CHAPTER 2
FRAME-TYPE BUILDINGS

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2.1 Features of architectural and structural solutions of frame-type buildings

Frame buildings and structures are a type of construction object in which the main load-bearing element is a frame consisting of vertical (columns, pylons, diaphragms) and horizontal (crossbars, beams, slabs) elements. The frame perceives the main loads (vertical and horizontal), and the enclosing structures (walls, partitions, facade elements) perform mainly the functions of heat and sound insulation and are not load-bearing.

Structural schemes of frame buildings determine the mutual arrangement and operation of the main load-bearing elements of the frame (columns, beams, floor slabs, ties, stiffeners, etc.). The choice of scheme depends on the number of storeys, the functional purpose of the object construction, loads, requirements for planning flexibility and architectural solutions.

The advantages of frame construction schemes are: strength and durability, wide architectural possibilities, energy efficiency (when using modern facade systems and effective thermal insulation materials), and material savings due to rational load distribution.

The disadvantages of frame construction schemes include: higher cost of construction work compared to frameless systems (especially when using steel structures), the need for highly qualified contractors, the need for specialized machines and mechanisms, the need for anti-corrosion protection and fire protection of steel structures, which increases the total cost and construction time.

By purpose, frame buildings can be residential (multi-story residential buildings, cottages), public (office centers, schools, hospitals, shopping and entertainment centers, sports arenas), industrial (workshops, warehouses).

Common features for all frame buildings and structures are: flexibility of planning (partitions are not load-bearing, so the internal space is easy to transform), versatility (used in residential, public and industrial construction), speed of construction (especially in the case of using prefabricated structures), the possibility of multi-storey construction (the ability to erect high-rise buildings).

By material, the frame can be steel (lightweight, allows for large spans), reinforced concrete (has high fire resistance and rigidity), wooden (lightweight and environmentally friendly) or combined (provides optimal properties for specific structures).

In frame buildings and structures, horizontal and vertical elements, connected in the transverse and longitudinal directions, form structures called frames. The connection of elements in the frame can be rigid or hinged. In the case of a hinged connection, the bending forces that arise in the beam are not transmitted to the strut. In contrast, a rigid connection of the beam with the rack ensures the transfer of not only compressive forces, but also bending forces and transverse forces to the rack and is more durable. By their structure, frames can be single-tier or multi-tier, single-span or multi-span.

The rigidity of flat frames can be ensured in two ways: according to the frame and truss schemes. The combination of these principles, when forming the elements of the load-bearing frame in both directions of the building allows for the implementation of three spatial structural schemes: frame, frame-truss, and truss (see Figure 2.1). In the third direction – horizontal – the floors are usually considered as stiffness diaphragms.

The frame scheme is a system of flat frames (single- and multi-span; single- and multi-storey), located in two mutually perpendicular (or at a different angle) directions – a system of uprights and crossbars, connected by rigid nodes at their junctions in any direction (see Figure 2.1, a).

The frame-tie scheme is solved in the form of a system of flat frames, hingedly connected in another direction by elements of interfloor ceilings (Figure 2.1, b). To ensure rigidity in this direction, ties or stiffening walls (diaphragms) are installed. Flat frames are more expedient to be located across the building.

The truss scheme of the building frame is the simplest to implement (see Figure 2.1, c). Trusses or stiffening diaphragms installed between columns are placed every 24...30 m, but no more than 48 m in the longitudinal and transverse directions; usually these places coincide with the walls of the stairwells.

