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SOME APPROACHES TO MODELLING BLAST WAVE IMPACT ON STRUCTURES IN LIRA-FEM

M.S. Barabash[1,2],
Doctor of Technical Sciences, Professor

O.V. Bashynskyi[3,4],
PhD, assistant

[1]*National aviation university, Kyiv*

[2]*LIRA-SAPR LTD*

[3]*National university of life and environmental sciences of Ukraine, Kyiv*

[4]*Kyiv national university of construction and architecture, Kyiv*

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Abstract. The article is devoted to the issues of automation of modelling of blast wave loads and analysis of structures of protective structures under the influence of blast loads. Several methods of building analysis for explosive dynamic loads are proposed. The analysis of the nature of blast wave propagation and impact on buildings, as well as methods of their finite element modelling in the LIRA-FEM with consideration of the time factor in the 'Time history analysis' module are performed.

Keywords: blast wave, stability, excessive pressure, dynamic load case, direct dynamic method, finite element method, nonlinear analysis, critical loads, plastic joints, force redistribution, LIRA-FEM.

Introduction. Due to active military operations in our country, the number of buildings and engineering structures exposed to blast waves is increasing every day. Providing a design engineer with a reliable and convenient tool for automating the process of collecting loads and performing analyses for various types of blast waves is an urgent task, especially for critical infrastructure facilities.

Usually, when designing buildings, the analysis of special dynamic loads is reduced to determining the safe impact pressure, exceeding which leads to the destruction of the building or structure.

In time of war, it becomes necessary to design public and industrial buildings to withstand the blast waves from explosions. The blast impact can lead to partial, significant or complete destruction of buildings. It is not possible to design a building's load-bearing structures to withstand all possible critical loads and impacts due to their uncertainty. However, it is possible to perform a numerical analysis of the structures of buildings and structures to predict their strength and stability in the event of emergency situations with explosions of different locations and intensities to prevent progressive destruction and complete collapse.

To determine the stress-strain state (SSS) of load-bearing structures under an external explosion, it is advisable to use software packages that implement the finite element method. An important factor when choosing a software package for strength analysis is the ability to perform the analysis by the direct dynamic method [1...5], since the load from explosions belongs to fast processes and has a clearly expressed dynamic character. The analysis by the direct dynamic method is similar to the analysis of unsteady thermal conductivity by the finite element method [6].

Analysis of recent research and publications. Works by M. S. Barabash [1-2], A. S. Horodetskyi [2], A.V. Perelmuter [7], V.P. Maksimenko, [3, 8], NemchynovYu.I. [9…11], S. Klovanich [12], foreign scientists H. Powell [13], J.R. Gilmore and K.S. Virdi [14], H. Kaevkulchai and E.B. Williamsonand A.J. Pretlov [15], M. Ramsden and AG Atkins [16] are devoted to the development of methods for preventing progressive destruction. These works show the influence of the dynamic effect during progressive destruction, which decreases with increasing plastic deformations. The article by scientists A.J. Pretlav, M. Ramsden and A.G. Atkins discusses the problem of the needing consider the dynamic redistribution of forces when calculating progressive destruction.

G. Kaewkulchai and EB Williamson prove the need to consider dynamic effects in applied problems. JR Gilmour and KS Virdi used a three-dimensional quasi-static nonlinear element to analyze the failure of a flat reinforced concrete frame. S. Klovanich proposed methods of ensuring the survivability of the building based on the dynamic calculation of a multi-story two-dimensional frame structure when the column of a certain floor is removed in two cases: the progressive destruction of a part of the building and the loss of the overall stability of the building.

From the analysis of scientific works, we can conclude that at present there is no unity in the views and methods of calculating structures for explosive effects. Not only are the methods for assessing the impact of damaging factors on buildings different, but also the calculated parameters of the blast wave.

