CHAPTER 1
BUILDINGS WITH A WALL CONSTRUCTION SCHEME MADE OF SMALL-SIZED ELEMENTS

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1.1 Brief overview and features of architectural and structural solutions of buildings with a wall structural scheme made of small-sized elements

In buildings with a wall construction scheme consisting of small-sized elements, vertical loads are primarily transmitted through load-bearing walls made of bricks, ceramic hollow stones, small concrete blocks, or aerated concrete blocks. The floor discs work as stiffness diaphragms and spatially close the system due to ties, monolithic belts and anchor connections [14; 38; 87].

The use of small-sized elements determines the architectural rhythm of facades, modularity and proportions of window and door openings, and also affects the formation of nodes in the places of wall joints and the arrangement of quarters and bends. The use also creates conditions for effective knotting with lintels, reinforced belts and interfloor seams. Figure 1.1 shows the types of systems for bridging joints between small-sized wall elements, which directly affects the monolithicity and bearing capacity of the walls [87].

Typical ceramic stones with cavities provide reduced masonry mass and increased thermal efficiency; concrete small blocks are characterized by more stable geometry, acoustic inertia and predictability of reinforcement nodes; aerated concrete adds thermal insulation advantage, but has lower density and brittle properties, which is important for assessing out-of-plane stability and resistance to local shocks [55; 69; 85; 87; 103].

Architectural and structural solutions for the wall scheme (see Figure 1.2 and 1.3) are based on the requirements for the bearing capacity of the masonry in compression and shear, verification of the wall's stability in out-of-plane work, as well as ensuring the spatial operation of the building through reliable connection of the floor diaphragms. Eurocode 6 systematizes the rules for the design of unreinforced and reinforced masonry, specifying the design strengths of materials, the ultimate thinness of walls (height/thickness ratio), effective heights and lengths depending on the spacing and anchorage lines, and the use of belts and joint dressings [69]. The American TMS 402/602-22 standard sets out requirements for structural reinforcement, anchoring, weld quality, material control and installation, which is particularly important for ensuring reproducibility and reliability in restoration work in resource-scarce conditions [94].

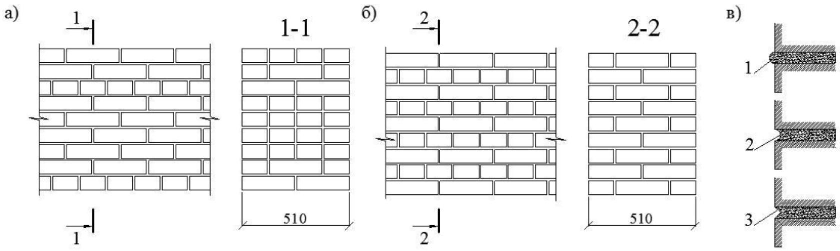


Figure 1.1 – Joint dressing systems: chain (double-row) and multi-row; the effect of dressing on the monolithicity and load-bearing performance of the wall [87]

Ukrainian manuals emphasize that the systematic use of horizontal monolithic belts, reinforcement in bedding joints, vertical rods in the area of piers and corners, and proper connection with slab diaphragms increases crack resistance, reduces the risk of local wall pushing out, and enhances seismic and shock resistance [38; 55; 87].

Under conditions of combat damage, scenarios of short-term action of excess pressure (shock wave), fragmentation and repeated impacts by fragments dominate, which provokes out-of-plane pushing of wall sections, the formation of horizontal cracks in the area of the upper supporting sections of the walls, and the appearance of diagonal shear cracks in the areas adjacent to the openings. Current research shows that thin unbound areas and lightweight porous materials (such as aerated concrete blocks) are more vulnerable to near-field blasts: significant deformation, rapid formation of crack fields, and risk of fragmentation with reduced residual load-bearing capacity are observed [44; 69; 85].

Numerical and experimental work on walls under explosive loading confirms typical failure mechanisms, the importance of an adequate block-mortar contact model, and the feasibility of reinforcing external layers (polyurea composites) to increase out-of-plane bearing capacity and failure energy intensity [33; 58; 93]. In architectural and construction practice, this is transformed into recommendations: make facade layers more maintainable and easily replaceable, ensure continuity and high-quality anchoring of cladding, arrange belts at the levels of floors and coatings, limit large unreinforced planes without cuts with deformation and temperature joints, and also ensure the possibility of transferring forces to the floor disk through mechanical anchors/dowels [14; 38; 93; 94].

