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BASIC CALCULATIONS OF DYNAMIC INTERACTION OF MECHANICAL SYSTEMS OF MODULAR SHELTERS ARE IMPLEMENTED IN THE LS-DYNA PROGRAM

The article presents a basic mathematical model of the explicit method for calculating dynamic systems of deformed bodies in the mathematical calculation of modular shelters. The subject of research is the solution of the problem of sample deformation in the formulation of the motion of a deformed body as a dynamic system for studying the stability of modular shelters. The purpose of the work is to use basic mathematical models of the explicit method of calculating dynamic systems to determine finite element approximations of the basic equations of these mechanical systems to ensure safe operating conditions for modular shelters. To achieve this goal, the following research tasks have been set: solving the problem of sample deformation in the formulation of the motion of a deformed body as a dynamic system; use of finite element approximation of the basic equations of the mathematical model; use of an explicit method of calculating the dynamics equations; development of a calculation scheme for the contact interaction of two deformed bodies when they touch; application of the method of mathematical modeling of crack propagation in a material. The scientific novelty of the study lies in the creation of a calculation basis for assessing the preservation of protective functions by the enclosing structures of modular shelters under the influence of explosions and impulse actions. After carrying out the calculations, the main results were obtained, which allow using mathematical modeling to investigate the physical and mechanical processes occurring in the structures of modular shelters, which will later become the scientific basis for improving the existing and creating a new regulatory framework for the arrangement of modular shelters.

Keywords: *Modular Shelter, Deformed Bodies, Mathematical Modeling, Finite Elements, Dynamics Equations.*

Statement of the problem. Modern construction and foreign construction experience make it possible to design ground-based modular shelters. This significantly reduces the time people have to take cover during shelling. This makes it urgent to modernize and improve existing or install new protective shelters, which would meet the modern conditions of dense urban development of large cities. To do this, it is necessary to develop and improve the appropriate regulatory framework, taking into account the generalized practical experience gained during the war.

The results of the study of the behavior of the main structural elements of modular shelters are the classification of the impacts on them. They are caused by explosions and the pulse action of warheads, and by the scattering of debris and fragments of building structures. When calculating the enclosing and supporting elements of ground-based protective shelters, it is necessary to take into account permanent, temporary and statistical loads equivalent to the action of the dynamic load from the action of an air shock wave (equivalent static load). In addition, the structures are checked by calculation taking into account the most unfavorable combinations of loads or the corresponding forces during the operation of storage facilities in peacetime. Also, on the resulting forces and maintaining the tightness of the storage facilities in the event of possible settlements of individual loaded supports (columns) of the storage facilities from the operational load of the above-ground part of the building or structure.

Analysis of recent achievements and publications. The significant amount of theoretical and experimental research on protective structures has been carried out by the following researchers: Kaftan O., Garnyk V., Gogol T., Nekora V., Nizhnyk V., Pozdeev S., Shibunko O., Duzhak A., Kyreykov O., Kiselyuk Yu., Klymenko E., Aagaard B., Hallquist J., Belytschko T., Chiapetta R., Bartel H., Murray Y. та інші [1–8]. It is worth considering that the enclosing and supporting structures of shelters are calculated as a special combination of loads, such as permanent, temporary and static loads equivalent to the action of the dynamic load from the action of an air shock wave. Also, the studies were limited to the excess pressure of the explosion from the protective structure and the protection factor (attenuation of ionizing radiation). Experimental studies of the safety of modular protective shelters in military operations are quite difficult to conduct, given the increased danger, high cost, and complexity of construction, preparation, and conducting full-scale fire tests. Therefore, in this case, the use of mathematical modeling to study the physical and mechanical processes occurring in the enclosing structures of shelters is relevant.

Presentation of the main research material.

