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ANALYSIS OF METHODS FOR CALCULATING THE PENETRATING EFFECT OF THE MAIN TYPES OF AMMUNITION AND FRAGMENTATION DAMAGE TO DEFENSIVE STRUCTURES

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Abstract In the current realities arising from the full-scale armed aggression of the Russian Federation against Ukraine, and in light of the rapid technological development of highly effective weapons, the issue of ensuring the reliability and stability of fortifications and defensive structures has acquired unpreceden-ted relevance. The critical task of engineering defence is to counter a wide range of threats, including the penetrating action of small-arms bullets, cumulative jets, armour-piercing shells, and the destructive impact of high-explosive fragmentation ammunition.

The impact of these factors is not limited to local damages, such as perforation or chipping of structural elements. It determines the overall survivability of the object - its ability to maintain integrity, load-bearing capacity, and essential functional characteristics directly during intense fire exposure. A wide range of methods is used to predict the behaviour of structures: from analytical and empirical approaches to complex numerical modelling.

The reliability and accuracy of such predictions directly depend on the comprehensive consideration of input parameters. Firstly, these are the kinematic characteristics of the striking elements: their mass, velocity vector, angle of encounter with the obstacle, and shape. Secondly, the physico-mechanical properties of the materials of the obstacle itself play a decisive role, in particular dynamic strength, ultimate plasticity, impact strength, and the degree of structural heterogeneity (for example, in reinforced concrete). Thirdly, the geometry and design of protective elements are essential, such as multilayered structures or spaced armor.

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In practical terms, there is a clear division of calculation methods. Empirical formulas, due to their simplicity, are indispensable at the stages of preliminary design for obtaining quick, albeit approximate, estimates. Instead, modern numerical methods, implemented using the finite element method (FEM), allow us to reproduce with high accuracy the mechanisms of interaction between the projectile and the structure in time and space.

Keywords. Engineering methodology, debris, ammunition, UAV, missile.

FORMULATION OF THE PROBLEM

The military actions in Ukraine have led to an urgent need to construct a large number of fortifications and protective structures of various purposes and designs, which must

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account not only for normal loads and influences but also for special effects related to threats of enemy attack. Such effects include blast wave action, shrapnel damage, partial or complete penetration of ammunition into the body of the protective structure, which may be accompanied by subsequent explosions, temperature changes, and so on.

To our great regret, the enemy is improving and increasing their means to inflict maximum damage on targets. Yes, there have been more frequent cases of using metal shrapnel in the bodies of unmanned aerial vehicles or in missiles (Fig.1).

Fig. 1. The body of the undetonated missile filled with shrapnel (photo by the Denys Mykhailovskyi)
Рис. 1 Корпус нездетонованої ракети заповнений шрапнеллю (фото зроблено Денисом Михайловським)

However, despite these threats, Ukraine still lacks regulatory documents that specify the methodology or procedures for calculating the elements of protective structures against the penetrating effects of the main types of ammunition and fragmentation damage. Recommendations for ensuring the thickness of elements to prevent penetration are provided in DBN V.2.2-5:2023 "Civil Defence Protective Structures" [2] in section 14.2.3; however, it does not specify which threats these values are intended to address, and it is not clear how to apply them to current realities.

As part of this work, a comparison was made of the calculation of the penetrating action of the main types of ammunition and fragmentation damage using the following methods:

1. Engineering method of Berezan V.I.;
2. Energy method (or energy balance method);
3. Engineering method of NDRC (National Defence Research Committee).

№	Material	Reduced coefficient	Min. Thickness, mm
1	Concrete heavy C16/20	0,917	360
2	Concrete heavy C20/25	0,943	350
3	Concrete heavy C25/30	1,0	330
4	Concrete heavy C30/35	1,032	320
5	Concrete heavy C32/40	1,065	310
6	Concrete heavy C35/45	1,1	300
7	Concrete heavy C40/50	1,138	290
8	Ordinary soil	0,134	2470
9	Clay	0,189	1750
10	Sandy loam	0,267	1240
11	Loam	0,228	1450
12	Sand	0,267	1240
13	Pine	0,152	2180
14	Maple	0,271	1220
15	Oak	0,341	970
16	Brick masonry	0,703	470
17	Steel	3,667	90

Fig. 2. Minimum wall thicknesses according to DBN V.2.2-5:2023 "Civil Defence Protective Structures" [2]

Рис. 2 Мінімальні товщини стін відповідно до ДБН В.2.2-5:2023 "Захисні споруди цивільного захисту"[2]

MAIN RESEARCH

Engineering methodology of Berezan V.I.

