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ANALYSIS OF METHODS FOR CALCULATING THE PENETRATING EFFECT OF THE MAIN TYPES OF MISSILES AND FRAGMENTATION DAMAGE TO THE STRUCTURES OF PROTECTIVE CONSTRUCTIONS

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Relevance. The duration of Russia's military actions against Ukraine, when the aggressor country resorts to psychological pressure on the civilian population by damaging critical infrastructure facilities (hereinafter - CIF) [1, 2] and simply erases entire settlements and fortifications of the Armed Forces of Ukraine with modern means of air attack, has revealed an urgent need to develop unified approaches to the construction of modern protective and fortification structures of high reliability.

In Ukraine, the vast majority of the CIF and other strategic facilities were built without taking into account the threats of enemy air attack associated with military operations [3]. Today, Ukraine is actively implementing the "Fortress Country" concept, which provides for the integrated protection of CIF and other facilities of strategic importance, which involves the organisation of echeloned air defence similar to the defence systems of Israel, the United States and other countries, combined with comprehensive civil and engineering defence measures, electronic warfare systems, decoys, camouflage, transition from the creation of large facilities of strategic importance to smaller, dispersed ones, as well as the transition to a priority In fact, Ukraine should develop a regulatory framework according to which the design of fortifications, critical infrastructure and other critical facilities should take into account the latest threats of air and other means of enemy attack.

Purpose of the work. The purpose of this paper is to review the existing methods of engineering and analytical calculations of the penetration of protective barriers by the main elements of damage from enemy attack means. The importance of choosing the right calculation methodology for different types of threats and materials of protective obstacles is a very important task for the proper design of fortifications and protective structures.

It is noted in [4, 5] that the main types of enemy means for air defeat of CIF are air-launched, ground-launched and water-launched missiles, as well as UAVs of the "barrage munition" type. And the main factors of defeat in this case are fragmentation (debris) and explosive shock wave.

Summary of the main material. Military actions in Ukraine have led to the urgent need to build a large number of fortifications and protective structures of various purposes and structural forms, which, in addition to the usual loads and impacts in accordance with [6], should take into account special impacts associated with the threats of enemy attack. Such impacts include: overpressure of the blast wave, fragmentation damage, partial or complete penetration of ammunition into the body of the protective structure, which may be accompanied by a subsequent explosion, temperature, etc. The issue of calculating the overpressure from the blast wave is well covered in many works [7-9, 12, 13], but the penetrating effect of ammunition or its parts, especially shrapnel damage, raises many questions.

The most common engineering methods for calculating projectile *penetration* into a material are the Wien equation [10, 11] and the equations contained in UFC 4-023-07 [14].

The depth of penetration of a munition (projectile, missile warhead, fragment) into a material is recommended to be determined by the formula:

$$h_t = \left(\frac{4}{\pi}\right)\frac{E_k}{(\sigma\times 10^6)\times d^2}\,, \tag{1}$$

where h_t is the thickness of penetration by the projectile, m; E_k is the kinetic energy of the projectile, J; σ is the average pressure, MPa; d is the diameter of the projectile, m.

The kinetic energy of the projectile (J) should be determined by the formula:

$$E_k = \frac{1}{2}mV^2. \tag{2}$$

where m is the projectile mass, kg; V is the projectile velocity, m/s.

Determine the average stress value (σ). To do this, we need to determine Alpha (α) and Beta (β) for a projectile with an Ogival nose (bullet-shaped) using Tables 1, 2, 3.

The following notations are used in Tables 1, 2, 3: E - Young's modulus of elasticity, GPa; v - Poisson's ratio; f_c - shear strength of the obstacle material, MPa; R_y - shear strength of steel, MPa.

The CRH (ψ) for use in the formulas in Tables 1, 2, 3 can be determined using the Nose Performance Factor ("N") value from UFC 4-023-07[17] Appendix C for the formula:

$$CRH(\psi) = \left(\frac{\overline{N}-0.72}{0.25}\right)^2 + 0.25. \tag{3}$$

Table 1

Parameter values for a metal obstacle

	α	β	σ_t	⎩
Tapered end face	$\frac{1}{2}\left[1+\ln\frac{2E}{(5-4v)R_y}\right]$	$2\sin\frac{\theta}{2}$	R_y	0
Flat end	$\frac{1}{2}\left[1+\ln\frac{2E}{(5-4v)R_y}\right]$	2	R_y	-
An animated ending	$\frac{2}{3}\left[1+\ln\frac{E}{3(1-v)R_y}\right]$	$\frac{3}{4\psi}$	R_y	0
Hemispherical end	$\frac{2}{3}\left[1+\ln\frac{E}{3(1-v)R_y}\right]$	$\frac{3}{2}$	R_y	0
Erosion penetration	$\frac{2}{3}\left[1+\ln\frac{E}{3(1-v)R_y}\right]$	$\frac{3}{2}$	R_y	1