In accordance with the requirements of building codes, certain types of building or engineering structures (e.g., protective structures, dual-purpose structures (DPS), etc.) are designed to take into account the impact of airborne blast waves on structures.

To simplify calculations, some standards [17...19] recommend that the enclosing and load-bearing structures of protective and dual-purpose structures be designed for a special combination of loads consisting of permanent, temporary loads and a static load equivalent to the action of a dynamic load from the impact of a shock wave (equivalent static load). Also, the standards [20] allow the use of direct dynamic analysis of structural systems for the dynamic effects of an airborne shock wave that cause significant acceleration of the structure.

The purpose of this article is to propose approaches to numerical modelling of the impact of an explosive blast wave on a building, to develop a methodology for automated collection of loads from the blast wave depending on the distance of the blast point and the blast force.

The main content. Let's consider airborne and ground explosions. The problem of the impact of a point explosion on load-bearing structures, taking into account backpressure, arises when the explosion occurs at a certain distance from the building and the pressure of the blast wave is comparable to the atmospheric pressure. During an airborne explosion, a spherical shock wave reaches the ground surface and is reflected from it (Fig. 1). At a certain distance from the explosion epicentre, the reflected wave front coincides with the incident wave front, resulting in the formation of a main wave with a vertical front that propagates from the epicentre along the ground surface.

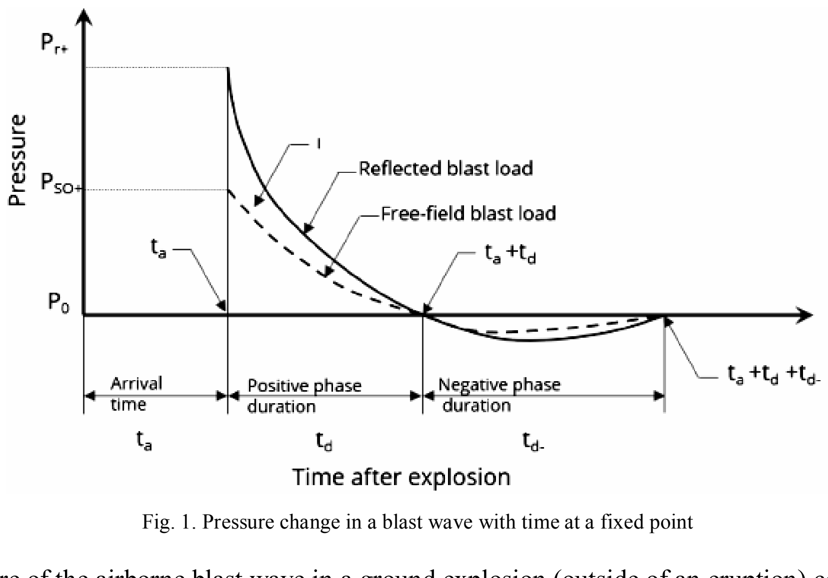

Fig. 1. Pressure change in a blast wave with time at a fixed point

The nature of the airborne blast wave in a ground explosion (outside of an eruption) corresponds to the far zone of an airborne explosion. Thus, both airborne and ground explosions typically produce an airborne shock wave that propagates from the epicentre in a vertical front.

From the moment the air shock wave front arrives at a point on the earth's surface, the pressure increases sharply to a maximum value of P_r, and then decreases to atmospheric P_0 and below atmospheric pressure. The period τ_+ of the increased overpressure (above atmospheric pressure) $\Delta P = P - P_0 > 0$ is the compression phase, and the period τ_- of the decreased pressure is the rarefaction phase $\Delta P < 0$. Simultaneously with the pressure in the shock wave, air moves from the epicentre of the explosion. The patterns of change in the mass velocity υ and density ρ of the medium in time are similar to the change in pressure, but due to the inertia of the air flow, the period τ_{+ck} of the positive phase of the velocity pressure $P_{ck} = ½\rho v^2 > 0$ is slightly longer than τ_+. The overpressure in the wave and the velocity pressure are the most important characteristics of the shock wave that determine the effect of its impact on the structure.

