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ANALYSIS OF STRUCTURAL FAILURE MECHANISMS IN BUILDINGS SUBJECTED TO BLAST LOADS

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Abstract. This paper presents a comprehensive analysis of damage to buildings and infrastructure resulting from military actions, with a particular emphasis on modern conflicts and their devastating consequences. The primary focus is on a profound examination of various factors causing deformation and destruction: from the destructive effects of explosive shock waves and dynamic loads to mechanical impacts (shrapnel, direct hits) and intense thermal factors (fires, high-temperature exposures).The study encompasses a representative sample of over 150 structures of various types, located in active combat zones. This enabled a detailed examination of typical failure and degradation mechanisms in key structural systems, such as panel buildings, traditional brick masonry, monolithic and precast reinforced concrete structures, as well as lightweight frame and rapidly assembled constructions. Key findings confirm the empirically established pattern that the intensity of damage decreases exponentially with increased distance from the explosion's epicenter, which is crucial for hazard zoning. A significant correlation was also established between the nature of the consequences, the type of explosion (airburst, ground-level, subsurface), its power, and the structural features that determine a building's inherent resilience to external influences. To accurately assess the parameters of explosive waves, including their pressure, impulse, and duration, advanced methods were employed. These methods combine empirical formulas derived from field tests with high-precision numerical modeling using the finite element method (FEM). Based on the comprehensive analysis, a set of practical recommendations is proposed. They include the use of more durable, ductile, and energy-absorbing materials, the retrofitting and strengthening of existing buildings, and the optimization of urban planning solutions, considering principles of protective design and infrastructure dispersion. The objective of this work is not only to document and analyze damages but also to significantly improve existing methodologies for calculating structural responses to blast loads. Furthermore, the study investigated the impact of secondary factors such as collapses, ground deformations, and subsequent settlements, which often accompany primary destructions and exacerbate the overall condition of affected objects.

Keywords: structural damage, blast loads, building resilience, damage assessment.

Relevance and statement of the problem. Explosions, whether from military activity, industrial accidents, or terrorist attacks, present unique challenges for structural engineering. Buildings, often designed for static and wind loads, are not equipped to handle the dynamic pressures of explosive shock waves. This study synthesizes findings from Ukraine and other conflict zones, providing a comprehensive analysis of damage mechanisms and offering global solutions for improving building resilience.

The analysis of the technical condition of buildings and structures was conducted based on inspections of more than 150 objects.

The loads and impacts experienced by structures during military operations have unique characteristics, as the industrial and civil buildings were not originally designed to withstand the following effects and loads associated with military actions:

- the impact of explosion shock waves;

- mechanical damage caused by missile strikes, shell impacts, fragments, and debris;
- dynamic loads resulting from shock waves or structural vibrations;
- thermal effects caused by fires.

Analysis of recent research and publications. Drawing on the extensive data provided in recent reports and studies [1-4], this section outlines the key findings related to the types of damage sustained, the methodologies employed in assessing these damages, and the factors influencing the severity of destruction. Damage from Explosive Shock Waves. Direct Effects: explosive shock waves cause widespread cracking, displacement, and destruction of both load-bearing and non-load-bearing structures. The formation of cracks and spalling in concrete and masonry walls, particularly near the explosion epicenter [1, 4]. The complete collapse of prefabricated panel buildings when exposed to close-range aerial bomb strikes [3].

Indirect Effects: shock waves generate vibrations that weaken structural connections, leading to secondary failures such as the collapse of window frames and ceilings [2].

Mechanical Damage from Fragments and Projectiles. Penetration and Fragmentation: high-velocity projectiles, including shrapnel and bullet fragments, cause perforations in walls and structural elements. These effects are particularly severe in lightweight construction [3, 4] Thermal Effects from Fires. The thermal effects of explosions result in the elongation and weakening of steel reinforcements and the destruction of combustible elements such as wooden beams and roofs [4]. Dynamic Loads and Vibrations. Prolonged exposure to dynamic loads from repeated shelling leads to structural fatigue, affecting the overall stability of buildings even without direct hits [1, 4].