Table 2

Parameter values for FRP (Fiber Reinforced Plastic) laminate barriers

	α	β	σ_t	⎩
Tapered end face	1	$2\sin\frac{\theta}{2}$	f_c	0
Flat end	1	2	f_c	0
An animated ending	1	$\frac{3}{4\psi}$	f_c	0
Hemispherical end	1	$\frac{3}{2}$	f_c	0

Table 3

Parameter values for obstacles made of concrete and soil

	α	β	σ_t	⎩
Tapered end face	$\frac{1}{2}\left[1+\ln\frac{2E}{(5-4v)f_c}\right]$	$2\sin\frac{\theta}{2}$	f_c	-
Flat end	$\frac{1}{2}\left[1+\ln\frac{2E}{(5-4v)f_c}\right]$	2	f_c	-
An animated ending	$\frac{2}{3}\left[1+\ln\frac{E}{3(1-v)f_c}\right]$	$\frac{3}{4\psi}$	f_c	2
Hemispherical end	$\frac{2}{3}\left[1+\ln\frac{E}{3(1-v)f_c}\right]$	$\frac{3}{2}$	f_c	2

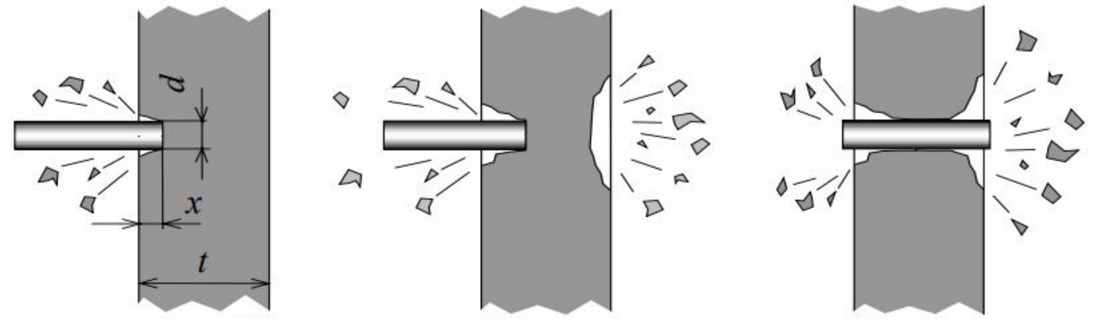
Using the values of alpha (α) and beta (β) taken from Tables 1, 2, 3, we determine the average stress (σ) using the formula:

$$\sigma = \left(\alpha + \beta\sqrt{\frac{\rho_t}{\left(\sigma_t \times 10^6\right)}}V_i\right)\sigma_t, \tag{4}$$

where ρ_t is the density of the target material, kg/m^3; σ_t is the shear strength (Y) of the target material, MPa; V_i is the projectile velocity at impact, m/s.

As can be seen from the above formulas, the depth of penetration of a munition (projectile, missile warhead, fragment) into an obstacle is influenced by the following characteristics: the velocity of the projectile and its mass; the shape of the munition (projectile, missile warhead, fragment) head (CRH) and its diameter and length; the material of the projectile, namely its density; and the properties of the obstacle material (protective structure): type and density of the material; material thickness; Brinell's hardness (for steel); compressive and shear strength; Poisson's ratio; Young's modulus.

If the thickness of the protective material is insufficient, penetration occurs (see Fig. 1). The direct hit protection must be designed in such a way that the projectile does not penetrate the protective shell and that the protective material does not split off from the interior.



(a) (b) (c)

Fig. 1. Types of damage to a concrete barrier when struck by a solid body:
(a) spallping from the front surface; (b) cracking from the inside; (c) punching

In domestic practice, the total depth of penetration of a charge (projectile, missile warhead), according to [15, 16], should be determined by an empirical expression:

$$h_p = \lambda k_p \frac{m}{d_{pr}^2} V_{pr} \cos\alpha, \tag{5}$$

where: h_p is the depth of penetration of the projectile normal to the outer surface of the obstacle in metres; λ - coefficient, which depends mainly on the shape of the projectile, is 1.3 when firing concrete-piercing projectiles at concrete and 1.0 in other cases; k_p - the coefficient of the medium's susceptibility to penetration; m is the weight of the projectile at the moment of impact with the obstacle, kg.