1. Basic mathematical model of the explicit method of calculating dynamic systems of deformed bodies. The formulation of the motion of a deformed body as a dynamic system is the basis of calculations for solving the problem of sample deformation. In the presented form, the diagram of a separate deformed solid body, determined at the initial moment of time and in the initial state t = 0 shown in fig. 1. The separate rigid deformed body has an initial volume Ω_0, which is limited by a surface G_0. At the current moment in time in the current body position t the volume acquired by the body is denoted as Ω, with boundary surface G. Body in motion movement from a standing position Ω_0 in position Ω, with coordinates of an arbitrary point X, which in the initial position belongs to a body with volume Ω_0, when it gains volume, it will belong to the same body Ω with coordinates at the current position x.

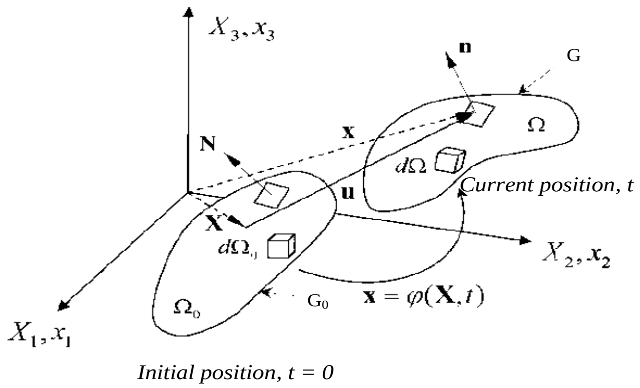


Figure 1 – The initial undeformed state and the current deformed state of a rigid body during its motion

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 laws of conservation in accordance with the work Belytschko, Flangan and other [8 – 10].

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

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

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 a body through a given point;
$\ddot{x}_i$ – acceleration of a given point belonging to the body.

The equation of conservation of mass is written as the following formula:

$$\rho \cdot \det(J) = \rho_0, \tag{2}$$

where
ρ_0 – density of the body material in the undeformed initial state;
$\det(J)$ – determinant of the tangential stiffness matrix (Jacobian).

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

$$P^{\mathrm{int}} + P^{\mathrm{kin}} = P^{\mathrm{ext}} + P^{\mathrm{heat}}. \tag{3}$$

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

$$P^{\mathrm{kin}} = 0.5 \frac{d}{\mathrm{dt}} \int_{\Omega} \rho v \cdot v d\Omega\,. \tag{4}$$

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

$$P^{\mathrm{ext}} = \int_{\Omega} v \cdot \rho b d\Omega + \int_{G} v \cdot t\, d\Gamma. \tag{5}$$

In the absence of internal and external sources of thermal energy, the energy conservation equation according to works [5–10] takes the form:

$$\frac{d}{\mathrm{dt}} \int_{\Omega} \rho w^{\mathrm{int}} + (0.5 \rho v \cdot v) d\Omega = \int_{\Omega} v \cdot \rho b d\Omega + \int_{G} v \cdot t\, \mathrm{dG}. \tag{6}$$

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

$$\rho \dot{w}^{\mathrm{int}} = 0.5 \sigma_{\mathrm{ij}} \left[\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right]. \tag{7}$$

The boundary conditions limiting the motion of a rigid deformed body are written as the formula:

$$\sigma_{\mathrm{ij}} n_j = t_i(t), \tag{8}$$

where n_j – the normal vector to the boundary surface of a solid deformed body, directed outward.

Regarding the boundary conditions that establish the deformation parameters on the boundary surface of a solid deformed body, the formula can be written:

$$x_i(X,t) = \bar{x}_i(t). \tag{9}$$

If contact interaction between deformed bodies is initiated, the compatible boundary conditions take the following form:

$$\left(\sigma_{\mathrm{ij}}^{+} - \sigma_{\mathrm{ij}}^{-}\right)n_j = 0. \tag{10}$$

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

$$\int_{\Omega}\left[\rho\ddot{x}_i + \sigma_{\mathrm{ij},j} - \rho f_i\right]\delta x_i d\Omega + \int_{G_f}\left[\sigma_{\mathrm{ij}} n_j - t_i\right]\delta x_i \mathrm{dG} + \int_{G_c}\left(\sigma_{\mathrm{ij}}^{+} - \sigma_{\mathrm{ij}}^{-}\right)n_j\, \delta x_i \mathrm{dG} = \tag{11}$$