Damage Patterns by Building Type. Panel Buildings. Most vulnerable to direct explosive impacts due to weak connections between prefabricated panels. Damage includes the detachment of panels, extensive cracking, and partial or complete collapse [3]. Brick Masonry Structures. Characterized by cracks at the corners and intersections of walls. Delamination and spalling are common, with significant damage concentrated near the explosion epicenter [4]. Reinforced Concrete Structures. More resilient to shock waves but experience localized damage such as spalling and cracking in beams and columns. Progressive collapse is often mitigated by the redistribution of loads [1, 3]. Lightweight and Temporary Structures. Wooden and lightweight metal structures are the least resilient, with widespread destruction even at moderate distances from explosion epicenters [2, 4]. Factors Influencing Damage Severity. Distance from Explosion: The intensity of damage decreases exponentially with distance, with near-epicenter structures experiencing catastrophic failure [1, 3].

Explosion Type: Airbursts cause widespread but less intense damage compared to ground-level explosions, which produce concentrated pressure loads [4]. Obstacles and Building Orientation: the presence of adjacent structures or natural barriers influences the distribution of shock wave forces and can shield or amplify damage [3]. Structural Characteristics: buildings with high spatial rigidity, such as monolithic-frame constructions, demonstrate greater resistance to collapse [1, 4].

Buildings and structures are most commonly affected by explosion shock waves. An explosion shock wave is a specific type of disturbance that occurs in the surrounding medium during an explosion (caused by high explosives, dust, or gas). It is characterized by a sudden, abrupt increase in pressure accompanied by compression, heating, and changes in the velocity of the medium.

An explosion shock wave in the air represents the explosion's propagation surface, moving at speeds of 300 m/s or more. A visual example of an explosion shock wave in the air can be seen in Fig. 1.

An explosion shock wave creates a load along the front of its propagation. Typically, the load (pressure on the wave's surface) acts perpendicular to the vertical surfaces of a building (walls, windows, doors) and spreads at a high velocity [5].

Purpose and tasks. The purpose of this work is to develop new engineering solutions and design standards that will enhance the safety, resilience, and survivability of civilian infrastructure in the face of hybrid threats and military conflicts, by thoroughly analyzing damages and improving methodologies for calculating structural responses to blast loads. The main tasks are determined:

- to conduct a comprehensive analysis of damage patterns and typical failure mechanisms in over 150 structures of various types (panel buildings, brick masonry, reinforced concrete, lightweight

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constructions) subjected to military actions, focusing on the destructive effects of explosive shock waves, dynamic loads, mechanical impacts, and thermal factors;

Fig. 1. Formation and propagation of an explosion shock wave in the air

- to establish and quantify the correlation between damage intensity, distance from the explosion's epicenter, type of explosion (airburst, ground-level, subsurface), its power, and the inherent structural features that determine a building's resilience;
- to utilize and integrate advanced methods, including empirical formulas and high-precision finite element modeling (FEM), for accurately assessing explosive wave parameters and simulating complex interactions between blast waves and different structural systems, thereby predicting their response to various loading scenarios;
- to develop a set of practical recommendations for enhancing structural stability in existing and newly designed constructions under potential military threats, focusing on material selection (durable, ductile, energy-absorbing), retrofitting strategies, and optimized urban planning principles (protective design, infrastructure dispersion);
- to investigate the impact of secondary damage factors, such as collapses, ground deformations, and subsequent settlements.

Materials and methods of research. The research was carried out with the extensive use of systems analysis methods and statistical research, as well as field observations and detailed documentation of damaged structures. The study employed advanced analytical techniques, including empirical formulas derived from blast testing and high-precision numerical modeling using the finite element method (FEM) for simulating blast wave propagation and structural response. The proposed methods made it possible to identify, analyze, and build empirical and computational dependencies crucial for understanding damage mechanisms and proposing mitigation strategies.