Since explosive processes are non-stationary, it is necessary to be able to determine their dynamic characteristics, taking into account the complex blast-wave interaction of the airborne blast wave as a destructive factor for a building structure. The complexity of this task requires the expansion of the arsenal of modern analysis methods by means of new approaches to determining the shape of the force pulse transmitted to the building structure from the blast wave.

The graph in Figure 1 shows key parameters such as:

P_r or P_{so} - is the maximum excessive pressure value achieved after an explosion.

t_a - time to reach peak pressure. The time interval from the start of the explosion to the maximum pressure.

t_d - duration of the positive phase (compression zone). The time interval from the moment the peak pressure is reached until the pressure returns to atmospheric level.

I - positive impulse. The total amount of energy transferred by a blast wave per unit area during the positive phase. In other words, it is the area under the pressure curve during the positive phase when the pressure is above atmospheric level.

t_d - duration of the negative phase (rarefaction zone). The time interval during which the pressure drops below atmospheric pressure after the initial peak. Accordingly, the negative impulse of the explosion is defined as the integral (area under the curve) of the negative phase of the explosion pressure time graph. This impulse reflects the magnitude and duration of the pressure drop during the negative phase.

The graph (Fig. 1) shows two curves. The reflected blast load is shown as a solid line. And the lateral blast load is shown by the dashed line. The lateral blast load (the load from an open space explosion) is denoted by the index "so". This is the pressure created by a blast wave in an open space, without taking into account the effect of obstacles or structures that may modify or reflect the shock wave. This load is applied to surfaces that are parallel to the direction of the airborne blast wave and along which the wave moves without obstacles (i.e., flow). These can be side walls and coverings that are not directly in the direct blast zone.

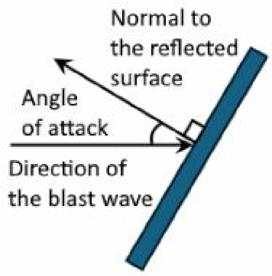

Fig. 2. Reflected angle of incidence of the blast wave

When a blast wave strikes a non-parallel inclined surface, a reflected blast load is produced, which is denoted by the index "r". A good example in this case would be any surface perpendicular to the blast wave, such as a front façade wall. Reflective surfaces of buildings in such cases increase the pressure and, as a result, the momentum. Obviously, there will be much higher pressure than when the wave passes over a parallel surface.

Figure 2 shows how the angle of incidence can be calculated, considering the initial direction of the blast wave and the wave reflected from this surface in the normal direction.

The main parameters that determine the intensity of the blast wave are the overpressure at the wave front ΔP_r and the duration of the compression phase t_d. These parameters depend on the mass of the explosive (i.e. the explosive energy in TNT equivalent), the height, the explosion conditions and the distance from the explosion epicentre to the structure. The mass of the explosive depends on the type of explosive device or the type of weapon (bomb, missile, drone, projectile).

The study of high-speed deformation processes characteristic of pulsed loading is of great interest in connection with the development of a general theory of material behaviour under load, taking into account its rheological properties. A distinctive feature of impulsive loading is the high level of stress in the material, which acts over a short period of time and determines a high rate of change in load over time, and hence a high rate of deformation.

The deformed state of a structural element under loading is an integral process of deformation of local volumes of material in accordance with a time-varying stress state. Due to the non-stationary nature of stress fields and the complexity of the shape of real structural elements, the calculation of stress and strain fields requires the use of numerical methods. It is assumed that the material goes into a plastic state taking into account the dynamic yield strength:

$$\sigma_i \geq \sigma_T^D \; \sigma_T^D = \sigma_T\left[1+(e_i/D^*)^{1/n^*}\right], \tag{1}$$

where σ_i, e_i – stress intensity and strain rate; σ_T, D^*, n^* – material parameters. The parameters at the blast wave front are determined from the following expressions if P is a known value (or): ΔP