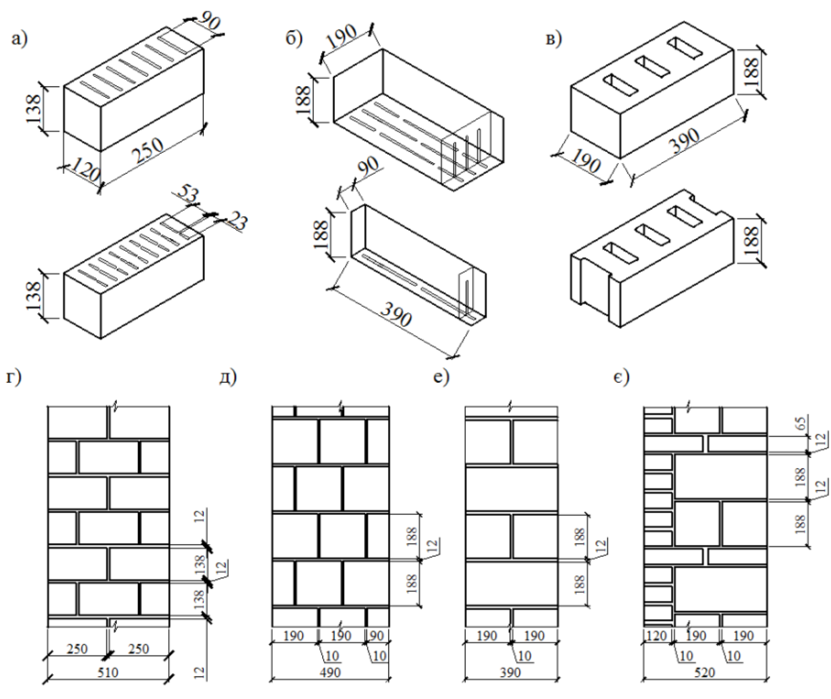


Figure 1.2 – Nomenclature of small-sized stone products (ceramic and lightweight concrete stones, porous blocks) and typical masonry schemes [87]

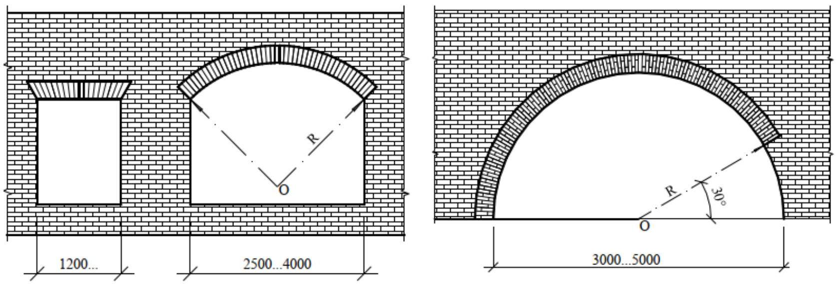


Figure 1.3 – Typology of lintels (regular, arched, prefabricated, reinforced brick) and support nodes; recommendations for height and reinforcement [87]

The thermal and acoustic qualities of small-sized elements are an additional factor in architectural form formation: multi-cavity ceramic blocks and aerated concrete blocks allow for reducing the thickness of insulation layers or the volume of additional facade systems, however, when restoring damaged areas, it is important to consider the potential for hidden damage in the thin walls of cavities and the degradation of adhesive contacts with the mortar [69; 85; 87; 103].

Comparatively, “heavier” small concrete blocks have better inertia and potential for infiltration of reinforcement or filling voids with fine-grained concrete, which is useful for local reinforcement of piers and stress concentration zones [14; 55; 94].

The architectural and structural strategy of wall buildings made of small-sized elements in the languages of combat operations should combine [14; 87; 93]:

1) modular division of facades and plans, which minimizes the areas of vulnerable canvases;

2) continuous “strength belts” at the level of floors and coatings;

3) standardized and reproducible diaphragm anchoring nodes;

4) local strengthening methods (seam reinforcement, injections, external composite shells) for piers and areas near openings;

5) use of regulatory checks outside and in the plane of the wall, taking into account the real quality of mortars, seams and blocks according to the results of the survey.