Since we are talking about mechanical permeability, in the case of missiles, the value can be taken as the weight of the missile at the time of impact; d_{pr} - diameter of a projectile (bomb, rocket), m; V_{pr} is the velocity of a projectile (bomb, missile) at the moment of impact with an obstacle, in m/s; α is the angle between the perpendicular to the outer surface of the obstacle and the tangent to the projectile trajectory; in the case of missiles, this is the angle of impact with the obstacle.

$$h_p = \lambda k_p \frac{m}{d_{pr}^2} V_{pr} \frac{\cos(n\alpha)}{\sqrt{\cos\alpha}}, \tag{6}$$

where m is the weight of the projectile at the moment of impact with the obstacle, kg; d_{pr} is the calibre of the projectile, mm; V_{pr} is the velocity of the projectile (bomb, missile) at the moment of impact with the obstacle, m/s; α is the angle at which the projectile penetrates the protective thickness, calculated from the normal to the protective surface,

$$\alpha \le \frac{90^{\circ}}{2n-1}, \tag{7}$$

$\lambda=\lambda_1\lambda_2$ is a coefficient that takes into account the shape of the projectile head and its calibre; k_p is a coefficient of material penetration; n is a coefficient that takes into account the possible distortion of the projectile trajectory in the protective thickness: for long-range projectiles, $n = 1.82$, for short-range projectiles, $n = 2.62$. The shape coefficient of the projectile head λ_1 is determined by the expression

$$\lambda_1 = 0,5 + 0,43\sqrt{\left(\frac{H_r}{d_{pr}}\right)^2}, \tag{8}$$

where H_r is the height of the projectile head (Fig. 2), m.

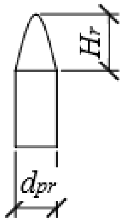


Fig. 2. Before determining the height of the projectile head

The projectile calibre coefficient λ_2 is determined by the expression

$$\lambda_2 = 2,8\sqrt[3]{d_{pr}} - 1,3\sqrt{d_{pr}}. \tag{9}$$

In the absence of data on the parameters of the ammunition, it is allowed to use the formula

$$h_p = 1,73 k_p \frac{m}{d_{pr}^{1,75}} v_{pr} \cos\alpha. \tag{10}$$

For supersonic impact velocities, when the velocity of the projectile V_{pr} exceeds the speed of sound of the obstacle material, the following formula for the depth of penetration can be used:

$$h_{p1} = \frac{L}{2\chi_0}\frac{\rho_{02}}{\rho_{01}} \ln\left(1 + \chi_0 \frac{\rho_{01} V_{pr}{}^2}{H}\right), \tag{11}$$

where χ_0 is the shape coefficient of the projectile head, for a projectile with a tapered head $\chi_0 = \sin 2\beta$ (where β is the angle of taper), and for a projectile with a live head $\chi_0 = \left(8(r/d_{pr}) - 1\right) / \left(24(r/d_{pr})^2\right)$. r is the radius of the live head; d_{pr} is the calibre of the projectile. Parameters ρ_{01} , ρ_{02} are, respectively, the densities of the obstacle material and the munition structure. Accordingly, the density of the fragment material can be assumed to be approximately $\rho_{02} = 2700$ kg/m³, as for duralumin. The density of the obstacle material in the adopted shell design depends on its filling. H is the dynamic hardness of the obstacle material. L is the length of the munition (fragment, shrapnel). When calculating for shrapnel penetration, $L = l_f$.

H is the dynamic hardness of the obstacle material, which can be approximated as the hardness of 09Г2С steel, H = 450...490 MPa, averaged 470 MPa.

To calculate the penetrating effect of shrapnel and the probability of fragments of protective structures breaking off at the impact sites with subsequent formation of secondary fragments, the empirical formulas below should be used.

Formulas (12) - (14) are used for the calculation of reinforced concrete fortifications in the United Kingdom.

$$X_f = 8.24 \cdot 10^{-3} \frac{m_f^{0.333} V_f^{0.825} \left(l_f / d_f \right)^{0.285}}{\left(f_{cd} \right)^{0.719}}, \tag{12}$$

where: X_f is the depth of fragment penetration, m; m_f is the average mass of the fragment, kg; V_f is the fragment velocity, m/s; d_f is the fragment diameter, m; f_{cd} is the calculated concrete compressive strength, MPa; l_f is the average fragment length, m.

The equation below determines the required concrete thickness to prevent the penetration of fragments:

$$h_t = 1.632 X_f {d_s}^{0.1} + 1.311 d_s, \tag{13}$$

where h_t is the thickness of concrete to prevent the penetration of fragments, m.

In addition, it is necessary to prevent spallping of the concrete inside the premises from fragments from the outside:

$$h_s = 1.754 X_f {d_s}^{0.1} + 2.12 d_s, \tag{14}$$

where h_s is the thickness of concrete to prevent spalling, m.