Berezana V.I.'s method is a classical empirical dependence widely used in the Soviet school of military engineering and fortification to calculate the penetration depth of a penetrator (projectile, fragment) into an obstacle (concrete, soil, brickwork).

According to this formula, the penetration depth is recommended to be determined using an empirical formula:

$$h_p = \lambda k_p \frac{m}{d_{pr}^2} V_{pr} \cos\alpha \qquad (1)$$

where: h_p – the depth of projectile penetra-tion along the normal to the outer surface of the obstacle in metres;

λ - the coefficient, which mainly depends on the shape of the projectile, is equal to 1.3 when firing armour-piercing shells at concrete and 1.0 in other cases;

k_p – the coefficient of compliance of this environment to penetration (taken as in Fig. 3);

m - the weight of the projectile at the moment of encountering an obstacle, kg.

d_{pr} - projectile diameter in metres;

V_{pr} - projectile speed at the moment of encountering an obstacle, in m/s.

Name of the medium	Values of coefficients			
	Penetration k_p	Explosion k_b	High-explosive action k_{exp}	Spalling, k_{ch}
Freshly placed loose soil	0,0000130	0,60	1,40	
Ordinary soil	0,0000065	0,53	1,07	
Dense sand	0,0000045	0,50	1,04	
Sandy loam	0,0000050	0,50	1,00	
Loam	0,0000060	0,50	1,00	
Dense clay	0,0000070	0,50	1,00	
Limestone or sandstone	0,0000020	0,25	0,92	
Granite or gneiss	0,0000016	0,20	0,86	
Pine	0,0000050	0,30	0,60	
Oak, beech, ash	0,0000040	0,30	0,60	
Dry brick masonry	0,0000030	0,25	0,96	
Dry stone masonry	0,0000030	0,25	0,96	
Brick masonry in cement mortar	0,0000025	0,25	0,88	0,81
Stone masonry in cement mortar	0,0000020	0,20	0,84	
Reinforced brick masonry	0,0000022	0,20	0,52	0,73
Rubble concrete	0,0000016	0,18	0,70	
Heavy concrete of class C 8/10, C 12/15.	0,0000012	0,18	0,65	
Reinforced concrete of class C 20/25.	0,0000010	0,12	0,30	0,37
Fortification concrete of class C 40/45	0,0000008	0,16	0,60	
Fortification reinforced concrete of class C 40/45	0,0000007	0,11	0,25	0,33
with flexible spall liner	0,0000008	0,13	0,52	
with rigid spall liner	0,0000008	0,13	0,42	
Monolithic reinforced concrete structures of concrete C45/60	0,0000007	0,11	0,25	0,33

Fig. 3. Coefficient of penetrability of the medium dvantages of the method [4]
Рис. 3 Коефіцієнт податливості середовища проникненню [4]

- Simplicity and convenience: The formula has a linear form and allows for quick calculations without the use of complex software. It is ideal for rapid assessment in field or engineering conditions.
- Clear physical meaning of parameters: All variables (mass, diameter, speed, angle of incidence) are understandable and easily measurable.
- Experimental confirmation: The methodology is based on a large number of field tests; therefore, for typical materials (concrete, reinforced concrete, soil), it provides sufficiently accurate results for engineering purposes.

Disadvantages of the method:

- Empirical nature: The formula depends on empirical coefficients that are selected for specific materials. If the material of the protective structure is non-standard (for example, ultra-strong fibre concrete), the accuracy of the calculation sharply decreases.
- Limited speed range: The formula works correctly within the range of speeds typical for ordinary artillery shells and fragments. At hypersonic speeds or in the case of cumulative jets, the physics of the process change, and the linear dependence ceases to be valid.
- Ignoring the material dynamics: The methodology considers the final result (depth), but does not account for wave processes within the wall, the formation of chips from the back side, or the interaction of the fragment directly with the reinforcement.