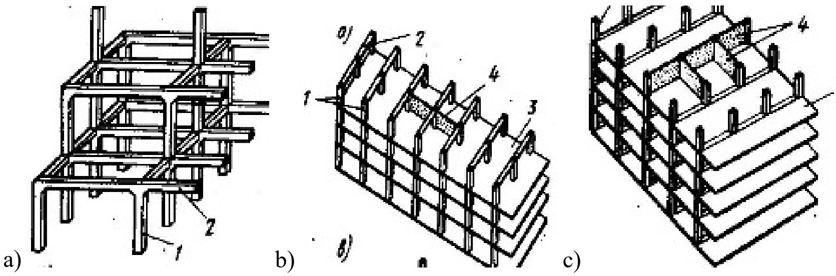


Figure 2.1 – Structural diagrams of frames [87]:
a) frame; b) frame-tie; c) tie;
1 – column; 2 – crossbar; 3 – rigid disk of the floor;
4 – stiffness diaphragm

The frame scheme is used relatively rarely. The complexity of construction and installation work related to ensuring the rigidity of the nodes, the increased consumption of steel, etc. limit its use in seismic areas, as well as in buildings where the installation of walls, partitions, or other obstacles, etc., is not allowed over a long length (48–54 m). More often, especially in industrial buildings, a frame-timbered scheme is used. The timbered scheme justifies its widespread use by the greater simplicity of construction and installation work, lower labor and material costs, etc. In the wall-bearing scheme, as well as in various frame systems with incomplete frames, a timbered scheme is typically used, and the external or internal walls themselves serve as diaphragms.

In frame buildings, the second defining feature of the structural scheme is the location of the transoms. There are four structural schemes: with transverse, longitudinal or cross transoms, and also without transoms (see Figure 2.2).

When selecting a structural scheme for the frame, both economic and architectural requirements are considered. Specifically, the frame elements should not restrict the planning solution, and the frame beams should not intersect the ceiling surface in living rooms, among other considerations.

In this regard, a frame with a transverse arrangement of beams is used in multi-story buildings with a regular planning structure (dormitories, hotels), combining the pitch of transverse partitions with the pitch of load-bearing structures. A frame with longitudinally arranged transoms is used in apartment-type residential buildings and large public buildings with a complex planning structure, such as school buildings.

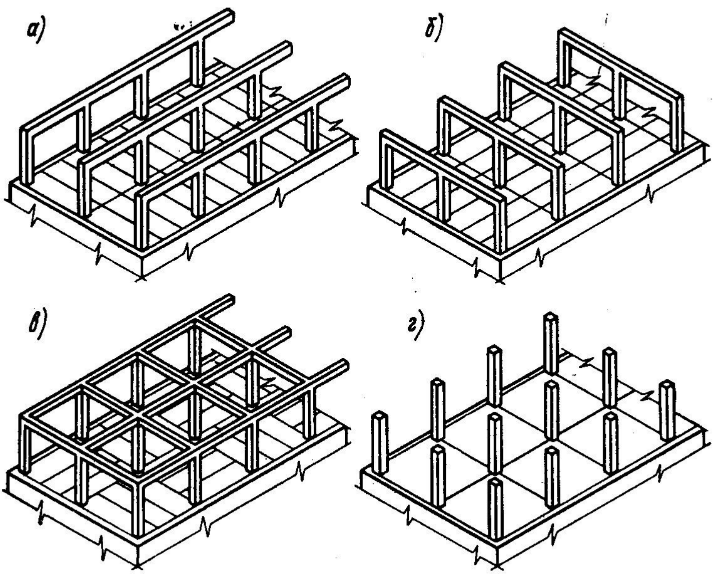


Figure 2.2 – Structural diagrams of frame buildings [87]:
a) with longitudinal arrangement of crossbars;
b) with transverse arrangement of crossbars;
c) with cross arrangement of crossbars; d) without crossbars

The transom-free (beam-free) frame is mainly used in multi-storey industrial buildings, less often in public and residential buildings, which is due to the lack of a corresponding production base in prefabricated housing construction and the relatively low cost of such a scheme. At the same time, due to the absence of transoms, this scheme is the most favorable among the frame ones in architectural and planning terms.