The sum of possible works must be equal to zero, performing certain transformations of equation (11), the latter can be written as a modified expression [8–12]:

$$\int_{\Omega}\rho\ddot{x}_i\delta x_i d\Omega + \int_{\Omega}\sigma_{\mathrm{ij},j}\delta x_i d\Omega - \int_{\Omega}\rho f_i \delta x_i d\Omega - G - \int_{G_c} t_i^c \delta x_i \mathrm{dG} = 0\,. \tag{12}$$

2. Finite element approximation of the basic equations of the mathematical model of the dynamic interaction of mechanical systems. The equation for interpolating the distributions of the corresponding data in the internal space bounded by the boundaries of the finite element has the following form:

$$x_i(X,t) = \bar{x}_i(X(\xi,\eta,\zeta),t) = \sum_{j=1}^{m}\varphi_j(\xi,\eta,\zeta)x_i^j\,(t), \tag{13}$$

where

ϕ_j – parametric shape function (parameters ξ, η, ζ);

m – number of nodes according to the geometric shape of the finite element;

x_i^j – current node coordinate along a given coordinate axis.

The potential energy for possible displacements relative to the finite element takes the form:

$$\delta\Pi_e = \int_{\Omega_e}\rho\ddot{x}_i\Phi_i^e d\Omega + \int_{\Omega_e}\sigma_{\mathrm{ij}}\Phi_{\mathrm{ij}}^e d\Omega - \int_{\Omega_e}\rho f_i\Phi_i^e d\Omega - \int_{G_e} t_i\Phi_i^e \mathrm{dG}\,. \tag{14}$$

де $\Phi_i^e = (\varphi_1, \varphi_2, \ldots, \varphi_k)_i^e$.

The principle of virtual displacements must be applied to the entire set of finite elements. With this approach, the equation of conservation of the total energy of the body, with the superimposed finite element mesh, is written as the formula:

$$\sum_{e=1}^{\mathrm{en}}\left[\int_{\Omega_e}\rho\ddot{x}_i\Phi_i^e d\Omega + \int_{\Omega_e}\sigma_{\mathrm{ij}}\Phi_{\mathrm{ij}}^e d\Omega - \int_{\Omega_e}\rho f_i\Phi_i^e d\Omega - \int_{G_e} t_i\Phi_i^e \mathrm{dG}\right] = 0. \tag{15}$$

In matrix form for finite elements, equation (15) takes the form:

$$\sum_{e=1}^{\text{en}}\left[\int_{\Omega_e}\rho N^T N a_e d\Omega+\int_{\Omega_e}B^T\sigma d\Omega-\int_{\Omega_e}\rho N^T b d\Omega-\int_{G_e}N^T t\mathrm{dG}\right]=0, \quad (16)$$

where
N – interpolation matrix by parametric functions of the finite element shape;
σ – tension vector;
B – stiffness matrix;
$\mathbf{a_e}$ – node acceleration vector;
b – vector of loads a vector of traction forces t nodes;
t – vector of traction forces.

3. Mathematical model of contact interaction. Fig. 2., shows a calculation diagram of the contact interaction of two deformed bodies when they touch. And further mutual penetration during their movement.

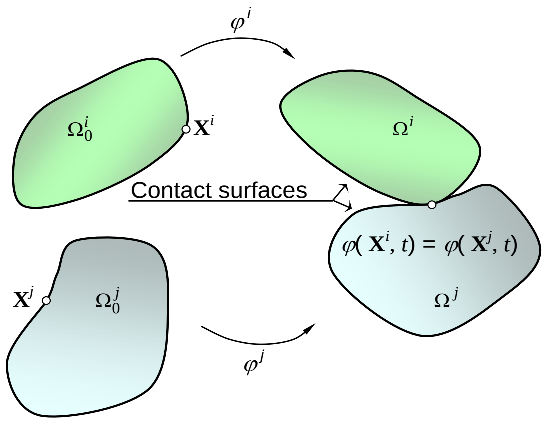


Figure 2 – Scheme of contact interaction between solid deformed bodies

To identify the moment of the beginning of the contact interaction of two contacting bodies, the fulfillment of the Hertz-Signorini-Mohr condition is recorded. [5 – 10]:

$$g\geq 0,\ \lambda\geq 0,\ g\lambda\geq 0, \quad (17)$$

where g – the gap value, calculated by the expression:

$$g(x^i,t)=(x^i-x^j)^T n. \quad (18)$$

The scheme for identifying the geometric parameters of bodies in contact with each other is shown in Fig. 3.