$$v = \frac{c_0 \Delta P_r' \gamma^{-1}}{\sqrt{1+\frac{1}{2}\Delta P_r'(\gamma+1)/\gamma}}, \tag{2}$$

where v – speed of the blast wave front;

$$D = c_0\sqrt{1+\frac{1}{2}\Delta P_r'(\gamma+1)/\gamma}, \tag{3}$$

where D – speed of propagation of the blast wave front;

$$\rho = \frac{\rho_0\left[1+\frac{1}{2}\Delta P_r'(\gamma+1)/\gamma\right]}{\left[1+\frac{1}{2}\Delta P_r'(\gamma-1)/\gamma\right]}, \tag{4}$$

where ρ – density of the blast wave front, c_0 – the speed of sound in the atmosphere, $\Delta P_r' = \Delta P_r / P_0$.

High-speed pressure of the blast wave:

$$P_{rv} = \frac{1}{2}\rho_r v^2 = \frac{\Delta P_r \Delta P_r'}{\left[(\gamma-1)\Delta P_r' + 2\gamma\right]}. \tag{5}$$

The temperature T at the blast wave front is determined by the formula:

$$T = \frac{T_0(1+\Delta P_r')\rho_0}{\rho}. \tag{6}$$

In such conditions, the material behavior is no longer linear, and standard linear models can no longer accurately describe the behavior of the structure.

The building code UFC 3-340-02 [20] provides a methodology for determining the parameters of a blast wave. This method is based on the Kingery-Bulmash method [21] and consists in determining the value of the scaled coefficient Z and based on this coefficient, the blast wave parameters are selected according to Figure 3.

$$Z = \frac{R}{\sqrt[3]{W}}, \tag{7}$$

where Z – scalable distance; R – distance from the explosion epicentre to the structure, ft; W – weight of explosive in TNT equivalent, lb.

According to the graph in Figure 3, we determine the values of the following parameters: P_r (reflected peak pressure), P_{so} (lateral peak pressure), I_r (reflected pulse), I_s (lateral impulse), t_a (time of approach of the blast wave), t_o (duration of the exponential load), U (speed of the blast wave front).

A special algorithm has been developed in LIRA-CAD (Fig. 4) to automate the creation of design models and quickly calculate various options for blast wave impact. It is built into the Generator system, which is based on parametric modelling and visual programming using nodes. The calculation of excessive pressure values on structural elements is performed in accordance with [20].

Let's consider the main stages of building an explosive impact model (Fig. 5):

– Determining the means of destruction and the position of the explosion epicentre. To set the impact properties, you need to go to the appropriate interface implemented in LIRA-CAD in the Calculations panel. The main parameters for the analysis are: charge mass in metric tonnes, selection of the explosion position (in the air or on the surface), setting the step for approximating the overpressure distribution function, and selecting the load number;

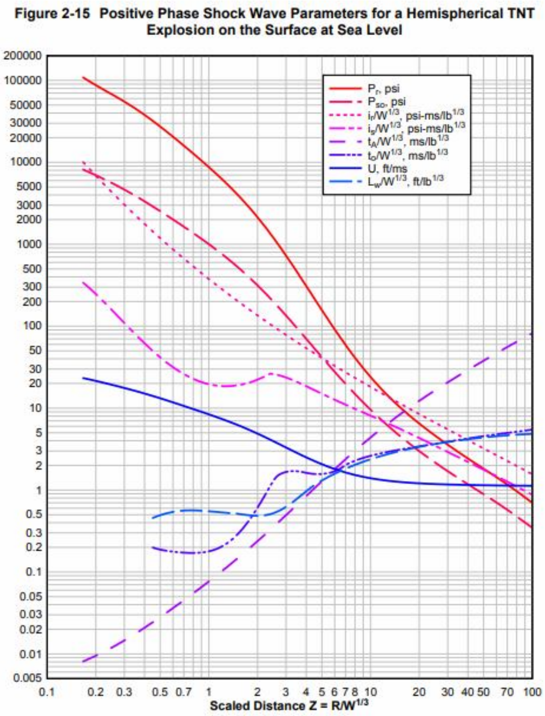

Fig. 3. Parameters of the positive phase of the blast wave for surface explosions