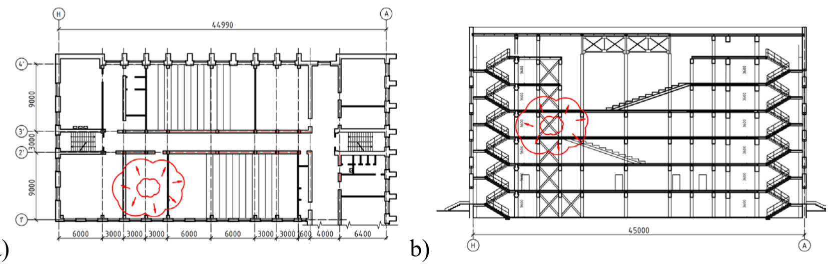
2.2 Analysis of damage to load-bearing structures of frame-type buildings

The analysis of damage to frame-type building structures caused by off-design impacts was performed using the example of two buildings: a multi-story public building, which is a frame of prefabricated reinforced concrete elements, which underwent an internal explosion due to the detonation of an explosive device (OTKR "Iskander") and a one-story warehouse building for industrial purposes, which was exposed to the shock wave, fragments and elements of an explosive device (OKR "Caliber"), as well as fragments of structures of neighboring buildings and structures that were destroyed as a result of the explosion.

According to the architectural and structural solution, the multi-storey public building is made according to the frame system using typical reinforced concrete structures and solutions in accordance with the II-20/70 series, namely: reinforced concrete composite columns with a cross-section of b×l = 400×600 mm at the level of the basement and 1st floors and b×l = 400×400 mm – at the level of the 2nd...5th and technical floors. The height of a typical floor is 3.6 m. The columns and beams form a three-span frame structure, in the transverse direction, with rigid joints. Between axes 1'-2' and 3'-4' the span is 9.0 m, and between axes 2'-3' the span is 3.0 m. The column pitch is mixed: 3.0 and 6.0 m. Between the 3rd and 4th frame of the frame (span 3.0 m) there is a tie block with cross ties on each floor, made of paired equilateral corners 200×12 mm. Between 4-8 frames at the level of 4 and 5 floors, an assembly hall is arranged, covered with three steel trusses with a span of 21 m. Ribbed roofing panels measuring 1.5×6.0 m and 300 mm high are laid on the trusses, and multi-hollow slabs with a height of 220 mm are laid on the extreme steps. The plan and section of the building with the conditional location of the explosive device are shown in Figure 2.3.

The interfloor beams are used with lowered shelves to support the floor slabs and of different heights: in the spans between the axes 1'-2' and 3'-4' –800 mm and between the axes 2'-3' –600 mm. The beams are supported on the column consoles with dimensions b×l = 400×350 mm and are fixed by welding to the embedded parts on the console at the bottom of the section and to the reinforcement outlets in the upper part. The floors are made of ribbed reinforced concrete panels measuring 1.5×6.0×0.45 m, located in the longitudinal direction. In some areas, monolithic sections are made or multi-hollow floor slabs with a height of 220 mm are used, which are installed on supports made of channel No. 20.

The external enclosure is made in the form of brick self-supporting walls with a thickness of 510...640 mm. The internal walls and partitions are made of brickwork with a thickness of 250...380 mm, gypsum blocks and light frame systems.



a) b)

Figure 2.3 – Scheme of primary damage to the structures of a multi-storey frame building: a) fragment of the plan; b) longitudinal section of the building