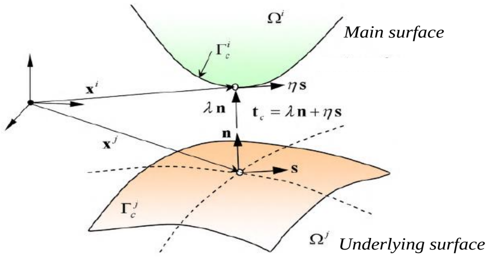


Figure 3 – Scheme for identifying geometric parameters of contact surfaces of solid deformed bodies

To introduce friction forces into the mathematical model during contact interaction, the generalized Coulomb's law is used. Under these conditions, the tangential velocity modulus is determined by the formula:

$$\dot{u}(x^i, t) = \left(\dot{u}^i - \dot{u}^j\right)^T s. \tag{19}$$

The expression for the generalized Coulomb's law takes the following form::

$$\begin{aligned} &|\,|\tau| \le 1 \\ &|\text{if } |\tau| < 1 \text{ is accepted } \dot{u} = 0 \\ &|\text{at } |\tau| < 1 \text{ is accepted } \operatorname{sign}(\dot{u}) = \operatorname{sign}(\tau) \end{aligned} \tag{20}$$

The parameter τ is calculated by the formula:

$$\tau = \frac{\eta}{\mu\lambda}, \tag{21}$$

where μ - coefficient of friction forces.

The penalty function method and the Lagrange multiplication method are used for mathematical modeling of the contact interaction between the boundary surfaces of finite elements. [8 – 12]. To describe the interaction between segments of a finite element surface limited to four nodes, the following computational procedure algorithm is used:

1. A pair of "subordinate node – master segment" finite elements is defined, adjacent to the surfaces of the body with the determination of compliance with the condition of the position of the projection of the subordinate node onto the main segment of the finite element in the first or fourth quadrant of the local coordinate system of the main segment. The corresponding projection of a node onto a segment is considered a contact point, and the distance between the subordinate node and the contact point is the projection distance. When analyzing a node and a segment together, the area of the segment is increased by a small amount (about 2%) to increase the reliability of the contact algorithm calculations.

2. Get a set of coordinates of a contact point in the local system associated with the main segment.

3. The projection distance in the local system associated with the main segment is calculated.

4. When the condition of negativity of the projection distance is met, it is perceived as the penetration depth and the force applied to the subordinate node is determined by the obtained value and calculated by the formula [1 – 6]:

$$f_s = K_c \cdot \delta, \tag{22}$$

where
f_s – contact force applied at the point of contact;
K_c – contact stiffness;
δ – penetration depth.

5. At the nodes of the main segment, contact forces are determined as a function of the shape of the finite element, which depend on the location of the contact point in the local coordinate system of the main segment. The equations to describe the shape function of the finite element are given below [5 – 10].

$$f_m^i = N_i(\xi,\eta) \cdot f_s, \quad \text{where} \quad \{N_1 = 0.25(1+\xi)(1+\eta)| \quad \{N_2 = 0.25(1+\xi)(\tag{23}$$

The contact stiffness is obtained by the formula:

$$K_c = \frac{f_s A^2 k}{V_e}, \tag{24}$$

where
f_s – penalty factor value
A – surface area of the main segment;
k – bulk modulus of elasticity;
V_e – volume of the finite element, with a given segment.