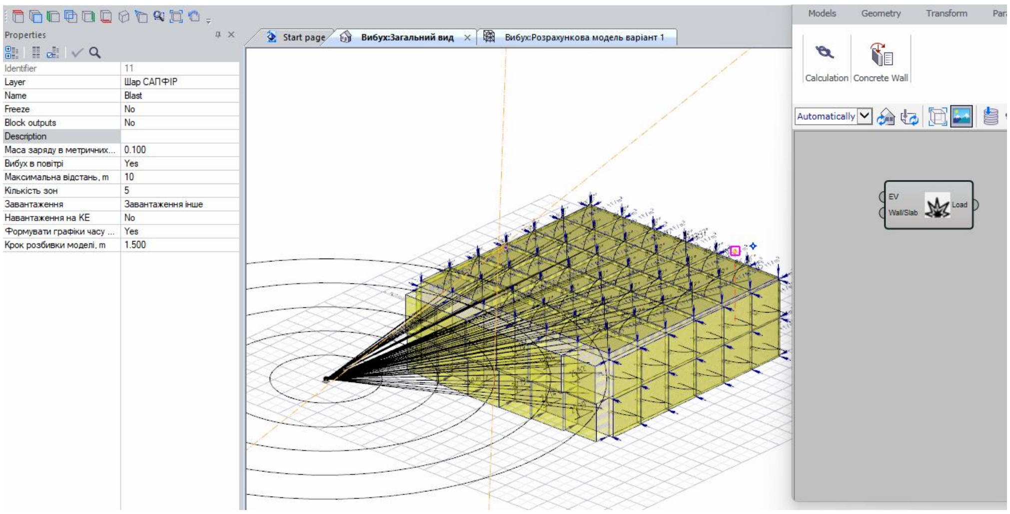

Fig. 4. Creation of a model of loads on a plate structure under the action of a blast wave in LIRA-FEM

– The position of the epicentre of the explosion is determined by the position of the point selected by the user and fed to the input of the corresponding node. This position will affect the definition of the scaled distance function, in the form of empirical parametric explosion curves (Fig. 3).

– According to the location of the epicentre, the reflected angle of incidence of the blast wave on the surface of each structural element is determined (Fig. 2). The following equation is used to determine the value of the reflected pressure P_r:

$$P_r = C_r P_{so}, \tag{8}$$

where P_{so} – the tangential pressure (pressure acting parallel to the surface of the object), and C_r – is a coefficient that takes into account the reflection of the airborne blast wave. C_r is a function of the angle of incidence and the tangential pressure. Figure 2 shows how the angle of incidence can be calculated given the initial direction of the blast wave and the wave reflected from this surface in the normal direction.

– Determination of the graph of explosion pressure change in time. For the purpose of this calculation, the idealised graph of explosion pressure over time (Fig. 1) shown above was simplified to a triangular distribution with an instantaneous rise and a linear decline in the positive phase (Fig. 5). It is important that the values of peak pressure and momentum are preserved (momentum is the area under the curve). Therefore, we find the conditional time interval using the formula:

