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ADAPTATION OF SEISMIC RESISTANCE PRINCIPLES FOR ENSURING BLAST RESISTANCE OF HIGH-RISE BUILDINGS

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Abstract. The strategic necessity and engineering mechanisms for adapting the principles of seismic-resistant design to ensure the blast resistance of multi-storey buildings in the context of the war in Ukraine are analyzed. The key goal is to prevent Progressive Collapse (PC) of structures caused by localized impulsive loads, which differ radically from cyclic seismic effects but, like them, necessitate the engagement of the plastic (post-limit) behavior of materials in building structures.

In the context of the ongoing military conflict in Ukraine, the design of high-rise buildings requires a radical restructuring, shifting the focus from traditional gravity and seismic loads (DBN V.1.1-12:2014, DBN V.2.2-41-2019) to extreme impulsive loads from explosions. The main threat is Progressive Collapse (PC), which arises after the localized failure of a key element. According to European standards (Eurocode EN 1991-1-7), the engineering objective changes: it is not to prevent damage, but to prevent its disproportionate propagation.

The introduction of the new DBN V.2.2-5:2023, which radically increased the design blast pressure to 100 kPa for protective structures, implicitly forces engineers to use Non-Linear Dynamic Analysis (NDA) methods. The article substantiates that the principles of seismic-resistant design – ductility and redundancy – are a critical basis for enhancing blast resistance, despite the differences in the frequency characteristics of the loads.

A key solution is the hybridization of national requirements with international methodologies for counteracting PC, specifically the Alternate Path (AP) method and the implementation of Tie Forces (TF), which ensure structural integrity after the removal of a vertical support by realizing the catenary action of the slabs. This requires adapting ASCE 41 acceptance criteria and utilizing innovative materials, such as Ultra-High Performance Fibre-Reinforced Concrete (UHPFRC), for effective structural strengthening. The study concludes the necessity of hybridizing Ukrainian requirements for local protective structures with international methodologies for general structural robustness to ensure comprehensive and high-level safety for high-rise buildings.

Keywords: high-rise buildings; blast re-sistance; progressive collapse (PC); tie force; ductili-ty.

PROBLEM STATEMENT

The ongoing military conflict in Ukraine has radically altered the engineering require ments for high-rise building design.

While traditional design of high-rise structures historically focused on gravity, wind, and, in relevant regions, seismic loads (in accordance with DBN V.1.1-12:2014 [9, 10, 19]) and high-rise building requirements (DBN V.2.2-41-2019 [1, 13]), the focus has now shifted to extreme localized loads caused by explosions and missile strikes. These loads are impulsive in nature and fundamentally differ from inertial seismic effects.

The primary structural threat resulting from localized impulsive loading is Progressive Collapse (PC), where the localized failure of a key load-bearing element (e.g., a column or wall) due to an explosion, fire [8], or impact propagates throughout the entire building, leading to its total collapse. Thus, the engineering strategy must be changed from preventing damage to preventing the spread of damage.

The concept of structural robustness is central to the design of high-rise buildings under military threats. A building's robustness is defined as the ability of its structure to prevent the disproportionate propagation of localized failure. European standards, particularly Eurocode EN 1991-1-7 (Actions on structures: General actions) [24], clearly articulate this key principle: localized damage caused by an accidental action is acceptable, provided that it does not threaten the overall load-bearing capacity of the structure and that this capacity is maintained for a sufficient time to implement necessary emergency measures.

To achieve the required robustness (especially for buildings classified under consequence classes CC3 and CC4, which have medium and major failure consequences) [11], Eurocode recommends strategies that encompass both physical protection and structural redundancy and ductility. This requires a departure from deterministic design and a shift toward the concepts that form the basis of seismic engineering.

ANALYSIS OF PREVIOUS RESEARCH

Seismic-resistant design possesses a number of fundamental principles that can be adapted to enhance the blast resistance of buildings. A common feature is that both types of loads are dynamic and require the structure to utilize its post-yield behavior to dissipate a significant amount of energy, in accordance with the principles of reinforced concrete design [14, 15]. However, there are significant differences. Seismic actions are cyclic and low-frequency, often causing resonance, whereas blast loading is typically impulsive—extremely fast and short-duration. A detailed comparison of these load types is provided in Table 1. In seismic events, engineers permit controlled element damage for energy dissipation; in explosions, due to their unpredictability and high intensity, the allowable damage level is often more restricted. Despite these differences, ductility and redundancy, which are core elements of seismic resistance, remain critically important for preventing blast-induced Progressive Collapse (PC).