4. Explicit numerical method for approximating dynamics equations. The determination of the values of the velocities of the nodal points of finite elements when using the explicit method of calculating the equations of dynamics is carried out using the expression [8, 10, 12]:

$$v^{n+0.5} = (u^{n+1} - u^n)/\Delta t^{n+0.5} \Rightarrow u^{n+1} = u^n + \Delta t^{n+0.5} v^{n+0.5}. \tag{25}$$

The calculation of the displacements of the nodes of the finite elements is carried out using the equation:

$$x^{n+1} = x^0 + u^{n+1}. \tag{26}$$

The basic equation for determining the accelerations of the nodes of finite elements when approximating the time derivative using finite differences is the expression:

$$a^n = (v^{n+0.5} - v^{n-0.5})/\Delta t^n \Rightarrow v^{n+0.5} = v^{n-0.5} + \Delta t^n a^n. \tag{27}$$

Using the above formulas, the equation takes the form:

$$Ma^n = F^n, \qquad F^n = \sum_{e=1}^{\text{en}} (F_e^{\text{ext}} - F_e^{\text{int}}). \tag{28}$$

The accelerations of the finite element nodes are determined by solving a system of linear algebraic equations using matrix inversion **M**:

$$a^n = M^{-1}F^n. \tag{29}$$

At each integration step, the time step is determined using the Courant-Friedrichs-Lévy number, which is calculated by the expression:

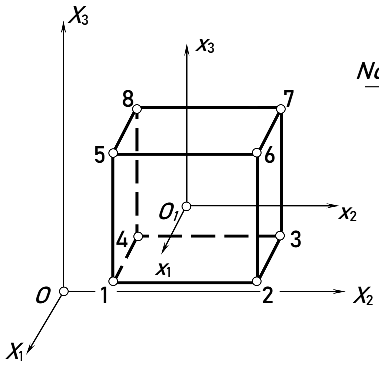
$$\Delta t \leq \Delta t_{\text{crit}} = \min \frac{l_e}{c_e}, \tag{30}$$

this c_e – the number obtained by the formula:

$$c_e = \sqrt{E_e/\rho_e}, \tag{31}$$

where l_e – spatial step of the finite element mesh model.

To model the stress-strain state in concrete, a hexahedral SOLID finite element with eight nodal points is used. The geometric configuration of an element of this type is shown in Fig.4.



Node	ξ	η	ζ
1	-1	-1	-1
2	1	-1	-1
3	1	1	-1
4	-1	1	-1
5	-1	-1	1
6	1	-1	1
7	1	1	1
8	-1	1	1

Figure 4 – Geometric configuration of a hexahedral finite element of type SOLID with eight nodal points

For a given type r, the finite element expression for calculating the coordinates of the shape nodes is written as:

$$x_i(X,t) = \bar{x}_i(X(\xi,\eta,\zeta),t) = \sum_{j=1}^{8} \varphi_j(\xi,\eta,\zeta)x_i^j(t), \tag{32}$$

this ϕ_j – parametric function of the shape of the finite element for the j-th node, which for a finite element of type SOLID is described by the equation:

$$\varphi_j = 0.125(1+\xi\xi_j)(1+\eta\eta_j)(1+\zeta\zeta_j). \tag{33}$$

Parameters ξ_j, η_j, ζ_j are determined according to the scheme in Fig.4.

For the described type of finite element, the matrix of interpolation functions of the form is written in terms of the matrix equation:

$$N(\xi,\eta,\zeta)=\begin{bmatrix}\varphi_1 & 0 & 0 & \varphi_2 & 0 & \cdots & 0 & 0\\ 0 & \varphi_1 & 0 & 0 & \varphi_2 & \cdots & \varphi_8 & 0\\ 0 & 0 & \varphi_1 & 0 & 0 & \cdots & 0 & \varphi_8\end{bmatrix}, \tag{34}$$

The components of the stress state are written as a vector:

$$\sigma=(\sigma_x \quad \sigma_y \quad \sigma_z \quad \tau_{\mathrm{xy}} \quad \tau_{\mathrm{yz}} \quad \tau_{\mathrm{zx}})^T, \tag{35}$$

The finite element has the form corresponding to Belichko-Tsaya [1, 2], which is based on the description of the process of dynamic interaction in a given element in the form of a combination of rotation and linear displacement of points together with deformation. The effectiveness of using this type of finite element lies in the mathematical simplification as a result of two given kinematic assumptions when introducing a local coordinate system associated with this type of finite element. The strain rate is related to the Cauchy stress tensor. Writing this formula allows you to bypass the complexity of calculations, provided that the nonlinearity of the deformation is taken into account.