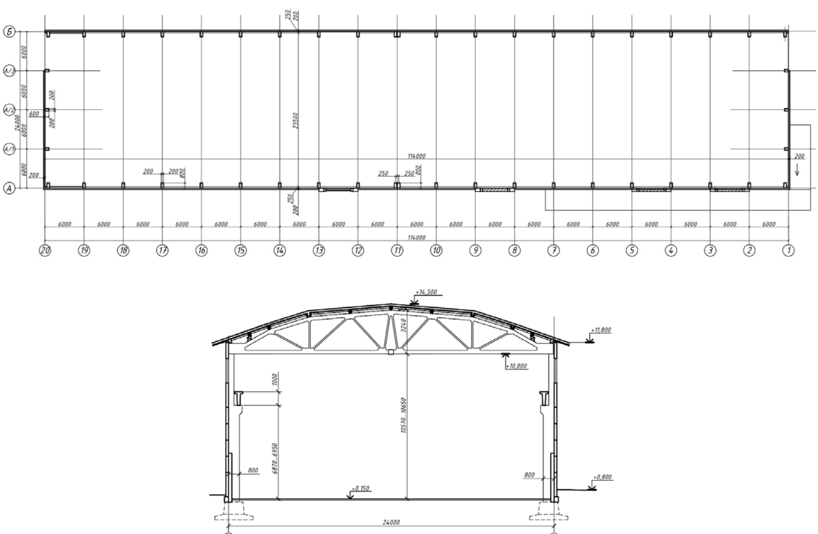
According to the architectural and structural solution, the production building is a one-story, single-span structure with dimensions in axes B×L = 24×114 m. The building is divided into 2 temperature blocks: in axes 1-11, length L = 60 m and in axes 11-20, length L = 54 m. The plan and section of the building are shown in Figure 2.4.

The height of the building is: to the top of the eaves of the roof – H = 12.2 m, to the ridge – H = 14.5 m. The supporting frame is made of transverse single-span frames with a pitch of 6.0 m, which form the spatial rigidity of the building.

The frame columns are prefabricated reinforced concrete with a height of H = 10.7 m, with sections: below the console – 400×800 mm, above – 400×380 mm, in the console location – 400×1000 mm. The console protrusions are supported by prefabricated crane beams of T-section with a height of h = 1.0 m, a span of L = 6 m. The frame beams are prefabricated reinforced concrete trusses with a span of L = 24 m, with belts b×h = 250×250 mm and lattice elements b×h = 250×120 mm.

The covering is made of ribbed prefabricated panels with a span of L = 6 m, width B = 1.5 and 3.0 m, laid on the upper belts of the trusses and fixed by welding. Spatial stability is ensured by vertical ties and running struts along axes A and D between axes 5-6 and 15-16. The roof is made of profiled steel sheets arranged on wooden bars, which are laid on top of the roofing felt carpet.

The external walls are prefabricated expanded clay concrete panels with a thickness of b = 200 mm, a length of l = 6 m, and a height of h = 1.2 and 1.8 m. The floor is concrete or asphalt concrete prepared from crushed stone and a layer of compacted soil.



a)

b)

Figure 2.4 – General view of a one-story frame building:
a) plan; b) cross-section

Recent research on the behavior of frame structures subjected to off-design impacts from explosive devices indicates that the response of reinforced concrete elements is primarily governed by their geometric configuration, stiffness characteristics, and the nature of the applied loading. Although frame systems can exhibit a certain capacity to resist progressive collapse even in the presence of localized damage, the potential for structural failure remains considerable [4; 31; 42; 99; 102].

Practical assessments of frame buildings of various types that have sustained damage from explosions or missile strikes enable the classification of structural damage severity, documentation of damage types and extent, evaluation of their impact on load-bearing capacity, and prediction of potential progressive collapse. These analyses provide a basis for accurately determining the technical condition of structures and for planning effective emergency stabilization and recovery measures [11; 18; 46; 59; 71]. As a result of the inspection after emergency off-design impacts, several defects and damages to the load-bearing and enclosing structures of buildings were recorded. The assessment of the frame house structure technical condition was carried out taking into account the provisions of Appendix B "Determination and assessment of the condition of foundations and technical condition of objects structures" and Section 5 "Categories of the technical condition of building structures and objects" of DSTU 9273:2024 "Guidelines for the buildings and structures inspection to determine and assess their technical condition" [24]. The identified defects and damage are shown in the diagram of their location (Figure 2.5) and in the photographs.