$$t_e = 2(I/P). \tag{9}$$

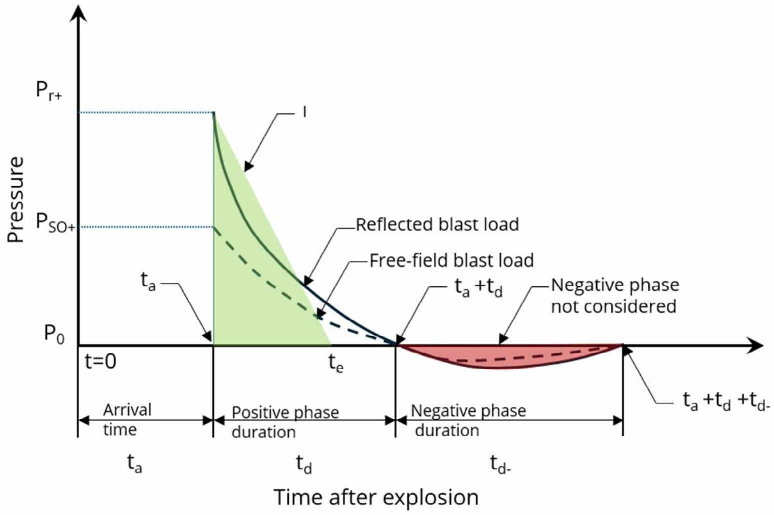

Fig. 5. Simplified graph of pressure change during an explosion

To simplify the analysis of simple structures, the negative phase is often ignored because its contribution to the blast wave impact is negligible. However, considering the negative phase of the blast wave in the calculations helps to provide more accurate and reliable results, which contributes to the creation of safe and stable structures. For example, the negative phase should not be neglected in the design of structures sensitive to alternating loads, as it creates reverse loads that can be critical for such structures.

After the model is transferred to LIRA-FEM, the software automatically applies loads to each finite element of the structure with the specified dynamic time law for each load. To do this, we apply a static load evenly distributed over the area normal to the surface of the front, side and rear walls, as well as the pavement, and convert it to a dynamic load. To convert the impact of a shock wave into a dynamic load, the corresponding graphs of pressure changes over time are set (Fig. 6). The load values from this graph will be automatically multiplied by the number specified as the static load intensity, in our case, by 1 psi (lb/inch²).

Fig. 6. Pressure versus time plot for the wall facing the explosion

The dynamic impact of the blast wave is calculated in the "Time history analysis" system. In this subsystem, the integration parameters are set - integration step and time, number of integration step fractions, and the required composition of the calculation results - displacement only; displacement and force; displacement, force and DCF/displacement, force and DCL.

The weights of the masses are obtained using transformations from static loads.

The integration time should be several times longer than the blast wave duration to allow time to assess the system behaviour and oscillation damping.

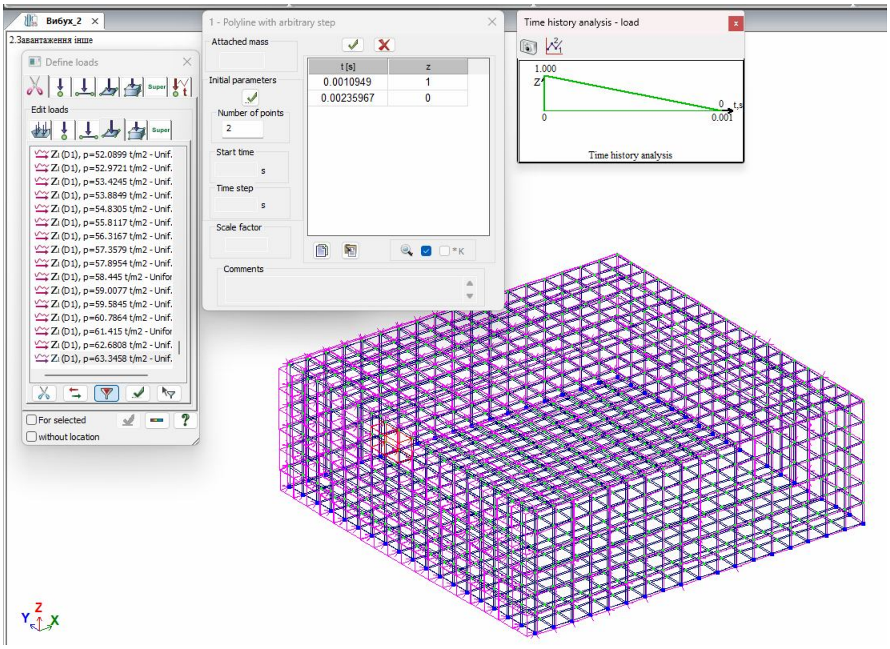

Fig. 7. Automatic collection of loads on elements with a given dynamic impact rule for analysis by the direct dynamic method