The modified NDRC (National Defence Research Committee) formula [17] allows determining the penetration thickness and the thickness of the barrier at which no spalling occurs. The formula is derived for the case of a cylindrical projectile striking a non-deformable (i.e. massive and sufficiently rigid) reinforced concrete barrier with 0.3÷1.5 % reinforcement in each direction. The depth of penetration into the obstacle is:

$$X_f = \begin{cases} \sqrt{4KNmd_{pr} \left(\dfrac{V_{pr}}{1000 d_{pr}} \right)^{1.8}} & \text{при } \dfrac{X_f}{d_{pr}} \le 2, \\ KNm \left(\dfrac{V_{pr}}{1000 d_{pr}} \right)^{1.8} + d_{pr} & \text{при } \dfrac{X_f}{d_{pr}} > 2, \end{cases} \tag{15}$$

where the parameters are set in the British system of measures: X_f - conditional depth of penetration, inch; d_{pr} - projectile diameter, inch; m - projectile weight, lb; V_{pr} - impact velocity, ft/s; N - coefficient depending on the shape of the projectile end:

$$N = \begin{cases} 0.72 - \text{ плоский торець;} \\ 0.84 - \text{ тупо загострений торець;} \\ 1.00 - \text{ середньогострий торець;} \\ 1.144 - \text{ дуже гострий торець;} \end{cases} \tag{16}$$

K is a coefficient characterising the strength of concrete:

$$K = 180 \left(f_{cd} \right)^{-1/2}, \tag{17}$$

where f_{cd} is the cylindrical compressive strength of concrete, lb/in^2 (related to the dynamic strength, which is determined by the ratio $f_{cd} = 1.07 R_c$).

Numerical studies have made it possible to write the modified NDRC formula (15) in metric units, with the result in cm:

$$X_f=\begin{cases}\sqrt{0.00255KNmd_{pr}\left(\dfrac{V_{pr}}{1000d_{pr}}\right)^{1.8}} & \text{при } \dfrac{X_f}{d_{pr}}\le 2\\ 0.1146KNm\left(\dfrac{V_{pr}}{1000d_{pr}}\right)^{1.8}+0.0254d_{pr} & \text{при } \dfrac{X_f}{d_{pr}}>2\end{cases}, \tag{18}$$

where: X_f - conditional penetration depth, m; d_{pr} - projectile diameter, m; m - projectile mass, kg; V_{pr} - impact velocity, m/s; N - coefficient depending on the shape of the projectile end, taken according to condition (16); K - coefficient characterising the strength of concrete:

$$K=14{,}946\left(f_{cd}\right)^{-1/2}, \tag{19}$$

where f_{cd} is the cylindrical compressive strength of concrete, Pa, (related to the dynamic strength determined by the ratio $f_{cd}=1.07R_c$).

The thickness of the punch h_t is determined from the ratios:

$$\frac{h_t}{d_{pr}}=\begin{cases}1.32+1.24\left(X_f/d_{pr}\right) & \text{при } 1.35\le\dfrac{X_f}{d_{pr}}\le 13.5,\\ 3.19\dfrac{X_f}{d_{pr}}-0.718\left(X_f/d_{pr}\right)^2 & \text{при } \dfrac{X_f}{d_{pr}}\le 1.35,\end{cases} \tag{20}$$

The spallping thickness h_s is determined from the following relations:

$$\frac{h_s}{d_{pr}}=\begin{cases}2.12+1.36\left(X_f/d_{pr}\right) & \text{при } 0.65\le\dfrac{X_f}{d_{pr}}\le 11.75,\\ 7.91\dfrac{X_f}{d_{pr}}-5.06\left(X_f/d_{pr}\right)^2 & \text{при } \dfrac{X_f}{d_{pr}}\le 0.65,\end{cases} \tag{21}$$

The depth of penetration determined by formulas (15) or (17) is satisfactorily tested if its ratio to the projectile diameter is $0.6 \le X_f / d_{pr} \le 2.0$. At smaller values of this ratio, the penetration depth, and, accordingly, the values of h_t and h_s , give underestimated results. In this case, it is better to use the Bechtel Corp and CEA-EDF formulas below. Formulas (15) - (21) give good results if the ratio of the thickness of the obstacle to the diameter $h / d_{pr} \ge 3$, otherwise the values of h_t and h_s are overestimated.

The above relations correspond to the impact of a solid cylindrical projectile, but can also be used when impacting a pipe end with an outer diameter d_0 and an inner diameter d_{in}. The depth of penetration x_n is calculated using formulas (14) or (17), where $N = 0.72$ and $d_{pr} = d_0$. The penetration and spallping thicknesses are calculated according to (20) and (21), where $d_{pr}=\sqrt{d_0^2-d_{in}^2}$ should be substituted.