The most severe damage caused by the shock wave affects the structures of external walls, including wall panels, brick masonry, enclosing structures, and transparent elements such as windows, skylights, gates, and doors[6].

The effect of air-based explosion shock waves on structures depends on the type of explosion: ground-level, airborne, or above-ground detonations. An air shock wave consists of two phases:

– Compression Phase, where the pressure exceeds atmospheric levels.

– Rarefaction Phase, during which the pressure drops below atmospheric levels (Fig.2).

The maximum pressure in the compression phase of an explosion shock wave significantly exceeds both atmospheric pressure and the pressure during the rarefaction phase. The key parameters of a shock wave propagating through the air from the explosion center are determined using empirical formulas [7, 8].

For an air explosion of a TNT charge [8]:

$$\Delta P_f = 0{,}084\frac{\sqrt[3]{c}}{R} + 0{,}27\frac{\sqrt[3]{c^2}}{R^2} + 0{,}7\frac{c}{R^3}, (\text{МПа}); \quad (1)$$

$$\tau_{(+)} = 1{,}5 \times 10^{-3}\sqrt[6]{c} \times \sqrt{R}, (c); \quad (2)$$

where c is the mass of the TNT charge (kg), and R is the distance from the explosion center (m) [9].

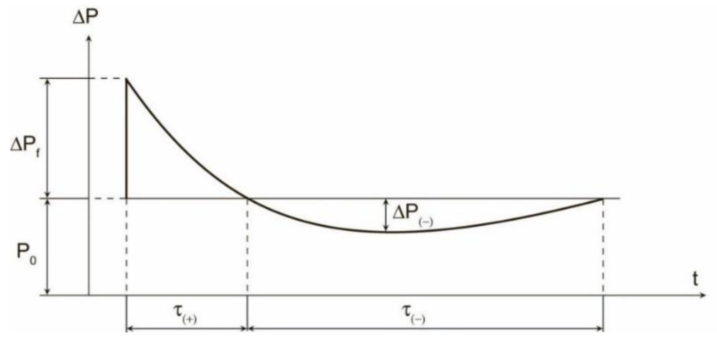

Fig. 2. Pressure variation graph along the front of the explosion shock wave

The change in pressure during the compression phase over time is determined by the following equation [8]:

$$\Delta P(t) = \Delta P_f \left(1 - \frac{t}{\tau_{(+)}}\right)^n, \quad 0 \le t \le \tau_{(+)}, \tag{3}$$

$$n = \Delta P_f \frac{\tau_{(+)}}{i} - 1, \qquad i = 6{,}3 \frac{\sqrt[3]{c^2}}{R}.$$

This corresponds to curve 1, shown in Figure 3 [10]. When calculating the effect of an air-based explosion shock wave on a structure, the linear dependence (line 2 in Figure 3) can be used as an alternative to equation (3).

$$\Delta P(t) = \Delta P_f \left(1 - \frac{t}{\Delta t}\right), \tag{4}$$

$\Delta t = \frac{2\tau_{(+)}}{n+1}$ – the effective duration of the shock wave, which is determined by the condition of impulse pressure equality.

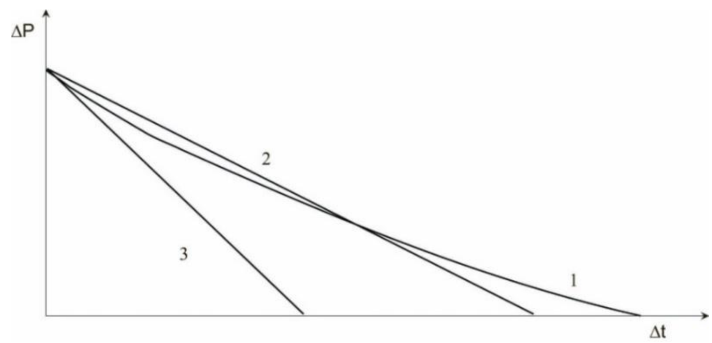

Fig. 3. Dependency of explosion pressure magnitude on time

The maximum reflection pressure $ΔP_V$, acting at the initial moment of time on a flat frontal obstacle perpendicular to the direction of wave propagation, reaches [8]:

$$\Delta P_V = 2\Delta P_f + \frac{6\Delta^2 P_f}{\Delta P_f + 0{,}72}, \tag{5}$$

and then decreases during the flow around the obstacle, according to the graph shown in Figure 4.