Thus, the algorithm for analysing structures against the impact of an explosive blast wave using the direct dynamic method can be represented as follows (Fig. 8).

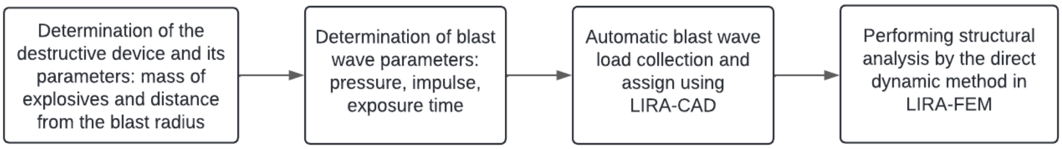

Fig. 8. Algorithm for analysis of structures under the influence of an explosive blast wave by the direct dynamic method

Conclusion. Thanks to the proposed approaches to modelling blast waves on the structures of buildings and structures, it is possible to improve safety by predicting the effects of blast waves using numerical methods.

Methods and algorithms implemented in the LIRA-FEM software allow performing analyses of objects of any complexity, taking into account strength and deformation criteria of performance, nonlinear behavior of materials, dynamic characteristics of soil, dampers, processes of change of stress-strain state of structures during their life cycle and under the influence of various loads and situations, including force majeure, such as modeling of dynamic effects of different nature and character, including processes occurring in structures as a result of critical loads, such as seismic, pulse and explosive.

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Барабаш М.С., Башинський О.В.

ДЕЯКІ ПІДХОДИ ДО МОДЕЛЮВАННЯ ВПЛИВУ ВИБУХОВОЇ ХВИЛІ НА КОНСТРУКЦІЇ В ПК ЛІРА-САПР

Стаття присвячена методиці моделювання розрахунку конструкцій на дію динамічних навантажень, що викликані впливом вибухової хвилі, та детально розглядає процес прикладення цих динамічних навантажень до будівельних конструкцій у програмному комплексі ЛІРА-САПР (LIRA-FEM). У цій статті описуються основні етапи проведення розрахунків, починаючи від обчислення основних параметрів вибухової хвилі, до збору і прикладання динамічних навантажень на елементи конструкції для виконання розрахунку прямим динамічним методом.

Одним із ключових аспектів статті є визначення основних параметрів вибухової хвилі, які впливають на величину та природу дії навантажень від вибуху. До таких параметрів належать піктиску, тривалість дії вибухової хвилі, імпульс

вибухово хвилі, а також форма фронту хвилі. У статті розглядаються типові значення цих параметрів в залежно від умов вибуху, таких як тип вибухової речовини та відстань до епіцентру вибуху.

Надано перевагу моделюванню дії вибухових навантажень на конструкцію як динамічний вплив. Такий вплив може призводити до значних деформацій конструкцій та відкрити додаткові особливості роботи конструкції.

У статті також описано послідовність розрахунку конструкцій на вибухові навантаження, яка включає кілька етапів. Першим кроком є визначення типу вибухового пристрою та його параметрів, а також відстань від епіцентру вибуху до конструкції. Далі обчислюються величини статичного навантаження (тиску) від вибухової хвилі та прикладають до елементів конструкції. Наступним кроком є задання динамічних параметрів вибухової хвилі, що визначаються за допомогою спеціальних методик або нормативних документів. На завершальному етапі виконуються розрахунки з використанням модуля «Динаміка в часі» програмного комплексу LIRA-FEM, що дозволяє враховувати динамічні ефекти та оцінювати поведінку конструкції в процесі дії вибухової хвилі.