Energy method (or energy balance method)

This method has gained widespread popularity in Western European countries (France, the United Kingdom). It is based on the law of conservation of energy.
According to this method, the penetration thickness is determined by the formula (2)

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

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

The kinetic energy of the projectile (J) should be determined using the formula (3):

$$E_k = \frac{1}{2} m V^2 \qquad (3)$$

m – mass of the projectile, kg;
V – projectile velocity, m/s

The average stresses are determined by the formula (4):

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

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

The alpha (α) and beta (β) coefficients, which depend on the material and shape of the projectile or fragment, are determined from the tables shown in Fig. 4.

Parameter values for steel target

	α	β	σ_t	ξ
Conical nose	$\frac{1}{2}\left[1+\ln\frac{2E}{(5-4v)R_y}\right]$	$2\sin\frac{\theta}{2}$	R_y	0
Flat nose	$\frac{1}{2}\left[1+\ln\frac{2E}{(5-4v)R_y}\right]$	2	R_y	-
Ogive nose	$\frac{2}{3}\left[1+\ln\frac{E}{3(1-v)R_y}\right]$	$\frac{3}{4\psi}$	R_y	0
Hemispherical nose	$\frac{2}{3}\left[1+\ln\frac{E}{3(1-v)R_y}\right]$	$\frac{3}{2}$	R_y	0
Eroding penetration	$\frac{2}{3}\left[1+\ln\frac{E}{3(1-v)R_y}\right]$	$\frac{3}{2}$	R_y	1

Parameter values for concrete and soil targets

	α	β	σ_t	ξ
Conical nose	$\frac{1}{2}\left[1+\ln\frac{2E}{(5-4v)f_c}\right]$	$2\sin\frac{\theta}{2}$	f_c	-
Flat nose	$\frac{1}{2}\left[1+\ln\frac{2E}{(5-4v)f_c}\right]$	2	f_c	-
Ogive nose	$\frac{2}{3}\left[1+\ln\frac{E}{3(1-v)f_c}\right]$	$\frac{3}{4\psi}$	f_c	2
Hemispherical nose	$\frac{2}{3}\left[1+\ln\frac{E}{3(1-v)f_c}\right]$	$\frac{3}{2}$	f_c	2

Fig. 4. Parameter values for mean stress determination [4]
Рис. 4. Значення параметрів для визначення серед ніх напружень [4]

Advantages of the methodology:

- Fundamentality: It is based on the law of conservation of energy, which makes it physically transparent and understandable for explanation.
- Versatility of input data: Allows operating with energy as a comprehensive parameter, without breaking it down separately into mass and velocity at each stage.
- Ease of adaptation: Convenient for comparative analysis of the effectiveness of different ammunition, if their energy is known.

Disadvantages of the method:

- Idealisation of the process: The method assumes that the resistance force of the material is constant throughout the entire penetration path, which is not the case in reality (resistance varies depending on speed and depth).

- The absence of a time factor: The energy balance shows the final state but does not describe the dynamics of the process over time (rate of deformation).

Engineering methodology of the US National Defence Research Committee

This method is the most common in Western engineering practice (in particular, in the standards of the USA and NATO countries). The difference between this method and the previous two is that it uses its own empirical formula for the main types of materials.

So, to calculate the penetration of ammunition or shrapnel into reinforced concrete, the formula for determining the depth of penetration takes the form (5):

$$h_t = \frac{56.6\left(\frac{m}{d^3}\right)^{0.075} \bar{N} m V^{1.8}}{d^2\sqrt{f_c}} \left(\frac{d}{c}\right)^{0.15} f_{age} + d \qquad (5)$$

where h_t - maximum concrete penetration thickness by projectile, mm;
d - projectile diameter, mm;
m - mass of the projectile, kg;
V - projectile speed, m/s;
f_c - compressive strength of concre-te, MPa; c – maximum stone size, mm (19 mm for heavy concrete and 4 mm for concrete masonry);
$\bar{N}$ - projectile end shape coefficient according to Annex C UFC 4-023-07 [18];
f_{age} – concrete age coefficient, which should be taken as:
1.05 - for concrete less than 28 days old;
1.02 - for concrete aged from 28 to 66 days;
1.01 - for concrete aged from 66 to 360 days;
1.00 - for concrete aged more than 360 days.
$\bar{N}$ = 0.91 – for low threat severity;
$\bar{N}$ = 1.26 – for medium threat severity level;
$\bar{N}$ = 1.39 – for a high level of threat severity;
$\bar{N}$ = 1.31 – for a very high level of threat severity;