Fig. 4. Graph of the impact of the explosion shock wave on a building

The complete picture of the flow around the obstacle is shown in Figure 5.

The time ΔtO from the beginning of reflection to the onset of the flow-around regime:

$$\Delta t_O = \frac{3H}{D_f}, \quad (6)$$

Where H is the height of the frontal wall. (or 0,5b);$D_f = 340\left[1 + 8{,}3\Delta P_f\right]^{\frac{1}{2}}$, – and is the speed of the shock wave front.

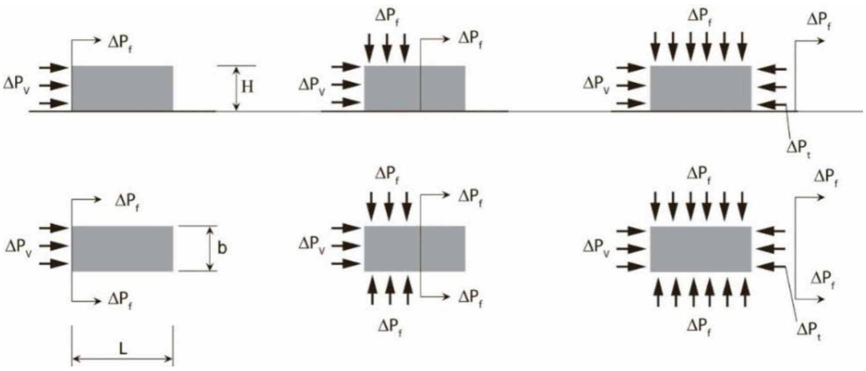

Fig. 5. Overall view of the impact of the explosion shock wave on the structure

When calculating the effect of explosive loads on structures, the actual laws of pressure variation over time are replaced with simplified ones, as shown in Figure 6.

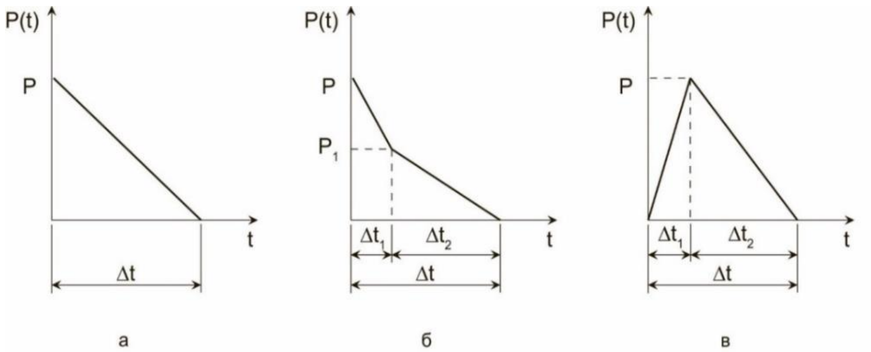

Fig. 6. Simplified laws of pressure variation over time

The load, the changes of which are shown in Figure 6, is used for calculating the roof and side walls (6a), frontal walls (6b), and the rear side of the structure (6c).

The functions used in the calculations depend on from $\Delta t\omega, \Delta t_1\omega, \Delta t_2\omega$,, where ω is the frequency of the natural vibrations of the structures [11].

If $t \geq \Delta t_1$or$\Delta t_2\omega \geq 50$, then during the calculation of the structure in the elastic stage, the load can be considered constant over time [12].

If the duration of the load is relatively short, such that$\Delta t\omega < \pi/2$, the structure can be calculated as being subjected to an instantaneous impulse.

$$I = \int_0^{\Delta t} P(t)dt. \quad (7)$$

If $\Delta t_1\omega \geq 20$, then the effect of the load on the structure will be equivalent to a static load P.