This configuration makes it possible not only to increase the survivability and maintainability of buildings, but also to form an architectural language where the constructive module, "belts" and the rhythm of openings work as a common framework of stability in situations of extreme impacts.

1.2 Assessment of damage and stability of wall buildings made of small-sized elements due to military factors

Buildings of a wall construction scheme made of small-sized stone elements are the basis of low-rise residential and public buildings in Ukraine. Such structures are created from ceramic hollow stones, bricks, small concrete blocks or autoclaved aerated concrete, which allows for obtaining walls with a thickness of 120–510 mm with a noticeably lower mass and better thermal properties compared to solid brickwork. Hollow ceramic stones and lightweight concrete blocks make it possible to reduce the thickness and weight of the wall by 30–35% and reduce the labor intensity of masonry, however, such walls have lower strength and require a plaster layer to protect against moisture [87]. Manual [87] specifies that the dimensions of ceramic blocks (250×120×138 mm), types of concrete stones (390×190×190 mm) and natural stone are coordinated with the modular scheme to ensure joint ligation and expected strength; at the same time, it is emphasized that natural stone requires additional waterproofing. Load-bearing walls made of small-sized elements interact with the floors, forming a wall structural scheme. In monolithic reinforced concrete buildings, the walls restrain the deformations of the floor slabs caused by temperature changes and shrinkage of the concrete, which creates a complex stressed-deformed state [38]. In traditional stone buildings, the classification of walls by thickness and number of masonry courses is coordinated with the modular system; the ligation of joints (chain or multi-course) ensures monolithicity and transfers vertical and horizontal forces to the foundation [87].

TMS 402/602 22 and Eurocode 6 require that load-bearing walls have sufficient out-of-plane strength and cooperate with the floors [94]. In [14] comments are provided on the latest editions of the TMS code, emphasizing the need to take into account dynamic effects and the introduction of new reinforcement recommendations.

In conditions of war and combat damage, buildings made of small-sized elements are exposed to shock waves, fragmentation and explosive loads.

Figure 1.4 shows the loss of external wall panels and part of the floors, which illustrates the typical nature of global damage in wall buildings made of small-sized elements in war conditions.

Figure 1.4 – General view of large-scale destruction of a building with a wall structural scheme after a direct hit [20]

Studies of the behavior of walls made of gas blocks under the influence of nearby explosions show that the main mechanism of destruction is local penetration in the middle part of the wall, forming a rectangular hole and causing blocks to separate from the masonry [58]. A fragment of the facade with rectangular lost areas of masonry, characteristic of penetration destruction from nearby explosions, and the clear separation of blocks from the wall mass is shown in Figure 2.5.

Numerical models and experimental data show that the penetration area increases with increasing block size and decreases with increasing wall thickness and mortar strength; at a constant charge equivalent, the distance to the explosion affects the penetration area nonlinearly: it first increases and then decreases [69]. The most vulnerable area is the contact surface between the blocks and the mortar; this is where deformations are concentrated and elements detach [85].

Figure 1.5 – Local wall penetration with the formation of a rectangular opening

Figure 1.6 – Separation at the contact point between the block and the mortar

As shown in Figure 1.6, weak adhesion and delamination are observed at the "block-mortar" interface, the most vulnerable zone of the masonry under explosion dynamics. Parametric studies, including numerical modeling [58] and review [85], indicate that wall thickness, block size, mortar strength, and clamping scheme affect the nature of failure. At small distances to the explosion source, the out-of-plane fault-skewed form of failure becomes dominant: the wall deforms like a cantilever and can completely fall out [93]. As the distance increases and the charge decreases in mass, diagonal shear cracks come to the fore, which are localized near the openings or in the upper part of the wall.

Oblique cracks emanating from the corner of the slot reflect the concentration of shear stresses (see Figure 1.7) and characteristic damage with more distant blasting or smaller charges. At the same time, when the wall is supported along the entire perimeter, the stiffness increases, which reduces deformations, but increases local stresses in the fastening zone and can cause delamination [69].