The residual velocity of the projectile after penetrating an obstacle can be calculated using the formula (6):

$$V_r = V\left(1 - \frac{t_{conc}}{h_t}\right)^{0.733} \qquad (6)$$

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

To determine the maximum penetration thickness of a steel obstacle in UFC 4-023-07, it is recommended to use the following formula (7):

$$h_t = d\left(\frac{Vm^{0.5}\cos^{0.8}\theta}{1.125d^{1.5}\log_{10} BHN}\right)^{1.25} \qquad (7)$$

where h_t - maximum steel penetration thick-ness, mm;
d - projectile diameter, mm;
m - ammunition mass, kg;
V – projectile velocity, m/s;
θ - obstacle inclination angle from steel, degrees;
BHN - Brinell hardness number, for ordinary steels 110–160, for armour steels 220–350.

The residual velocity of the projectile after penetrating steel obstacles in accordance with UFC 4-023-07 21 should be determined using the formula (8):

$$V_r = \left(V^2 - \left[\frac{1.1275\left(\frac{t}{d}\right)^{0.8} d^{1.5}\log_{10} BHN}{m^{0.5}\cos^{0.8}\theta}\right]^2\right)^{0.5} \qquad (8)$$

where t - actual thickness of the steel, m;
d - diameter of the projectile, mm;
m - mass of the ammunition, kg;
V - velocity of the projectile, m/s;
θ - angle of inclination of the steel obstacle, degrees;
BHN – Brinell hardness number, for ordinary steels 110–160, for armour steels 220–350.

To determine the maximum penetration thickness of an obstacle made of wood, UFC 4-023-07, it is recommended to use the formula (9):

$$h_t = 0.64 \frac{V^{0.4113} m^{1.4897}}{\rho \left(\frac{\pi d^2}{4} \right)^{1.3596} H^{0.5414}} \qquad (9)$$

where h_t - maximum drilling thickness of the wood, m;
d - projectile diameter, m;
m mass of the projectile, kg; V – velocity of the projectile, m/s;
ρ - wood density, kg/m³;
H- wood hardness, kg.

Although we note that the hardness values are for American and European timber, for our purposes of performing similar calculations, we need to standardise these data for our own timber.

The residual velocity of the projectile after penetrating obstacles made of wood should be determined according to UFC 4-023-07 using the formula (10):

$$V_r = V \left[1 - \left(\frac{t}{h_t} \right)^{0.5735} \right] \qquad (10)$$

where t - the actual thickness of the wood, m.

Advantages of the method:

- High accuracy for different materials: These formulas are considered the 'gold standard' for calculating concrete barriers, steel plates, and wooden barriers, as they take into account the specific characteristics of the material (for concrete, this includes the concrete strength, aggregate size, and concrete age).
- A wide testing base: The methodology relies on a vast array of experimental data obtained by US military engineers.

Disadvantages of the method:

- Difficulty of calculation: The formula contains fractional exponents, which complicate manual calculation;
- Speed limitation: The formula gives an error at high impact speeds when the projectile begins to deform (it is designed for a 'rigid' non-deformable projectile).

To analyse the results of calculations using different methodologies in this work, a reinforced concrete element was calculated using various concrete classes. The results of the calculation were also compared with the parameters specified in Tables 14 and 13 of DBN B.2.2-5:2023 'Protective Structures of Civil Defence'. The calculation was carried out for threats posed by fragments from the explosions of UAVs and missiles, in accordance with the latest recommendations of the Central Directorate of Military Education and Science of the General Staff of the Armed Forces of Ukraine, as shown in Fig. 5.

UAV	
TNT equivalent weight of warhead charge, kg	100
Impact velocity, m/s	145
Impact angle, °	20-60
Fragment dimensions, A x B x C (thickness), cm; mass, g	9 x 2 x 0,7; 80
Initial fragment velocity, m/s	2300
Missile	
TNT equivalent weight of warhead charge, kg	718,2
Impact velocity, m/s	800
Impact angle, °	80-90
Fragment dimensions, A x B x C (thickness), cm; mass, g	3,5x3,5 (Cylindrical shape)
Initial fragment velocity, m/s	2380

Fig. 5. Threats from fragments caused by UAV and missile explo-sions in accordance with the latest recommendations of the Central Directorate of Mili-tary Education and Science of the General Staff of the Armed Forces of Ukraine