For engineering calculations of building structures subjected to air shock waves, simpler dependencies are used, as presented in works [1, 2], which allow for determining [8]:

$$\Delta P_f = 89{,}79\frac{r}{R} + 2204\left(\frac{r}{R}\right)^2 + 0{,}71;$$
$$\Delta P_V = \Delta P_f \frac{8\Delta P_f - 1}{\Delta P_f + 6}; \quad (8)$$
$$\Delta t = \frac{r}{D}\frac{6\Delta P_f + 1}{4\Delta P_f + 3},$$

$D_f = 306{,}7[\Delta P + 1{,}18]^{\frac{1}{2}}$–the velocity of the air shock wave;

$\Delta P = \Delta P_f - P_0; r = 0{,}062\left(\frac{c}{\gamma}\right)^{\frac{1}{3}}$–the average radius; γ– the specific weight of the charge.

Research results. During the analysis of structural damage caused by military operations, it was found that the damage to the structure occurs as a result of the air shock wave, mechanical damage from the delivery of explosive devices, and dynamic loads [13, 14].

The greatest damage from the shock wave is typically observed in the external walls of buildings, external wall panels of residential buildings, and transparent elements that are oriented perpendicular to the shock wave's propagation front.

It should be noted that as the explosion distance from the object increases, the speed and pressure of the shock wave at the front of the wave decrease significantly, inversely proportional to the square of the distance from the explosion's epicenter to the object. At a large distance, the shock wave degenerates into a sound wave.

The speed of propagation of the sound wave is lower than the speed of sound, but even at a speed exceeding 100 m/s, it causes significant damage to transparent elements (windows), roofing, and roof structures.

The shock wave in the ground quickly dissipates and cannot be considered as a factor of destruction. The fastest attenuation of the shock wave is observed in non-cohesive soils. Even at small distances from the explosion (within 6–10 meters), the foundations of buildings experience almost no damage, except in cases where the explosive device directly hits the upper part of the foundation.

Building damage also occurs due to mechanical destruction caused by the impact of explosive delivery devices (Figure 7).

Fig. 7. Mechanical destruction of building structures in the elevator shaft by an explosive delivery device (the explosive device did not detonate)

The greatest damage to the building's structure occurs as a result of the simultaneous impact of the explosion shock wave and the mechanical action of the explosive delivery device (Figure 8).

Fig. 8. Panel building structures damaged as a result of the explosion shock wave and the impact of the explosive delivery device (the explosion occurred inside the building)

Significant damage occurs in the structures of lightweight concrete wall panels and self-supporting external wall structures (brick masonry, ceramic block masonry). These structures have relatively low mass and low inertia, which is why they respond quickly to excitation. Panel buildings, in which external wall panels and ceiling slabs are made of heavy concrete, are more resistant to the effect of the shock wave.

It should be noted that panel buildings with load-bearing external and internal transverse walls have quite high spatial rigidity, especially buildings with a square floor plan (for example, single-section 16-story panel buildings).

If the explosive device detonates inside the building, the shock wave propagation affects the structure from the inside. Significant damage from such explosions occurs to the external enclosing structures, leading to their collapse and the destruction of parts of the building (Figure 9).

Monolithic-frame buildings exhibit the highest resistance to the effects of explosion shock waves. Significant damage typically occurs in non-load-bearing enclosures and partitions. The building's frame elements, pilasters, columns, and monolithic slabs experience defects such as chips and cracks. In powerful explosions, the structural frame elements undergo destruction. However, the forces in the frame elements are redistributed, preventing progressive collapse.

Frame buildings (reinforced concrete, steel, or mixed-frame structures) suffer damage in the form of concrete spalling, cracking, and deformation. In large explosions, individual structural elements collapse. In single-story industrial buildings, separate ceiling panels, beams, and trusses may collapse. Fragmentation damage affects ceiling panels, beams, trusses, and columns. There may also be damage to the joints, but this usually does not lead to the overall collapse of the building.