Figure 1.7 – Diagonal cracks in the section near the window opening

The material of the walls affects the blast resistance. Autoclaved aerated concrete is a lightweight material with low density and relatively high porosity; its blocks have good thermal protection and moderate strength [85]. Review of [103] highlights current trends and challenges in the use of aerated concrete blocks for building structures, in particular increasing strength while maintaining thermal insulation properties. However, experiments have shown that walls made of aerated concrete blocks have a limited ability to withstand explosive loads: with a thickness of 200 mm and a density of 500-700 kg/m^3, they are only suitable for two to three-story buildings, and during a close explosion of 5-7 kg in TNT equivalent at a distance of 2 m, they undergo significant deflections and destruction [85]. Increasing the wall thickness to 250 mm and using a stronger mortar reduces deflections, but does not prevent punching failure. Walls made of ceramic stones and lightweight concrete blocks have greater mass and better crack resistance, but in the absence of reinforcing belts and anchoring of floors, they lose their integrity under the influence of blast waves [38; 93].

The presence of openings (windows, doors) and incorrectly made lintels create stress concentrations, which under explosion conditions turn into diagonal or horizontal cracks. Calculation schemes show that with opening heights of up to 2 m, ordinary lintels on ordinary mortar are not sufficiently rigid and sensitive to dynamic influences; for wider openings, it is necessary to use reinforced stone or reinforced concrete lintels [55]. Figure 1.8 clearly shows cracks in the lintel area and delamination of the mortar, a manifestation of insufficient rigidity of ordinary lintels under dynamic actions. Unfortunately, many buildings are built without such reinforcements, which leads to the collapse of the piers and upper zones above the openings.

Masonry design standards TMS 402/602 22 and Eurocode 6 offer methods for assessing out-of-plane strength and provide recommendations for ensuring the bearing capacity of walls by reinforcing joints, installing monolithic belts and connecting to floors [14; 94]. However, it has been experimentally established that the specified normative dependences are calculated for static or quasi-static loads. In the case of dynamic impact actions, additional reinforcement becomes necessary. For example, experiments with wall reinforcement with glass polymer polyurea (GFRPU) showed an increase in peak load by 16-50% and a significant increase in plastic deformability compared to unreinforced samples [33]. Other studies have shown that the use of OSB or FRP cladding significantly increases out-of-plane stiffness and delays collapse [44].

According to the results of the above studies, it is possible to identify typical defects and damage to wall buildings as a result of military operations. These include [58; 93]: a) local punching holes and ejection of blocks from the wall in the middle part of the canvas; delamination and peeling of the facing from the back side; b) diagonal and horizontal shear cracks around the openings; c) separation of the piers and upper zones above the openings; deflection (out of plane); d) loss of bearing capacity and complete collapse of the wall; e) destruction of the contact zones between the mortar and the blocks; f) partial disruption of the connection between the walls and the floors.

Detail of the ceiling support assembly on the wall with noticeable opening of the seams and chips – an indicator of the loss of joint operation of the enclosing and horizontal elements (see Figure 1.9). The degree of damage depends on the distance to the explosion, the mass of the charge, the thickness of the wall, the size of the blocks, the strength of the mortar, the presence of reinforcing belts and the scheme of fastening the floors [58].

Figure 1.8 – Defect of the jumper above the slot and stress concentration

Figure 1.9 – Violation of the “wall-floor” connection and edge delaminations

In the case of a distant explosion, diagonal cracks dominate, while in the case of a close explosion, a punching hole and complete collapse. The high porosity of aerated concrete and the weak interaction of the block with the mortar contribute to rapid destruction; in walls made of ceramic and concrete stones, the strength is higher, but the lack of sufficient reinforcement or the presence of corrosion damage can reduce their explosion resistance [93].

Thus, the analysis of defects and damage to buildings of a wall structural scheme made of small-sized elements as a result of military operations indicates a high vulnerability of such structures to explosive loads. Important factors are the choice of material, geometric characteristics of blocks, quality of masonry, reinforcing belts, anchoring of floors and compliance with regulatory requirements for out-of-plane strength. Research conducted in [33; 44] shows that the implementation of reinforcement using composite wraps, glass-polyurea coatings, FRP or OSB panels, as well as increasing the strength of the mortar and reducing the size of the blocks, can significantly reduce the area of penetration and prevent complete collapse. The planning and reconstruction of existing buildings should take these results into account, and the technical condition of objects made of small-sized elements requires systematic inspection and modernization in accordance with modern standards and methods of reinforcement.