To establish basic geometric and force relationships in a finite element of the Belichko-Tsaya shell type, a local coordinate system is introduced. $(\hat{x},\hat{y},\hat{z})$, whose unit vectors $\hat{e}_1,\hat{e}_2,\hat{e}_3$ are installed according to the diagram in Fig. 5 [1, 2].

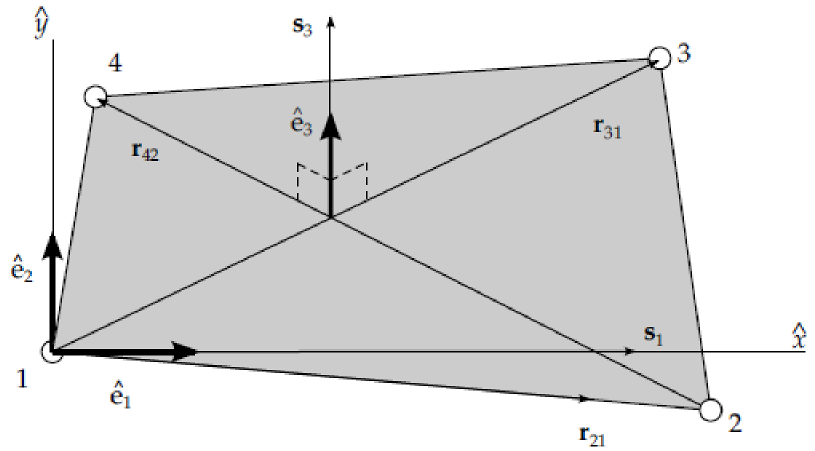


Figure 5 – Scheme of setting the parameters of the geometric configuration of the finite type of Belichko-Tsaya shell

To establish basic relations for finite elements of the Belichko-Tsai shell type, Mindlin theory is used. [1, 2]. According to this theory, the velocity of an arbitrary point belonging to finite elements of this type is calculated by the formula:

$$v=v^m-\hat{z}e_3\times\theta, \tag{36}$$

where
$\mathbf{v}^m$ – velocity vector of the center point of the finite element;
$\hat{z}$ – current coordinate of a point along a specific axis of the local coordinate system;
$\boldsymbol{\theta}$ – angular velocity vector.

5. Method of mathematical modeling of crack propagation in a material.

To divide the material into parts in the event of reaching destructive deformation or force factors in it, depending on the strength theory used, a finite element is used using an independent method, proposed in the works [2 – 5]. This method uses a mesh reconstruction algorithm that is used at the location of the defect that was formed. The algorithm for dividing a finite element mesh into different parts consists of performing the following procedures.

1. Nodes are identified where the parameter, which is the reference for the accepted theory of material strength, reaches the limit values in this model.

2. The crack plane is drawn along the obtained points.

3. If the crack plane passes near an existing node, the crack position and node position are adjusted to create a correct mesh near the newly formed surfaces.

4. Cracked elements are removed using a specific crack plane geometry. This is achieved by redefining new nodes on the surfaces of the finite elements separated by the crack plane in the last step.

5. The database is restored by redefining the identified nodes and elements that are adjacent to the surfaces of the crack edges.

6. The resulting surfaces and nodes are added to a new list of contact surfaces and nodes.

Conclusions. The study used: a comprehensive analysis and generalization of previously completed work on assessing the consequences of excessive pressure from the explosion of military weapons, mathematical modeling methods, based on the explicit method of integrating dynamics equations and stress-strain equations of solid state when approximating them by the finite element method in a nonlinear formulation.

Based on the results of the analysis of the structural systems of protective shelters, the main provisions and assumptions of the computational-theoretical approach to mathematical modeling of the impact of an explosion on reinforced concrete structures of the developed modular block-type shelters were substantiated. Calculation schemes and a set of mathematical models of mechanical interaction between elements of protective shelters, structural materials and the soil on which they are installed, as well as models of the mechanical impact of an explosion on the soil and shelter elements, were substantiated. Based on the mathematical analysis, a conclusion was made about the safety of protective shelters of the proposed design in their practical application for protection against explosions and penetrating ionizing radiation.