Fig. 9. Destruction of the building's structure due to an explosion inside the building

In buildings with a steel frame, explosions cause significant deformations, bending, and rupture of elements. In intense explosions, the cross-sections of metal elements, the frame, connection joints, welds, bolts, and the formation of through holes in the metal structures may be destroyed. Major explosions can lead to the collapse of trusses, purlins, and roof structures (Figure 10).

Fig. 10. Destruction of metal structures of the roof in an industrial building

In the case of powerful internal explosions, significant or complete destruction of the external enclosing structures occurs, while the frame elements are preserved (Figure 11).

Fig. 11. Destruction of the external enclosing structures of a frame building due to an internal explosion

In panel buildings, depending on the location of the impact zone and the explosion’s strength, cracks, chips, significant deformations, and destruction occur in the walls. Significant linear or angular displacements arise at the junctions of the panels, weld seams, anchoring details fail, and stretching or destruction occurs in the connecting metal elements. In large explosions, the collapse of wall structures, floors, balconies, and staircases within the structural blocks (sections) may occur (Figures 12).

Brick walls of buildings, due to significant kinetic impact from the delivery of explosive devices, suffer damage in the form of holes in the structures, chips, cracks, and delamination of the masonry. Significant vertical cracks develop at the corners of walls and at their intersections, leading to the separation of sections of walls and a substantial reduction in their spatial rigidity. Wooden floor structures in brick buildings experience significant damage and destruction over several floors. The destruction of reinforced concrete slabs is more limited, resulting in cracks and significant deformations. In the case of large explosions, the destruction of external walls leads to the complete collapse of floor slabs (Figure 12).

Fig.12. Destruction of floor slabs, wall panels, and panel connection joints in a residential building

In brick buildings with a wooden truss roof system, explosions within the attic lead to partial or complete destruction of the truss system and roof. The collapse of destroyed elements occurs on the roof slab or, if it is also destroyed, on the inter-floor slab structure (Figure 13).

Buildings with wooden load-bearing walls, wooden floor structures, and wooden roofs, when subjected to minor explosions, experience defects and damage in the form of cracks, destructions, and significant deformations of the entire structure, typically rendering them unfit for further use.

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Fig. 13. Damage to wooden roof structures caused by the explosion shock wave

Conclusion. Explosive shock waves present unique and severe challenges to structural integrity, particularly in conflict zones. Empirical studies from Ukraine, the Middle East, and other regions reveal consistent patterns of damage and highlight the importance of engineering innovations. Proactive design, retrofitting, and urban planning can significantly mitigate risks, protecting lives and infrastructure worldwide.

1. Material Advancements. Ultra-High-Performance Concrete (UHPC): Provides superior resistance to compressive forces. Blast-Resistant Glass: Reduces injuries and secondary damage from glass fragmentation.

2. Structural Reinforcements. Cross-bracing and shear walls improve stiffness and distribute dynamic loads. Enhanced connections between structural components reduce progressive collapse risks.

3. Urban Planning. Zoning regulations should ensure adequate distances between industrial facilities and residential areas. Protective barriers and blast walls can shield critical infrastructure.

4. Advanced Computational Tools. Finite Element Analysis (FEA) allows engineers to model blast impacts accurately, identifying failure points and optimizing designs for blast resistance.

Recommendations for Global Applications [15]:

– Standardized Blast-Resistant Codes: International guidelines should integrate findings from conflict zones to develop robust building standards [15].

– Retrofitting Existing Infrastructure: Governments and engineers should prioritize retrofitting critical buildings with blast-resistant technologies.

– International Collaboration: Sharing data from conflict zones, such as Ukraine and Syria, can advance global engineering practices and save lives in future scenarios.

References

[1] O.I. Meneilyuk, I.O. Meneilyuk, V.V. Russiy, "Doslidzhennya stanu budivel ta sporud poshkodzhenykh vnaslidok voyennykh diy", *Budivelne Vyrobnytstvo*, vol. 75, pp. 17-26, 2023. [Online]. Available: https://ndibv-building.com.ua/index.php/Building/article/view/439/202. Accessed on: September 19, 2025.