Ukraine has taken a significant step towards enhancing civil protection by adopting the new DBN V.2.2-5:2023 "Civil Protection Protective Structures" [12], which aligns with the conclusions of previous research [3, 5, 17]. These standards substantially strengthened the requirements for mechanical strength, blast, and fire resistance, replacing the outdated 1997 norms. A key factor influencing the design methodology is the sharp increase in the design load for the load-bearing structures of protective facilities (safety capsules, bomb shelters, civil defense structures), which must withstand the external pressure of the blast wave. Previous standards (DBN V.2.2-5-97) stipulated a design peak overpressure of about 20 kPa, while the new DBN V.2.2-5:2023 [12] raised this requirement to 100 kPa. Such a radical increase in design parameters requires engineers to abandon classic simplified static calculation methods. To accurately assess structural behavior under such extreme impulsive loads and to validate an acceptable deformation level, the application of Non-Linear Dynamic Analysis

Table 1. Comparison of Key Characteristics of Seismic and Blast Loads
Таблиця 1 Порівняння основних характеристик сейсмічних і вибухових навантажень

<table>
<tr><th>Parameter</th><th>Seismic Load</th><th>Blast Load (External/Contact)</th><th>Impact on Design</th></tr>
<tr><td>Duration</td><td>Seconds to minutes (Cyclic)</td><td>Milliseconds (Impulsive)</td><td rowspan="4">Requirement to consider strain rate effects
Requirement for isolation systems (for seismic) or local strengthening (for blast)</td></tr>
<tr><td>Frequency</td><td>Low (Close to natural frequencies)</td><td>Extremely high (Shock wave)</td></tr>
<tr><td>Key Stability Mechanism</td><td>Controlled energy dissipation through plastic hinges</td><td>Maintenance of structural integrity after localized failure (tie forces)</td></tr>
<tr><td>Primary Risk for Multi-Storey Buildings</td><td>Large inter-storey drift</td><td>Local punching and Progressive Collapse (PC)</td></tr>
</table>

(NDA) becomes essential. These methodologies were previously the prerogative of highly seismic design or military facilities.

Thus, the requirements of the new DBN [12] implicitly compel the Ukrainian engineering community to adopt advanced analytical and structural approaches developed for seismically active areas and special facilities, as well as to integrate international methodologies for preventing Progressive Collapse (PC), such as the Alternate Path (AP) method and the Tie Force (TF) method, specified in standards like UFC 4-023-03 [26] and Eurocode EN 1991-1-7 [24].

MAIN RESEARCH

Seismic loads are generated by inertial forces, which are a function of the building's mass and ground acceleration. They are characterized by a relatively low frequency, which often coincides with the natural frequencies of the high-rise building. This coincidence can induce resonance, leading to significant inter-storey drifts and cyclic loading of elements. The primary failure mechanism in seismic design for high-rise buildings aims at the controlled formation of plastic hinges in the beams (the "strong column – weak beam" principle), allowing the structure to dissipate energy throughout the prolonged cyclic loading [4, 16]. A detailed comparison of the key characteristics of seismic and blast loads and their impact on multi-storey building design is presented in Table 1.

In contrast to seismic activity, blast loading is impulsive. It creates a shock wave characterized by an extremely high rise time (within milliseconds), peak overpressure, and impulse. Depending on the location of the charge, distinctions are made between external blast (air shock wave) and internal blast (confinement).

The failure mechanisms under blast are localized and intense:

- *Localized impact and breach*: An explosion near an external load-bearing wall or a key column can cause instantaneous local failure.
- *Strain rate effects*: Due to the high speed of impulse application, materials (especially concrete and steel) exhibit an increase in strength, which must be accounted for in modeling.
- *Dynamic punching*: This is a critical mechanism that directly leads to Progressive Collapse (PC).

The problems arising from impulsive loading reveal a structural vulnerability often ignored in seismic design. This is particularly evident in monolithic reinforced concrete flat slabs. Studies, notably [5, 27], have shown that impulsive loading can lead to dynamic punching failure at the slab-column connection. In this scenario, failure is concentrated in a narrow zone around the column, while the rest of the slab remains practically undamaged. The critical point is that integrity rebars, traditionally used to prevent gravitational collapse, prove ineffective under impulsive loading. These reinforcement bars often fail near the column boundary and cannot perform their function of keeping the slab from falling. This necessitates abandoning traditional node detailing methods and adopting concepts developed to counteract PC.

Despite differences in frequency characteristics, the high ductility of reinforced concrete structures (the capacity for plastic deformation without rupture) remains a key factor in the stability of framed reinforced concrete high-rise buildings [1, 14, 15].

The design of high-rise framed reinforced concrete structures must ensure a transition to plastic regime (flexure) before brittle failure (shear, block-shear). This means that connection details designed for energy dissipation under seismic cyclic loading can also work effectively under a single blast impulse, providing significant rotational capacity. However, for blast resistance, these connections must be designed to withstand significant axial tension which arises when elements transition into catenary action after support loss.