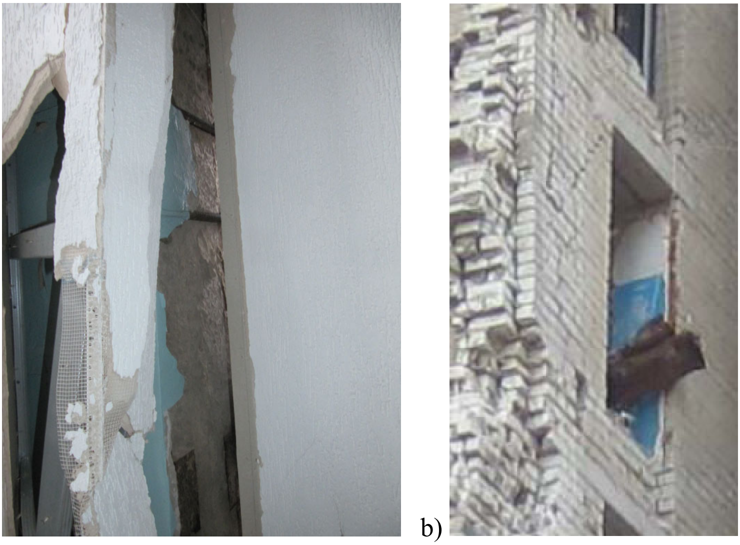
1.3 Failure mechanisms and loss of load-bearing capacity in masonry structures composed of small-scale units under explosive and debris loading

Walls built of small-sized elements (bricks, ceramic and silicate blocks, aerated concrete, etc.) remain one of the most vulnerable groups of structures in the war zone. Under the conditions of modern combat influences: artillery shelling, air strikes, detonations of explosive devices and strikes by kamikaze drones – these structural elements exhibit destruction mechanisms that differ from damage to frame structures. Study reveals the extent of destruction and develops recommendations for strengthening [14; 55].

The most common type of damage is through holes and cracks, which are formed as a result of bullet or shrapnel damage. They are localized within one or more rows of bricks or blocks and are accompanied by cracking of the masonry joints. In the case of multiple impacts, a "net-like" delamination of the wall is observed, which significantly reduces the bearing capacity even while maintaining the external geometry [93]. Such damage is especially dangerous for buildings with significant spans between load-bearing walls, where the stability of the entire object depends on the integrity masonry. Figure 1.10 shows local explosive/fragmentation damage: detachment of the plaster layer, exposure of the wall base and "ragged" contours of the holes. The primary mechanism of loss of masonry monolithicity from small-sized elements under close explosive influences is illustrated.

Another critical form of failure is the formation of vertical and inclined cracks resulting from the action of the shock wave from nearby explosions (see Figure 1.11). Studies show that even a relatively small blast wave creates high stresses in the joints of small-sized elements, leading to a loss of monolithicity. In works [58103], numerical modeling of the behavior of aerated concrete walls under explosive loads is presented, which confirms that critical tensile stresses are localized precisely in vertical joints. In real conditions, this manifests itself in the form of crack opening from the base to the ceiling, which can lead to partial delamination of the entire wall plane.

Particularly dangerous for a wall structural scheme is a combined damage – a combination of holes from fragments with general deformations from the explosion. In this case, the masonry undergoes scattering with the formation of "funnels" and the collapse of individual sections. Analysis of experimental studies [44; 93] confirms that reducing the density of the masonry (for example, when using autoclaved aerated concrete) increases the risk of local collapses, although at the same time it reduces the transmission of shock waves into the interior of the building. This indicates a difficult balance between the energy efficiency of the material and its blast resistance.



a) b)

Figure 1.10 – Local breakdowns and delamination of the wall's outer part

During massive shelling, damage to the load-bearing corner sections of buildings is common. The destruction of corners from small-sized elements often begins with the detachment of individual blocks and spreads along adjacent walls (see Figure 1.12). The loss of corner nodes leads to the loss of spatial rigidity and partial or complete collapse of floors. In the study [33], the use of reinforcing coatings for the external surfaces of masonry is proposed, which increases resistance to tearing and can be used in renewable construction.