[2] "Report on damages to infrastructure from the destruction caused by Russia's military aggression against Ukraine as of January 2024", Kyiv School of Economics, Kyiv, Ukraine, 2024. [Online]. Available: https://kse.ua/wp-content/uploads/2024/05/Eng_01.01.24_Damages_Report.pdf. Accessed on: September 19, 2025.

[3] S. Shatov, D. Goncharov, D. Nikolayev, "Determination of the parameters of destruction of construction objects as a result of military operations", *Materialy naukovo-praktychnoi konferentsii studentiv, aspirantiv i molodykh vchenykh*, Dnipro, Ukraine, 2023, pp. 572-574. [Online]. Available: http://srd.pgasa.dp.ua:8080/xmlui/handle/123456789/10594. Accessed on: September 19, 2025.

[4] O.S. Molodid, O.Yu. Kovalchuk, V.I. Skochko, R.O. Plokhuta, O.O. Molodid, I.V. Musiiaka, "Inspection of war-damaged buildings and structures by the example of urban settlement Borodianka", *Strength of Materials and Theory of Structures*, vol. 110, pp. 328-342, 2023. [Online]. Available: http://omtc.knuba.edu.ua/article/view/284943. Accessed on: September 19, 2025.

[5] V.V. Russiy, "Analyz prykladiv poshkodzhen' viiskovoho kharakteru v tsetlyanykh budivel", *Naukovyi visnyk budivnytstva*, vol. 104, no. 2, pp. 208-211, 2021. [Online]. Available: https://svc.kname.edu.ua/index.php/svc/article/view/106. Accessed on: September 19, 2025.

[6] A.V. Kovrov, O.I. Meneilyuk, V.V. Russiy, "Matematychne modelyuvannya optymizatsiyi protsesiv likvidatsiyi poshkodzhen' tsetlyanykh budivel", in *IV Mizhnarodna naukovo-praktychna konferentsiya "Enerhooshchadni mashyny i tekhnolohiyi"*, Kyiv, Ukraine, 2023, pp. 134-138. [Online]. Available: http://esmt.knuba.edu.ua/wp-content/uploads/2023/07/ESMT_2023_Conference_proceedings_Le_finale.pdf. Accessed on: September 19, 2025.

[7] N.M. Bezuhov, O.V. Luzhin, *Stability and Dynamics of Structures in Examples and Problems*. New York, NY, USA: Van Nostrand Reinhold, 1987.

[8] *Dinamicheskiy Raschet Sooruzheniy na Spetsialnye Vozdeystviya: Spravochnik Proektirovshchika*. Stroyizdat, 1981.

[9] B. Basok, O. Nedbailo, D. Davydenko, N. Bespala, "Physical factors of the influence the explo-sion on enclosure glass structures. Overview of testing methods", *Energy: Economics, Technologies, Ecology*, vol. 2, pp. 88-94, 2024. [Online]. Available: https://ela.kpi.ua/server/api/core/bitstreams/f60f06f8-3daa-49e7-aba1-1efeab4e1ba6/content. Accessed on: September 12, 2025.

[10] L. Kutsenko, E. Sukharkova, D. Saveliev, V. Kokhanenko, M. Zhuravskij, "Method of simulation of reflected explosive waves from the cylindrical surface of the sinusoidal profile", *Problems of Emergency Situations*, vol. 38, 2023. [Online]. Available: http://repositsc.nuczu.edu.ua/handle/123456789/19750. Accessed on: September 12, 2025.

[11] J. Krishna Vaishnavi, B. Murali Krishna, "Determination of response of multistorey structure subjected to blast loading", *Journal of Building Pathology and Rehabilitation*, vol. 7, no. 1, p. 75, 2022. [Online]. Available: https://doi.org/10.1007/s41024-022-00222-6.