The CEA-EDF formula (CEA - Commissariat à l'Energie Atomique - Atomic Energy Commission (France); EDF - Elecricité de France) is also used to determine the thickness of the obstacle penetration [24] . When hitting a solid body, the penetration thickness is determined by the formula:

$$h_t=0.765\cdot\left(f_{cd}\right)^{-0.375}V_{pr}^{0.75}\sqrt{m/d_{pr}}\ , \tag{22}$$

where: h_t - penetration thickness, inches; f_{cd} - cylindrical compressive strength of concrete, lb/inch^2; V_{pr} - impact velocity, ft/s; m - weight of the projectile, lb; d_{pr} - diameter of the projectile, inches.

In formula (22), all notation is as above, and the values are given in the British system of measurements. They should be applied in the following ranges of target and material parameters maintained in the experiments: $1.5 \le t/d \le 3$; cylindrical strength of concrete $3000 \le f_{cd} \le 4500$ lb/inch^2

($0.21 \cdot 10^8 \le f_{cd} \le 0.31 \cdot 10^8$ Pa); concrete density 155 lb/ft^3 (2500 kg/m^3); reinforcement 0.8÷1.5% in each direction.

Numerous studies have made it possible to write the CEA-EDF formula (22) in metric units:

$$h_t = 0.31 \cdot \left(f_{cd}\right)^{-0.375} V_{pr}^{0.75} \sqrt{m/d_{pr}} \,, \tag{23}$$

where: h_t - thickness of penetration, cm; f_{cd} - cylindrical compressive strength of concrete, Pa; d_{pr} - projectile diameter, m; m - mass of the projectile, kg; V_{pr} - impact velocity, m/s.

Formula (23) should be applied in the following ranges of target and material parameters maintained in the experiments: $1.5 \le t/d \le 3$; cylindrical strength of concrete $0.21 \cdot 10^8 \le f_{cd} \le 0.31 \cdot 10^8$ Pa; concrete density 2500 kg/m^3 ; reinforcement 0.8÷1.5% in each direction.

To determine the thickness of an obstacle that will not spall, use the Bechtel Corp formula [25] , which looks like this:

$$h_s = 15.5 \cdot \frac{m^{0.4} \sqrt{V_{pr}}}{d_{pr}{}^{0.2} \sqrt{f_{cd}}} \,, \tag{24}$$

where: h_s is the thickness of the obstacle at which no spalling occurs, inch; f_{cd} is the cylindrical compressive strength of concrete, lb/in^2 ; V_{pr} is the impact velocity, ft/s; m is the mass of the projectile, lb; d_{pr} is the diameter of the projectile, inch.

Numerical studies have made it possible to write the Bechtel Corp formula (24) in metric units:

$$h_s = 39 \cdot \frac{m^{0.4} \sqrt{V_{pr}}}{d_{pr}{}^{0.2} \sqrt{f_{cd}}} \,, \tag{25}$$

where: h_s is the thickness of the obstacle at which no spalling occurs, m; f_{cd} is the cylindrical compressive strength of concrete, Pa; d_{pr} is the diameter of the projectile, m; *m is the* mass of the projectile, kg; V_{pr} is the impact velocity, m/s.

Formula (24) applies to the impact of a solid body. When a pipe with a diameter of d_0 is hit, only the numerical coefficient changes:

$$h_s = 5.42 \cdot \frac{m^{0.4} \sqrt{V_{pr}}}{d_{pr}^{0.2} \sqrt{f_{cd}}} \,, \tag{26}$$

where: h_s - thickness of the obstacle at which no spalling occurs, inch; f_{cd} - cylindrical compressive strength of concrete, lb/inch^2 ; V_{pr} - impact velocity, ft/s; m - weight of the projectile, lb; d_{pr} - diameter of the projectile, inch.

In metric units, formula (26) takes the form:

$$h_s = 13.6 \cdot \frac{m^{0.4} \sqrt{V_{pr}}}{d_{pr}^{0.2} \sqrt{f_{cd}}} \,, \tag{27}$$

where: h_s is the thickness of the obstacle at which no spalling occurs, m; f_{cd} is the cylindrical compressive strength of concrete, Pa; d_{pr} is the diameter of the projectile, m; m is the mass of the projectile, kg; V_{pr} is the impact velocity, m/s.

The pipe wall thickness s must be within $0.06 \le 2s/d_{pr} \le 0.125$.

Taking into account the limited experimental data used and the scatter of results on the basis of which the above formulas were obtained, the values of h_t and h_s should be increased by 10÷20%.

Another formula that can be used to determine the amount of projectile penetration into concrete according to UFC 4-023-07 [17] requires explicit ballistic parameters to the Wien equation, but includes the maximum size of coarse aggregate in the concrete (c) and the age of the concrete (f_{age}).

$$h_t = \frac{56.6 \left(m/d^3\right)^{0.075} \overline{N} m V^{1.8}}{d^2 \sqrt{f_c}} \left(\frac{d}{c}\right)^{0.15} f_{age} + d \,, \tag{28}$$

where h_t is the maximum thickness of concrete penetration by a projectile, mm; d is the diameter of the projectile, mm; m is the mass of the projectile, kg; V is the projectile velocity, m/s; f_c is the compressive strength of concrete, MPa; c is the maximum size of stones, mm (19 mm for heavy concrete and 4 mm for concrete masonry); N is the shape coefficient of the projectile end according to Annex C of UFC 4-023-07 [17]; f_{age} is the age coefficient of concrete.