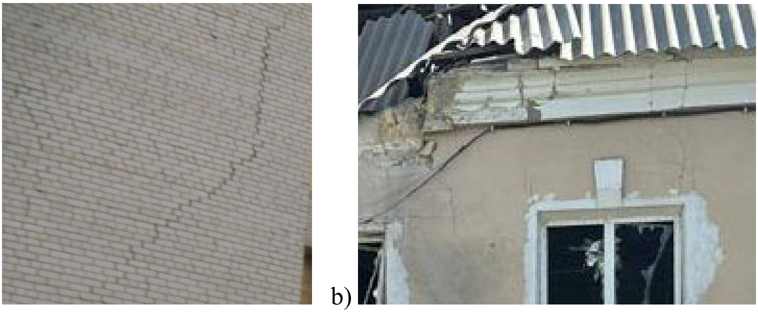


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Figure 1.11 – Formation of vertical and inclined cracks in brickwork

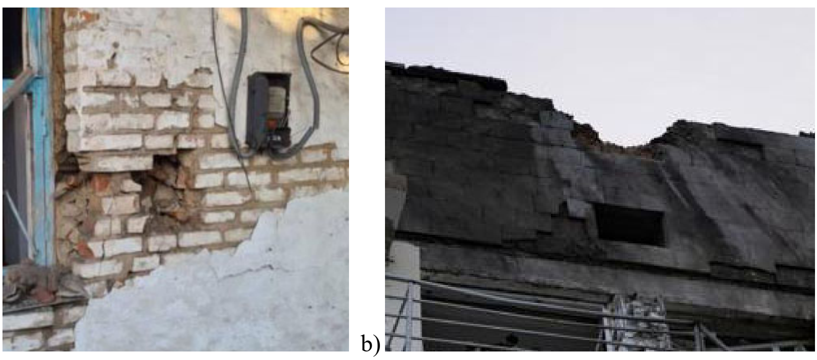

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Figure 1.12 – Damage to the corner parts of the brick walls of the building

The failure of a corner element, resulting in the loss of spatial interaction among adjacent walls, represents a primary trigger for progressive structural degradation, the weakening of the building's "rigid rib." Although reinforced concrete floor slabs in such structures often remain largely intact, the instability of wall elements leads to significant deflection or even collapse. This observation supports the conclusion that wall systems composed of small modular elements constitute the most vulnerable component under martial law conditions, as their load-bearing capacity depends on the integrity of individual blocks and joints, which exhibit limited resistance to impact and dynamic loads [38; 85].

An important feature of wartime destruction is its heterogeneity in the building plan. Damage is often concentrated in the lower floors, which are exposed to the maximum impact of the shock wave. This leads to a "domino effect", when the collapse of the lower rows of walls initiates the progressive destruction of the upper parts of the building. In some cases, only the external facade walls were damaged, while the internal partitions remained relatively intact. This unevenness confirms the importance of using multi-layer protection systems (e.g. double masonry with a thermal insulation layer) to increase overall resistance [94].

Secondary damage is also a problem – loss of the protective layer of mortars, exposure of the reinforcing mesh or destruction of plaster coatings. They do not always lead to immediate collapse, but they accelerate the degradation of materials through moisture absorption and corrosion. In the study [85] noted that the lack of timely conservation of damaged aerated concrete walls sharply reduces their residual resource. Therefore, after shelling, one of the priorities should be to close the exposed surfaces even before major repairs are carried out.

Overall, the analysis shows that the most destructive factors for walls made of small-sized elements are:

– through holes from fragments and bullets;

– vertical cracks from shock waves;

– combined lesions combining local destruction and general deformations;

– loss of angular areas and spatial rigidity;

– progressive destruction of the lower tiers with spread to the upper ones.

Restoration of such structures requires a comprehensive approach: local reinforcement of damaged areas, replacement of masonry sections and application of the latest reinforcement methods. Promising are the use of polymer composite materials, as well as the integration of seismic and explosion-resistant solutions in new construction [33; 44]. Thus, military operations actualize the need to review regulatory approaches to the design of buildings with a wall structural scheme. Standards based on conventional operational influences do not consider the scale of dynamic loads of modern combat operations. That is why damage analysis is the basis for the development of adaptive structural strategies aimed at increasing the stability of low-rise and medium-rise buildings from small-sized elements in areas of potential risks.