[12] V. Ambavaram, A. Muddarangappagari, A. Mekala, R. Chenna, "Dynamic performance of multi-storey buildings under surface blast: A case study", *Innovative Infrastructure Solutions*, vol. 6, no. 3, pp. 1-14, 2021. [Online]. Available: https://doi.org/10.1007/s41062-021-00585-y.

[13] "Poriadok provedennia obstezhennia pryiniatykh v ekspluatatsiiu obiektiv budivnytstva", Resolution No. 257 of the Cabinet of Ministers of Ukraine, Kyiv, Ukraine, Apr. 12, 2017 (with amendments adopted by Resolution No. 423 of the Cabinet of Ministers of Ukraine, Apr. 5, 2022). [Online]. Available: https://zakon.rada.gov.ua/laws/show/257-2017-п#n8. Accessed on: August 10, 2025.

[14] "Metodyka obstezhennia budivel ta sporud, poshkodzhenykh v naslidok nadzvychainykh sytuatsiy, boiovykh dii ta terorystychnykh aktiv" Order No. 144 of the Ministry of Development of Communities and Territories of Ukraine, Kyiv, Ukraine, Aug. 6, 2022. [Online]. Available: https://zakon.rada.gov.ua/laws/show/z0898-22#Text. Accessed on: August 10, 2025.

[15] "Recovery Plan for Ukraine," National Council for the Recovery of Ukraine from the Consequences of War, Kyiv, Ukraine, 2022. [Online]. Available: https://www.kmu.gov.ua/storage/app/sites/1/recoveryrada/ua/audit-of-war-damage.pdf. Accessed on: August 10, 2025.

АНАЛІЗ МЕХАНІЗМІВ РУЙНУВАННЯ БУДІВЕЛЬНИХ КОНСТРУКЦІЙ ПРИ ВИБУХОВИХ НАВАНТАЖЕННЯХ

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Анотація. У цій статті представлено всебічний аналіз пошкоджень будівель та інфраструктури, що сталися внаслідок військових дій. Основна увага зосереджена на вивченні різноманітних факторів, що спричиняють деформації та руйнування: від руйнівних ефектів вибухових ударних хвиль та динамічних навантажень до механічних ударів (уламки, прямі влучення) та інтенсивних термічних факторів (пожежі, високотемпературні впливи). Дослідження охоплює репрезентативну вибірку з понад 150 споруд різного типу, розташованих у зонах активних бойових дій. Це дозволило детально вивчити типові механізми руйнування та деградації в ключових конструктивних системах, таких як панельні будівлі, традиційна цегляна кладка, монолітні та збірні залізобетонні конструкції, а також легкі каркасні та швидкомонтовані споруди. Ключові висновки підтверджують емпірично встановлену закономірність, що інтенсивність пошкоджень експоненціально зменшується зі збільшенням відстані від епіцентру вибуху, що має вирішальне значення для зонування небезпеки. Встановлено значну кореляцію між характером наслідків, типом вибуху (повітряний, наземний, підземний), його потужністю та конструктивними особливостями, що визначають притаманну стійкість будівлі до зовнішніх впливів. Для точної оцінки параметрів вибухових хвиль, їх тиску, імпульсу та тривалості були використані передові методи, що поєднують емпіричні формули та високоточне чисельне моделювання методом скінченних елементів (МСЕ). На основі проведенного аналізу запропоновано комплекс рекомендацій, спрямованих на підвищення стійкості існуючих та проєктування нових конструкцій в умовах потенційних військових загроз. Ці рекомендації включають використання більш міцних, пластичних та енергоємних матеріалів, модернізацію та посилення існуючих будівель. Метою цієї роботи є не лише документування та аналіз пошкоджень, а й суттєве вдосконалення існуючих методик розрахунку реакції конструкцій на вибухові навантаження. Це дослідження є важливим внеском у розробку нових інженерних рішень та стандартів проєктування, що сприятимуть підвищенню безпеки та живучості цивільної інфраструктури в умовах гібридних загроз та військових конфліктів.

Ключові слова: пошкодження конструкцій, вибухові навантаження, стійкість будівель, оцінка пошкоджень.

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