According to another formula contained in UFC 4-023-07 [17], it is possible to calculate the residual velocity of a projectile after penetrating an obstacle:

$$V_r = V\left(1-\frac{t_{conc}}{h_t}\right)^{0.733}, \tag{29}$$

where V_r - residual velocity, m/s; V - impact velocity, m/s; t_{conc} - concrete thickness, mm; h_t - maximum penetration thickness, mm.

It is recommended to use the following formula to determine the maximum thickness of the penetration of a wooden obstacle:

$$h_t = 9837\frac{V^{0.4113}m^{1.4897}}{\rho\left(\pi d^2/4\right)^{1.3596}H^{0.5414}}, \tag{30}$$

where h_t is the maximum thickness of wood penetration by the projectile, inch; d is the diameter of the projectile, inch; m is the mass of the projectile, lb; V is the projectile velocity, ft/s; ρ is the density of wood, lb/ft^3 ; H is the hardness of wood, lb.

Formula (30) in metric units takes the form:

$$h_t = 0.64\frac{V^{0.4113}m^{1.4897}}{\rho\left(\pi d^2/4\right)^{1.3596}H^{0.5414}}, \tag{31}$$

where h_t is the maximum thickness of wood penetration by the projectile, m; d is the diameter of the projectile, m; m is the mass of the projectile, kg; V is the projectile velocity, m/s; ρ is the density of wood, kg/m^3; H is the hardness of wood, kg.

The residual velocity of a projectile after penetrating a wood barrier should be determined by the following formula:

$$V_r = V\left[1-\left(t/h_t\right)^{0.5735}\right], \tag{32}$$

where t is the actual thickness of the wood, m

Determination of the maximum flying radius of fragments

When an explosive charge is detonated on the ground surface, the maximum fragmentation radius $R_{\max}$, m, is determined by the formula:

$$R_{\max} = 238\sqrt[3]{m_{ef}}, \tag{33}$$

where: m_{ef} is the total mass of the explosive charge, kg, determined by the formula: $m_{ef} = m_1 k_{ef} + m_2$, where m_1 is the mass of the active explosive charge, kg; k_{ef} is the efficiency coefficient of the explosive compared to a TNT charge of the same mass; m_2 is the mass of the external contact charge of TNT to detonate the active explosive charge, kg.

All of the above methods are empirically derived and have certain limitations of use with additional confirmation of the possibility of application to other types of damaging elements.

Those equations are derived for impact velocities of up to 1000 m/s, and how they will behave at higher velocities inherent in modern weapons (e.g. ballistic missiles) is unknown and requires further in-depth research.

To prevent the penetrating effects of shells and fragments, the protective structure must have sufficient penetration resistance, and to avoid secondary fragmentation, internal protective membranes are used inside the rigid structure, and requirements for reinforcement of reinforced concrete structures are established [13].

For example, [18] recommends the use of lacing reinforcement, where bent zigzag rods are used in addition to the main working reinforcement (Fig. 2). Such a reinforcement design prevents concrete colourants from spallping off under dynamic impact.

Domestic design standards 19 set the following requirements for the reinforcement of protective structures (in particular, shelters in civil protection structures): in order to reduce the risk of penetration and increase the structure's resistance to secondary spalling, reinforced concrete floor structures and exterior walls should be reinforced with 3 rows of mesh with a rod diameter of at least 12 mm with the mesh offset from each other by 1/3 of the mesh pitch. The protective layer of concrete on the inner surface should be at least 25 mm and not more than 40 mm. The spacing of the rods in the grids in the longitudinal and transverse directions shall not exceed 200 mm. The meshes shall be spaced along the thickness of the structure section at a distance of at least 50 mm between the meshes in the lumen.