REFERENCES

1. Aagaard, B.T. (2000): Finite-Element Simulations of Earthquakes. PhD-Thesis, California Institute of Technology: Pasadena, California 2000.

2. Hallquist, J.O. (2005): LS-DYNA Theory Manual, Livermore Software Technology Corporation: California, USA 2005.

3. Pozdieiev S., Novhorodchenko A., Shnal T., Yakovchuk R., Tur N. (2023) The study of the behavior of reinforced concrete structures of modular shelter in conditions of explosion. Proceedings of CEE 2023 Civil and Environmental Engineering and Architecture. Springer/Rzeszów, Poland. P 286-295.

4. Novhorodchenko A., Shnal T., Yakovchuk R., Tur N.C. Поздєєв, А. Новгородченко, Т. Шналь, Р. Яковчук, Н. Тур. (2023) Математичне моделювання розрахункових схем конструкцій модульного захисного укриття. «Надзвичайні ситуації: попередження та ліквідація», Том 7 № 2. Черкаси. С. 183-192.

5. Maiboroda R., Zhuravskij M., Otrosh Y., Karpuntsov V. (2024). Determination of the Required Area of Easily Removable Structures to Protect against Progressive Collapse. In Key Engineering Materials (Vol. 1004, pp. 73–83). Trans Tech Publications, Ltd. https://doi.org/10.4028/p-v0xa6h.

6. Skob Y., Dreval Y., Vasilchenko A., Maiboroda R. (2023). Selection of Material and Thickness of the Protective Wall in the Conditions of a Hydrogen Explosion of Various Power. In Key Engineering Materials (Vol. 952, pp. 121–129). Trans Tech Publications, Ltd. https://doi.org/10.4028/p-st1vet

7. Tolok I., Rybka E., Pozdieiev S., Novhorodchenko A., Kustov M., Plisko Yu. (2024) Regularities of behavior of reinforced concrete structures of modular shelters under explosion conditions. Problems of Emergency Situations 2024-12. С. 258-268. DOI: 10.52363/2524-0226-2024-40-18.

8. Nizhnyk, V., Pozdieiev, S., Nekora, V., Teslenko, O. (2024) Substantiation of the Method for Studying the Behavior of Enclosing Structures with Glazing Under Conditions of Fire Thermal Influence. Lecture Notes in Civil Engineering, p. 273–285

9. ANSYS, Inc. (2004) ANSYS Structural Analysis Guide, ANSYS, Inc.: Canonsburg, PA.

10. Belytschko T.; Chiapetta, R.L. & Bartel, H.D. (1976) Efficient Large Scale Non-Linear Transient Analysis by Finite Elements. International Journal for Numerical Methods in Engineering, 10 1, pp. 579-596.

11. Bakeer T. (2009) Collapse analysis of masonry structures under earthquake actions. Publication Series of the Chair of Structural Design, TU Dresden.

12. Murray Y.D., A. Abu-Odeh, and R. Bligh (2006) Evaluation of Concrete Material Model 159, FHWA-HRT-05-063.

ПЕРЕЛІК ПОСИЛАНЬ

1. Aagaard, B.T. (2000): Finite-Element Simulations of Earthquakes. PhD-Thesis, California Institute of Technology: Pasadena, California 2000.

2. Hallquist, J.O. (2005): LS-DYNA Theory Manual, Livermore Software Technology Corporation: California, USA 2005.

3. Novhorodchenko Alina, Shnal Taras, Yakovchuk Roman,Tur Nazarii. (2023) The study of the behavior of reinforced concrete structures of modular shelter in conditions of explosion. Proceedings of CEE 2023 Civil and Environmental Engineering and Architecture. Springer/Rzeszów, Poland. P 286-295.

4. С. Поздєєв, А. Новгородченко, Т. Шналь, Р. Яковчук, Н. Тур. (2023) Математичне моделювання розрахункових схем конструкцій модульного захисного укриття. «Надзвичайні ситуації: попередження та ліквідація», Том 7 № 2. Черкаси. С. 183-192.