The summary in Table 1 on loads and response demonstrates why a unified approach to structural integrity must be applied to high-rise buildings subjected to dynamic loads.

Designing against Progressive Collapse is the most direct and effective adaptation of seismic principles for ensuring the blast resistance of high-rise buildings. The goal is to ensure the building's ability to remain stable despite localized failure.

The primary methodology is the Alternate Path (AP) method, detailed in international standards such as UFC 4-023-03 [26] and Eurocode EN 1991-1-7 [24]. It requires the structure to be capable of redistributing the load after the removal of a key vertical element (column or wall) without initiating global collapse. Eurocode EN 1991-1-7 [24] proposes a quantitative criterion: the damage caused by local failure should not exceed 15% of the floor area on two adjacent storeys. Ensuring this redundancy and reserve strength directly stems from seismic design principles, which demand multi-level protection systems for building structures.

For reinforced concrete structures, the key strategy for preventing PC is the implementation of an integrated system of ties (reinforcement) – the Tie Force (TF) method. This reinforcement ensures the structural integrity after the primary load-bearing elements have failed.

According to UFC 4-023-03 [26], a typical solution for reinforced concrete frames involves adding a system of ties (reinforcement) along the perimeter of the structure and across the entire area of the floor slabs. It is required that the tie forces (TF) be carried specifically in the floor slabs or roof and not concentrated in beams, girders, or perimeter bands. This allows the realization of catenary action. After the removal of a column, the slab, which previously carried the load primarily in flexure, begins to sag and act as a cable net, where the internal ties (reinforcement) work in pure axial tension, which requires a special approach to the detailing of reinforced concrete frames [16, 17]. Since standard integrity reinforcement does not withstand impulsive loading, the application of calculated TF provides the necessary robustness against dynamic punching and prevents slab failure.

Innovative materials offer significant advantages in providing dual resistance to seismic and blast loads. Ultra-High Performance Fibre-Reinforced Concrete (UHPFRC) is a cementitious composite reinforced with steel fibres that exhibits exceptional mechanical strength, ductility, low permeability, and high resistance to abrasion and fire [20]. Research has confirmed that UHPFRC and Reactive Powder Concrete (RPC) have significantly better blast resistance compared to ordinary concrete [28]. These improved characteristics are achieved through reduced free water content, the use of high-strength steel fibres, fine aggregate, and active pozzolanic materials.

UHPFRC is an especially effective material for the strengthening of existing reinforced concrete building structures. UHPFRC jacketing of columns significantly enhances their shear and axial capacity, as well as their ductility. Compared to traditional concrete jacketing, which requires a thickness of 70–100 mm, UHPFRC allows for the use of a much smaller thickness, reducing the overall mass and architectural intervention while maintaining excellent bond with the existing concrete [20].

Table 2. Matrix of Design Principle Transfer (from Seismic Resistance to Blast Resistance)
Таблиця 2. Матриця передачі принципів проєктування (від сейсмостійкості до вибухостійкості)

Seismic Design Principle	Blast Resistance / PC Adaptation	Technical Rationale
Ductility-Based Design	Maximizing the Rotational Capacity of Connections (≈ 0.20 rad)	Ensuring plastic energy dissipation and avoiding brittle failure
Redundancy and Integrated Systems	Alternate Path (AP) Method and 3D Tying	Maintaining the overall load-bearing capacity after localized failure of a key element
Provision of Transverse Reinforcement	Implementation of Tie Forces (TF) in Slabs	Supporting the Catenary Action of slabs, preventing dynamic punching failure at slab-column nodes
Use of Dampers (FVD)	Hybrid Isolation and Damping Systems	Reducing drift and absorbing the high-energy impulse
Use of High-Strength Concrete	Application of UHPFRC for Element Strengthening	Increasing resistance to impact, improving shear strength and ductility in retrofitting

Since designing for both seismic and blast resistance requires utilizing the post-limit (plastic) behavior of materials, linear static analysis is insufficient. For buildings classified as high-consequence category objects or those designed to withstand significant accidental loads (such as explosions), international standards require the use of either Non-Linear Dynamic Analysis (NDA) or, at minimum, Non-Linear Static Analysis (Pushover). In the context of Ukrainian design, the implementation of NDA becomes mandatory for the structures of protective facilities integrated into multi-storey buildings [12].