1.4 Generalization of damage patterns in wall structural systems composed of small-scale elements

Based on the analysis of residential surveys and public buildings carried out in combat zones, it was found that buildings with a wall structural scheme made of small-sized elements (brick, small concrete blocks, aerated concrete stones) are particularly vulnerable to shock and explosive loads. Unlike frame structures, where the main forces are perceived by frame or truss systems, in wall structures, the destructive effect is concentrated on massive extended planes that directly carry vertical and horizontal loads [55; 87].

The most common injuries are:

– formation of through cracks and delamination of masonry extending along horizontal and vertical seams. Such defects occur because of explosive loads or a shock wave, when there is a sharp increase in air pressure. Delamination weakens the wall along its entire height, bringing it to a state of loss of bearing capacity even with small additional loads [69; 93];

– local knocking out or falling out of individual small blocks (bricks or aerated concrete stones), which is typical of direct hits by shell fragments or kamikaze drones. The loss of even a limited number of elements leads to stress concentration and further progressive destruction [58];

– crushing and partial destruction of building corners – one of the most vulnerable areas. Here, longitudinal wall sections are torn apart due to the lack of spatial connection, which causes the loss of stability of corner fragments [14; 38];

– deformations and collapses of lintels above window and door openings, which quickly fail due to the short support length and localization of forces. In this case, the collapse of lintels often entails the collapse of adjacent sections of the wall [85; 94];

– complete collapse of walls inter-storey sections under the combined effects of the explosion and vibrations from the collapse of floors. This is particularly hazardous in multi-storey buildings, where the failure of one floor leads to the progressive collapse of the upper sections [93; 103].

In the zone of action of explosion waves of considerable power, buildings made of autoclaved aerated concrete showed a characteristic pattern of brittle failure: chipping off of thin walls of block cavities, complete destruction of thin piers, and significant areas of material spraying [69; 85]. This results in high sensitivity to nearby explosions even with a relatively small charge mass.

An additional factor is the lack of proper reinforcement. In many of the buildings studied, the reinforcement belts were partially or completely absent, which led to complete splitting of wall sections without the possibility of redistribution of forces [55; 87]. Experimental and numerical studies in recent years confirm that even thin reinforcing elements or external reinforcement (e.g. GFRP or OSB panels) significantly increase resistance to out-of-plane deformations and reduce the risk of collapses [33; 44].

The nature of the destruction differs depending on the combat effects scale [58; 93]:

– with local damage (shrapnel, debris), the damage is limited to the knocked-out blocks, but quickly develops into cracks due to the weak ability of the masonry to dissipate energy;

– with medium loads (mortar shells, kamikaze drones), local penetration and collapse of individual sections of the walls occurs with the spread of cracks along the seams;

– with powerful explosions (aircraft bombs, missiles), progressive destruction is formed: detachment of external walls, collapse of floors and loss of spatial stability of the entire building.

In general, several systemic features of damage can be distinguished:

1. Predominance of brittle failure – walls made of small-sized elements do not have significant plastic reserves and collapse instantly after exceeding the strength limit.

2. High role of nodes – corners, openings, areas of adjacency to floors are places of stress concentration and are the first to experience loss of integrity.

3. Limited possibility of local reinforcement – repair of individual areas is often ineffective, since the damage is complex and requires replacement of entire fragments.

4. Tendency to progressive destruction – initial local defects quickly develop into major emergency states.

The findings of international studies confirm these patterns. For example, numerical modeling and experiments have shown that even at small explosive loads, walls made of aerated concrete and bricks demonstrate a rapid increase in out-of-plane deformations and loss of load-bearing capacity [58; 69]. In turn, modern studies emphasize the need to implement systemic strengthening methods, such as reinforcement with fiberglass or polymer shells, which can significantly reduce the scale of damage [33; 44].

Thus, damage to buildings with a wall construction scheme made of small-sized elements as a result of military actions has a clearly expressed fragile, progressive and systemically dangerous character. This requires not only local repair measures, but also a comprehensive approach: detailed inspection, design of reinforcement using modern materials, and in cases of severe damage – complete replacement of wall sections or even demolition of the building [38].