Ключові слова: вибухова хвиля, стійкість, надлишковий тиск, динамічне навантаження, прямий динамічний метод, метод скінченних елементів, нелінійний аналіз, критичні навантаження, пластикові з'єднання, перерозподіл сил, LIRA-FEM.

Barabash M.S., Bashynskyi O.V.

SOME APPROACHES TO MODELLING BLAST WAVE IMPACT ON STRUCTURES IN LIRA FEM

The article is devoted to the methodology of modeling the calculation of structures for the action of dynamic loads caused by the impact of a blast wave and considers in detail the process of applying these dynamic loads to building structures in the LIRA-FEM software. This article describes the main stages of the calculations, starting from the calculation of the main parameters of the blast wave to the collection and application of dynamic loads to structural elements to perform the calculation by the direct dynamic method.

One of the key aspects of the article is to determine the main parameters of the blast wave that affect the magnitude and nature of the effects of the explosion loads. These parameters include pressure peak, blast wave duration, blast wave impulse, and wave front shape. The article discusses the typical values of these parameters depending on the explosion conditions, such as the type of explosive and the distance to the explosion epicenter.

The preference is given to modeling the effect of explosive loads on a structure as a dynamic impact. Such an impact can lead to significant deformations of structures and reveal additional features of the structure.

The article also describes the sequence of analysis of structures for explosive loads, which includes several stages. The first step is to determine the type of explosive device and its parameters, as well as the distance from the epicenter of the explosion to the structure. Next, the static load (pressure) from the blast wave is calculated and applied to the structural elements. The next step is to set the dynamic parameters of the blast wave, which are determined using special methods or regulatory documents. At the final stage, calculations are performed using the Time Dynamics module of the LIRA-FEM software package, which allows taking into account dynamic effects and assessing the behavior of the structure during the blast wave action.

Keywords: blast wave, stability, excessive pressure, dynamic load case, direct dynamic method, finite element method, nonlinear analysis, critical loads, plastic joints, force redistribution, LIRA-FEM.

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Барабаш М.С., Башинський О.В. **Деякі підходи до моделювання впливу вибухової хвилі на конструкції в LIRA-FEM** // Опір матеріалів і теорія споруд: наук.-техн. збірник – К.: КНУБА, 2024. – Вип. 113. – С. 241-249. – Англ.
Визначається методика моделювання впливу вибухового навантаження на конструкції.
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The methodology for modeling the blast load impact on structures is determined.
Fig. 8. Ref. 21.

Автор (науковийступінь, вченезвання, посада): доктор технічних наук, професор, професор кафедри комп’ютерних технологій будівництва та реконструкції аеропортів НАУ Барабаш Марія Сергіївна.
Адреса: 03058 Україна, м. Київ, проспект Гузара Любомира 1, Національний авіаційний університет.
Робочий тел.: +38(044) 406-79-01
Мобільний тел.: +38(095) 286-39-90
E-mail: bmari.lira@gmail.com
ORCID ID: https://orcid.org/0000-0003-2157-521X

Автор (науковийступінь, вченезвання, посада): доктор філософії, ассистент кафедри будівництва НУБІП, ассистент кафедри металевих та дерев’яних конструкцій КНУБА, Башинський Олексій Володимирович.
Адреса робоча: 03041, Україна, м. Київ, вул. Героїв Оборони, 15, Національний університет біоресурсів і природокористування України;
03680 Україна, м. Київ, проспект Повітряних сил 31, Київський національний університет будівництва і архітектури.
Робочий тел.: +38(093) 766-46-76
E-mail: alex.bashinsky97@gmail.com
ORCID ID: https://orcid.org/0000-0003-2466-4306