5. Maiboroda R., Zhuravskij M., Otrosh Y., Karpuntsov V. (2024). Determination of the Required Area of Easily Removable Structures to Protect against Progressive Collapse. In Key Engineering Materials (Vol. 1004, pp. 73–83). Trans Tech Publications, Ltd. https://doi.org/10.4028/p-v0xa6h.

6. Skob, Y., Dreval, Y., Vasilchenko, A., & Maiboroda, R. (2023). Selection of Material and Thickness of the Protective Wall in the Conditions of a Hydrogen Explosion of Various Power. In Key Engineering Materials (Vol. 952, pp. 121–129). Trans Tech Publications, Ltd. https://doi.org/10.4028/p-st1vet

7. Толок І. В., Рибка Є. О., Поздєєв С. В., Кустов М. В. Новгородченко А. Ю., Пліско Ю. В. (2024) Закономірності поведінки залізобетонних конструкцій модульних укриттів в умовах вибуху. Problems of Emergency Situations 2024-12. С. 258-268. DOI: 10.52363/2524-0226-2024-40-18.

8. Nizhnyk, V., Pozdieiev, S., Nekora, V., Teslenko, O. (2024) Substantiation of the Method for Studying the Behavior of Enclosing Structures with Glazing Under Conditions of Fire Thermal Influence. Lecture Notes in Civil Engineering, p. 273–285

9. ANSYS, Inc. (2004) ANSYS Structural Analysis Guide, ANSYS, Inc.: Canonsburg, PA.

10. Belytschko, T.; Chiapetta, R.L. & Bartel, H.D. (1976) Efficient Large Scale Non-Linear Transient Analysis by Finite Elements. International Journal for Numerical Methods in Engineering, 10 1, pp. 579-596.

11. Bakeer T. (2009) Collapse analysis of masonry structures under earthquake actions. Publication Series of the Chair of Structural Design, TU Dresden.

12. Murray, Y.D., A. Abu-Odeh, and R. Bligh (2006) Evaluation of Concrete Material Model 159, FHWA-HRT-05-063.

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ОСНОВНІ РОЗРАХУНКИ ДИНАМІЧНОЇ ВЗАЄМОДІЇ МЕХАНІЧНИХ СИСТЕМ МОДУЛЬНИХ УКРИТТІВ РЕАЛІЗОВАНІ У ПРОГРАМІ LS-DYNA

В статті наведена базова математична модель явного методу розрахунку динамічних систем деформованих тіл при математичному розрахунку модульних укриттів. Предмет досліджень є розв'язок задачі в постановці руху деформування тіла подібного до динамічної системи щодо дослідження стійкості модульних укриттів. Мета роботи полягає у використанні базових математичних моделей явного методу розрахунку динамічних систем з визначення кінцево-елементних апроксимацій основних рівнянь даних механічних систем щодо забезпечення безпечних умов роботи модульних укриттів. Для виконання цієї мети поставлені такі завдання дослідження: розв'язок задачі в постановці руху деформування зразків деформованого тіла подібного до динамічної системи; застосування кінцево-елементної апроксимації основних рівнянь математичної моделі; використання явного методу обчислень рівнянь динаміки; розробка розрахункової схеми контактної взаємодії двох деформованих тіл при їх дотиканні; застосування методу математичного моделювання поширення тріщин у матеріалі. Наукова новизна дослідження полягає у створенні розрахункової бази для оцінки зберігання огороджувальними конструкціями модульних укриттів своїх захисних функцій в умовах впливу вибухів та імпульсних дій. Після проведення розрахунків отримано головні результати, які дозволяють за допомогою математичного моделювання дослідити фізико-механічні процеси, що відбуваються у конструкціях модульних укриттів, це в подальшому стане науковим підґрунтям удосконалення існуючої та створення нової нормативної бази щодо улаштування модульних укриттів.

Ключові слова: *модульне укриття*, *деформоване тіло, математична модель, кінцеві елементи, рівняння динаміки.*