часової нерівномірності дії ударної хвилі на огороджувальні та несучі конструкції.

Метою даної роботи є систематизація існуючих методів розрахунку будівельних конструкцій на дію вибухово-ударної хвилі, аналіз їх переваг та обмежень, а також удосконалення підходів до моделювання навантажень і динамічної реакції споруд.

Результати. У роботі узагальнено та систематизовано основні методи розрахунку будівельних конструкцій на дію вибухово-ударної хвилі, зокрема квазістатичний метод, метод ударного імпульсу та метод прямого інтегрування рівнянь руху, що дозволило визначити їх області ефективного застосування. Запропоновано удосконалений підхід до моделювання навантаження від вибухово-ударної хвилі, який враховує просторово-часову дискретизацію тиску та послідовність проходження фронту хвилі по поверхні споруди. Результати дослідження можуть бути використані для вдосконалення нормативної бази у сфері проєктування конструкцій на особливі впливи.

Ключові слова: споруди інженерного захисту, фортифікаційні споруди, об'єкти критичної інфраструктури, фактори ураження, вибухово-ударна хвиля, будівельні конструкції.

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STRUCTURAL DESIGN UNDER BLAST LOADING: FROM SIMPLIFIED MODELS TO ADVANCED DYNAMIC ANALYSIS

Relevance. In the context of the full-scale war of russia against Ukraine, the issues of ensuring the reliability and survivability of buildings and structures under blast loading caused by aerial attack means, missile and artillery strikes, and other damaging factors are of particular relevance.

Modern engineering practice provides the use of several principal methods for analyzing structures under blast wave effects, among which the most widely applied are the quasi-static method, the impulse (shock impulse) method, and the direct integration method of the equations of motion.

Despite the availability of these methods, their practical application in the design of protective structures is complicated by the lack of generalized recommendations for selecting an appropriate calculation method depending on loading conditions, structural configuration, and the consequence class of the facility.

The aim of this study is to systematize existing methods for analyzing building structures under the action of blast waves, to examine their advantages and limitations, and to improve approaches to modeling loads and the dynamic response of structures.

Results. The work summarizes the main methods of calculating building structures for the effects of an blast-shock wave, the shock impulse method, and the method of direct integration of equations of motion, which allowed us to determine their areas of effective application. It was established that the quasi-static method is advisable to use at the initial stages of design to obtain engineering estimates, while the method of direct integration of equations of motion provides the most accurate results in a detailed analysis of the operation of structures under the action of a blast-shock wave. The results of the study can be used to improve the regulatory framework in the field of designing structures for special impacts.

Keywords: engineering defense structures, fortification structures, critical infrastructure objects, damage factors, blast-shock wave, building structures.

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Михайловський Д.В., Коцюруба В.І., Скляров І.О., Комар О.А. **Розрахунок конструкцій під вибуховим навантаженням: від спрощених моделей до розширеного динамічного аналізу** / Опір матеріалів і теорія споруд: наук.-тех. збірн. – К.: КНУБА, 2026. – Вип. 116. – С. 243-250. – Англ.

У роботі узагальнено та систематизовано основні методи розрахунку будівельних конструкцій на дію вибухово-ударної хвилі, зокрема квазістатичний метод, метод ударного імпульсу та метод прямого інтегрування рівнянь руху, що дозволило визначити їх області ефективного застосування. Запропоновано удосконалений підхід до моделювання навантаження від вибухово-ударної хвилі, який враховує просторово-часову дискретизацію тиску та послідовність проходження фронту хвилі по поверхні споруди..

Табл. 0. Іл. 4. Бібліогр. 19 назв.

UDC 624.01; 623.1/.3
Mykhailovskyi D.V., Kotsiuruba V.I., Skliarov I.O., Komar O.A. **Structural design under blast loading: from simplified models to advanced dynamic analysis** / Strength of materials and theory of structures: scientific and technical collection - Kyiv: KNUBA, 2026. - Issue 116. - P. 243-250.

The work summarizes and systematizes the main methods of calculating building structures for the effects of an blast-shock wave, the shock impulse method, and the method of direct integration of equations of motion, which allowed us to determine their areas of effective application. An improved approach to modeling the load from a blast-shock wave is proposed, which takes into account the spatio-temporal discretization of pressure and the sequence of the wave front passing over the surface of the structure.

Tabl. 0. Fig. 4. Ref. 19.

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