Рис. 5 Загрози від уламків при вибуху БпЛА та ракети відповідно до останніх рекомендацій Централь-ного управління військ-кової освіти та науки Генераль-ного штабу Збройних Сил України

Table 1. Penetration depth of reinforced concrete elements by missile blast fragments
Табл. 1. Глибина пробиття залізобетонних елементів при враженні уламками від вибуху ракети

Class of concrete	Depths of drilling into the reinforced concrete element, mm			
	DBN V.2.2-5: 2023	Method of Berezan V.I.;	Energy method	Engineering Methodology NDRC
C20/25	350	340	497	512
C25/30	330	340	457	476
C30/35	320	310	440	446
C35/42	310	290	425	422

Table 2. Penetration depth of reinforced concrete elements by UAV blast fragments
Табл. 2. Глибина пробиття залізобетонних елементів при враженні уламками від вибуху БпЛА

Class of concrete	Depths of drilling into the reinforced concrete element, mm			
	DBN V.2.2-5: 2023	Method of Berezan V.I.;	Energy method	Engineering Methodology NDRC
C20/25	350	410	615	458
C25/30	330	410	565	425
C30/35	320	340	544	399
C35/42	310	270	525	377

As we can see from the calculation results, the energy method and the engineering methodology of the US National Defence Research Committee give quite similar results, but they significantly exceed the required thickness according to the Berazan method,
which in turn is quite close to the thickness values given in DBN V.2.2-5:2023 "Civil Defense Protective Structures"[2].

CONCLUSIONS AND PROSPECTS FOR FURTHER RESEARCH

Based on these results, it can be concluded that when calculating according to the methodologies of the USA and the United Kingdom, the recommended wall thicknesses are not sufficient in accordance with DBN B.2.2-5:2023 'Civil Defence Protective Structures'. A promising direction for further research is improving the calculation method for penetrative effects on various obstacle materials and all potential damage mechanisms. Developing modern calculation methods, considering existing military threats, will enable the most effective construction of engineering protective and fortification structures, which will significantly support the realisation of the 'Country-Fortress' concept.

It should be noted that a critical task is the development of modern regulatory documents that would regulate the basic requirements and calculation methods for fortification and protective structures of various purposes, taking into account contemporary military threats.

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

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Анотація. У поточних реаліях, що склалися внаслідок повномасштабної збройної агресії рф проти України, а також з огляду на стрімкий технологічний розвиток високоефективних засобів ураження, проблематика забезпечення надійності та стійкості фортифікаційних і захисних споруд набула безпрецедентної актуальності. Критичним завданням інженерного захисту стає протидія широкому спектру загроз, що включає проникну дію куль стрілецької зброї, кумулятивних струменів, бронебійних снарядів, а також руйнівний вплив осколково-фугасних боєприпасів.

Вплив цих факторів не обмежується лише локальними пошкодженнями, такими як пробиття чи відкол елементів конструкції. Він визначає загальну живучість об'єкта — його здатність зберігати цілісність, несучу здатність та основні функціональні характеристики безпосередньо під час інтенсивного вогневого впливу. Для прогнозування поведінки споруд використовується широкий спектр методик: від аналітичних та емпіричних підходів до складного чисельного моделювання.

Достовірність та точність таких прогнозів напряму залежать від комплексного врахування вхідних параметрів. По-перше, це кінематичні характеристики вражаючих елементів: їхня маса, вектор швидкості, кут зустрічі з перешкодою та форма. По-друге, вирішальну роль відіграють фізико-механічні властивості матеріалів самої перешкоди, зокрема динамічна міцність, гранична пластичність, ударна в’язкість та ступінь гетерогенності структури (наприклад, у залізобетоні). По-третє, важливими є геометрія та конструктивні рішення захисних елементів, такі як багатошаровість або наявність рознесеного бронювання.

У практичній площині існує чіткий розподіл застосування методів розрахунку. Емпіричні формули, завдяки своїй простоті, є незамінними на етапах ескізного проєктування для отримання швидких, хоча й наближених оцінок. Натомість сучасні чисельні методи, що реалізуються через метод скінченних елементів (МСЕ) дозволяють з високою точністю відтворити механізми взаємодії снаряду з конструкцією у часі та просторі.

Ключові слова: інженерна методика; уламки; боєприпаси; БпЛА; ракета.

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