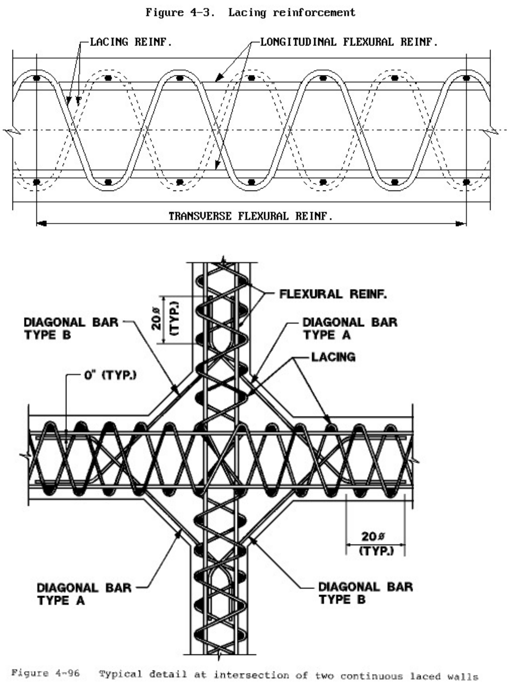


Fig. 2. Recommended reinforcement of reinforced concrete columns and beams according to UFC-3-340-02

They are used as an internal anti- spalling layer of walls:

– steel sheets that are laid between vertically installed I-beams (only for front walls

– mesh of rods 4-6 mm in diameter with a mesh size not exceeding 50x50 mm, with a protective layer of concrete 20 mm, fixed to the outermost mesh of the working reinforcement;

– formwork made of 50 mm thick boards or 16-20 mm plywood sheets with fastening to U-shaped anchors 8-12 mm in diameter with a staggered spacing of 500 mm in advance embedded in concrete, or on chemical anchors.

The anti-spalling layer is constructed by laying rigid reinforcement from I-beams with the gap between them filled with steel sheets 5-8 mm thick, 50 mm thick board or 16-20 mm thick plywood sheets. The I-beams are placed at a distance of no more than 250 mm from each other, with the ends extending at least 250 mm into the outer walls. Sheet steel or reinforcing bars are placed between the beams.

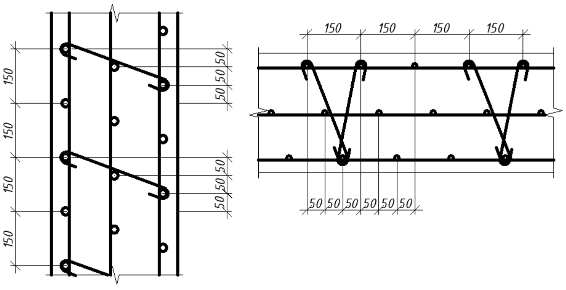


Fig. 3. Recommended reinforcement of reinforced concrete structures according to DBN B.2.2-5:2023

A layer of concrete is placed on the anti-spalling layer, as if it were formwork, on which the first mesh is placed 50 mm from the top of the beams.

It is advisable to increase the dynamic strength of concrete against explosive impact loads by increasing the content of plastic structural elements (use of low-grade cements with mineral additives, etc.), as well as improving the structure (use of clean aggregates, plasticisers, thorough mixing, high-quality compaction of the concrete mix and concrete maintenance). It is advisable to use fibre-reinforced concrete.

This approach makes it possible to increase the reliability and safety of shelter structures.

Conclusions. Scientific novelty and practical significance of the results. The paper considers the existing world methods of penetrating effects of various kinds of destructive elements (missile warheads, shells, bullets, fragments).

The question of the need to develop a clear engineering methodology for calculating the penetrating effect of all possible elements of damage into obstacles of various materials is raised.

The algorithms for calculating shrapnel damage from various types of ammunition, as well as for calculating the protective properties of fortifications and engineering defences are presented.

The prospect of further research is to improve the methodology for calculating the penetrating effect of all possible elements of damage into obstacles of various materials.

The development of modern calculation methods with an awareness of the existing wartime threats will allow for the most efficient construction of engineering defences and fortifications, which will help implement the Fortress Country concept to the maximum extent possible.

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Михайловський Д.В., Скляров І.О., Хомік М.М., Вавілова Н.В.