For realistic modeling of blast effects, Nonlinear Finite Element Method (Nonlinear FEM) must be applied, often integrated with hydrocodes (software for modeling shock wave propagation and its interaction with the structure). Hydrocodes are used to model the propagation of the blast wave and its interaction with the structure. Key aspects of advanced modeling include:

- *Constitutive Models*: The use of history- and strain-rate-dependent constitutive models for concrete and steel, considering their behavior under tension and compression, as well as the influence of the strain rate.
- *Reinforcement Modeling*: Steel reinforcement is modeled using truss or membrane elements embedded in concrete elements, assuming perfect bond.
- *Validation*: The effectiveness of such numerical simulations, which reproduce the entire process from detonation to complete failure, has been confirmed by comparison with photographs of real damage caused by terrorist attacks.

Acceptance Criteria in NDA, which were initially developed for seismic assessment (e.g., ASCE 41 [29]), are being adapted for blast resistance. They are based on strain limit states, not strength. It must be considered that the models and acceptance criteria in ASCE 41 are based on cyclic loading (for seismic), whereas blast requires modification to account for non-cyclic impulsive loading and the interaction of flexure and axial tension that occurs during PC.

CONCLUSIONS AND PROSPECTS FOR FURTHER RESEARCH

The new Ukrainian standards, DBN B.2.2-5:2023 [12], have created a tangible opportunity to enhance the robustness of buildings, yet they necessitate a significant restructuring of design practices. The key requirement to increase the design impulsive pressure to 100 kPa directly pertains to protective structures (shelters, capsules, civil defense structures) that must now be integrated into high-rise buildings. Since this leads to the need for a substantial increase in reinforcement and displacements, static design becomes inadequate [6, 7].

DBN B.2.2-5:2023 [11] establishes stringent requirements for local protective structures, but it does not contain detailed methodologies for preventing Progressive Collapse (PC) for the entire high-rise building after an impact on an unprotected area. Given this, designers must hybridize Ukrainian requirements for local protection with international principles of structural robustness, which are the foundation of seismic design but adapted to counteract PC (AP/TF methods) (Table 2) [24, 26, 29].

Further research directions include the creation of detailed national guidelines and manuals on the application of Non-Linear Dynamic Analysis (NDA) to assess the blast resistance of high-rise buildings. These guidelines should be adapted to the specific utilization of building structures and engineering software, and must incorporate the experience gained from military actions in Ukraine [23].

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АДАПТАЦІЯ ПРИНЦИПІВ СЕЙСМОСТІЙКОСТІ ДЛЯ ЗАБЕЗПЕЧЕННЯ ВИБУХОСТІЙКОСТІ ВИСОТНИХ БУДІВЕЛЬ

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Анотація. Проаналізовано стратегічну необхідність та інженерні механізми адаптації принципів сейсмостійкого проєктування для забезпечення вибухостійкості багатоповерхових будівель в умовах війни в Україні. Ключовою метою є запобігання прогресуючому обвалу (ПО) конструкцій, спричиненому локалізованими імпульсивними навантаженнями, які радикально відрізняються від циклічних сейсмічних впливів, але, як і вони, вимагають залучення пластичної (пост-граничної) поведінки матеріалів в будівельних конструкціях.

В умовах триваючого військового конфлікту в Україні проєктування висотних будівель вимагає кардинальної перебудови, зміщуючи фокус із традиційних гравітаційних та сейсмічних навантажень (ДБН В.1.1-12:2014, ДБН В.2.2-41-2019) на екстремальні імпульсивні навантаження від вибухів. Основна загроза – прогресуючий обвал (ПО), що виникає після локального руйнування ключового елемента. Згідно з європейськими стандартами (Eurocode EN 1991-1-7), інженерна мета змінюється: не запобігання пошкодженню, а запобігання його непропорційному поширенню.

Введення нових ДБН В.2.2-5:2023, які радикально підвищили розрахунковий тиск вибуху до 100 кПа для захисних споруд, неявно змушує інженерів використовувати методи нелінійного динамічного аналізу (*NDA*). У статті обґрунтовується, що принципи сейсмостійкого проєктування – дуктильність та надмірність – є критичною основою для підвищення вибухостійкості, незважаючи на відмінності у частотних характеристиках навантажень.

Ключовим рішенням є гібридизація національних вимог з міжнародними методиками протидії ПО, зокрема методами альтернативного шляху навантаження (AP) та впровадження в'яжучих зусиль (*Tie Force, TF*), які забезпечують структурну цілісність після видалення вертикальної опори, реалізуючи катанійну дію плит. Це вимагає адаптації критеріїв прийнятності ASCE 41 та використання інноваційних матеріалів, як-от Ультрависокопродуктивний сталефібробетон (UHPFRC), для ефективного посилення конструкцій.

Дослідження підсумовує необхідність гібридизації українських вимог до локальних захисних споруд з міжнародними методиками загальної структурної стійкості для забезпечення комплексної та високорівневої безпеки висотних будівель.

Ключові слова: висотні будівлі; вибухостійкість; прогресуючий обвал (ПО); в'яжучі зусилля (*tie force*); деформативність.

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