АНАЛІЗ МЕТОДИК РОЗРАХУНКУ ПРОНИКНОЇ ДІЇ ОСНОВНИХ ВИДІВ БОЄПРИПАСІВ ТА ОСКОЛКОВОГО УРАЖЕННЯ КОНСТРУКЦІЙ ЗАХИСНИХ СПОРУД

Актуальність. Повномасштабне вторгнення рф в Україну виявило досить велику кількість питань, в тому числі і пов'язаних зі зведенням захисних та фортифікаційних споруд. Як виявилось, цей напрямок в нашій країні фактично не розвивався. Відсутня нормативна база щодо урахування багатьох специфічних факторів, таких як вибухово-ударна хвиля, пробивання боєприпасами та осколками (уламками). Окремо слід відзначити той факт, що засоби нападу постійно розвиваються та удосконалюються, у той час як науковий підхід по протидії ним майже в усьому світі застиг на місці. Ця стаття присвячена огляду наявних методик, які можуть бути застосовані при розрахунку елементів конструкції на пробивання осколками (уламками). Вибір правильної методики для розрахунку дозволить відпрацювати методичний підхід до проєктування фортифікаційних та споруд інженерного захисту об'єктів критичної інфраструктури (далі - ОКІ), що в даний час є дуже важливою і актуальною задачею. Цей підхід в подальшому може бути включений в спеціалізовані нормативні документи щодо розрахунку та проєктування захисних та фортифікаційних споруд, що значно б покращило їх якість та надійність з урахуванням сучасних загроз воєнного часу. **Метою роботи** є огляд існуючих методик інженерно-аналітичних розрахунків пробивання захисних перешкод основними елементами ураження від засобів нападу противника. Важливість вибору правильної методики розрахунку для різних видів загроз та матеріалів захисних перешкод, є дуже важливою задачею для правильного проєктування фортифікаційних та захисних споруд. **Результати.** У роботі розглянуто існуючі світові методики проникної дії різного роду уражаючих елементів (бойові частини ракет, снаряди, кулі, осколки). Піднято питання необхідності розроблення чіткої інженерної методики розрахунку проникної дії в різноманітні за матеріалом перешкоди всіх ймовірних елементів ураження. Наведено алгоритми розрахунку осколкового ураження від різних видів боєприпасів, а також для обчислення захисних властивостей фортифікаційних та інженерних захисних споруд.

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

Mykhailovskyi D.V., Skliarov I.O., Khomik M.M., Vavilova N.V., Skliarova T.S.

ANALYSIS OF METHODS FOR CALCULATING THE PENETRATING EFFECT OF THE MAIN TYPES OF MISSILES AND FRAGMENTATION DAMAGE TO THE STRUCTURES OF PROTECTIVE CONSTRUCTIONS

Relevance. The full-scale invasion of Ukraine by Russia raised a number of questions, including those related to the construction of defensive and fortification structures. It turned out that this direction in our country was practically undeveloped. There is a lack of regulatory framework for accounting for many specific factors, such as blast waves, penetration of projectiles and fragments. It is worth noting separately that means of attack are constantly evolving and improving, while the scientific approach to countering them has almost stagnated worldwide. This article is dedicated to reviewing existing methodologies that can be applied in calculating elements of construction for fragment penetration. Choosing the right methodology for calculations will help develop a methodical approach to designing fortifications and structures for the engineering protection of critical infrastructure objects, which is currently a very important and relevant task. This approach could eventually be included in specialized regulatory documents for calculating and designing defensive and fortification structures, significantly improving their quality and reliability considering modern wartime threats.. **The aim** of this work is to review of existing methods of engineering and analytical calculations of penetration of protective barriers by the main elements of damage from enemy attack means. The importance of choosing the right calculation methodology for different types of threats and materials of protective obstacles is a very important task for the proper design of fortifications and protective structures. **Results.** The paper considers the existing world methods of penetrating effects of various kinds of destructive elements (missile warheads, shells, bullets, fragments). The question of the need to develop a clear engineering methodology for calculating the penetrating effect of all possible destructive elements in obstacles of various materials is raised. The algorithms for calculating fragmentation damage from various types of ammunition, as well as for calculating the protective properties of fortifications and engineering defenses are presented.

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

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Михайловський Д.В., Скляров І.О., Хомік М.М., Вавілова Н.В., Склярова Т.С. **Аналіз методик розрахунку проникної дії основних видів боєприпасів та осколкового ураження конструкцій захисних споруд** / Опір матеріалів і теорія споруд: наук.-тех. збірн. – К.: КНУБА, 2021. – Вип. 113. – С. 171-182. – Англ.

У роботі розглянуто існуючі світові методики проникної дії різного роду уражаючих елементів (бойові частини ракет, снаряди, кулі, осколки). Піднято питання необхідності розроблення чіткої інженерної методики розрахунку проникної дії в різноманітні за матеріалом перешкоди всіх ймовірних елементів ураження. Наведено алгоритми розрахунку осколкового ураження від різних видів боєприпасів, а також для обчислення захисних властивостей фортифікаційних та інженерних захисних споруд.

Табл. 3. Іл. 15. Бібліогр. 9 назв.

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Mykhailovskyi D.V., Skliarov I.O., Khomik M.M., Vavilova N.V., Skliarova T.S. **Analysis of methods for calculating the penetrating effect of the main types of missiles and fragmentation damage to the structures of protective constructions** / Strength of materials and theory of structures: scientific and technical collection - Kyiv: KNUBA, 2021. - Issue 113. - P. 171-182.

The paper considers the existing world methods of penetrating effects of various kinds of destructive elements (missile warheads, shells, bullets, fragments). The question of the need to develop a clear engineering methodology for calculating the penetrating effect of all possible destructive elements in obstacles of various materials is raised. The algorithms for calculating fragmentation damage from various types of ammunition, as well as for calculating the protective properties of fortifications and engineering defenses are presented.

Tabl. 3. Fig. 15. Ref. 9.

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