The main damages to the structures of frame buildings after short-term action of dynamic non-projective loads are:

– partial or complete destruction (collapse) of external enclosure elements: brickwork of self-supporting walls; hinged expanded clay concrete wall panels; ribbed and multi-hollow covering slabs;

– damage to external fencing elements: loss of the design position of brick walls; detachment of embedded elements fastening hinged wall panels; formation of through cracks in wall panels (see Figure 2.10);

– damage to the frame columns: formation of through cracks in individual sections or destruction of concrete (column shearing); loss of straightness due to shearing shear effects (see Figure 2.6, 2.12);

– damage to transverse elements of the floor: destruction of concrete and formation of cracks in the crossbars along their entire height in places as close as possible to the place of the explosive device detonation (see Figure 2.7);

– damage to structures of prefabricated reinforced concrete floor/roof slabs: formation of transverse and inclined cracks in the ribs; local fractures and cracks of different orientation in slab sections; deflections exceeding the limit value (see Figure 2.8, 2.13);

– damage to ties: separation of elements from embedded parts of reinforced concrete columns and bending from the plane of vertical cross ties (see Figure 2.9); loss of design position; separation of elements from embedded parts; collapse of individual structures of crane beams, which act as horizontal ties of a single-story frame (see Figure 2.11);

– damage to metal roof trusses: loss of cross-sectional shape, design position and general residual deflections of structures resulting from the fire (see Figure 2.9);

– damage to reinforced concrete roof trusses: destruction and formation of cracks in the elements of the upper and lower belts of reinforced concrete trusses; separation and mixing of truss support nodes from the support sections of columns (see Figure 2.14).

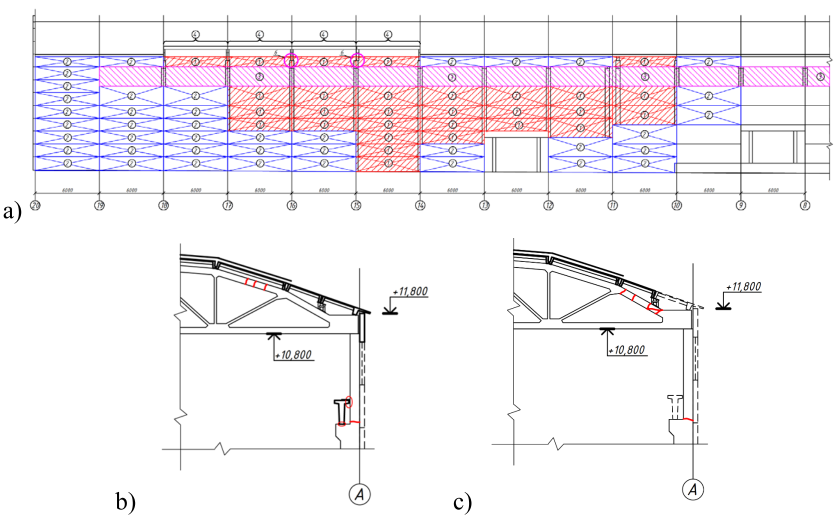


Figure 2.5 – Scheme of the damage to reinforced concrete structures location: a) fragment of the facade with the selection of damaged walls; b, c) fragments of the section of the building along axis 12 and along axis 16

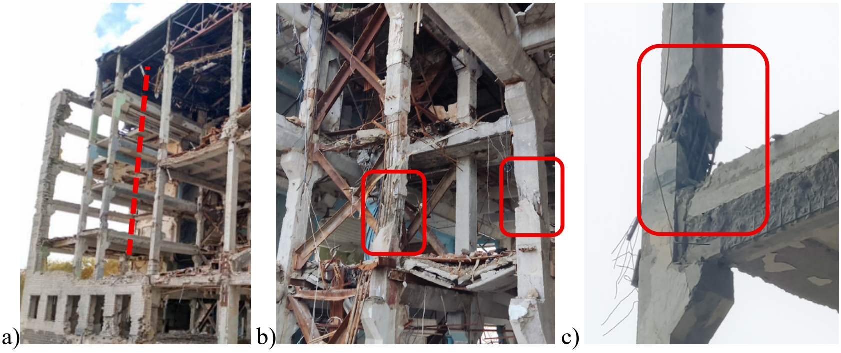
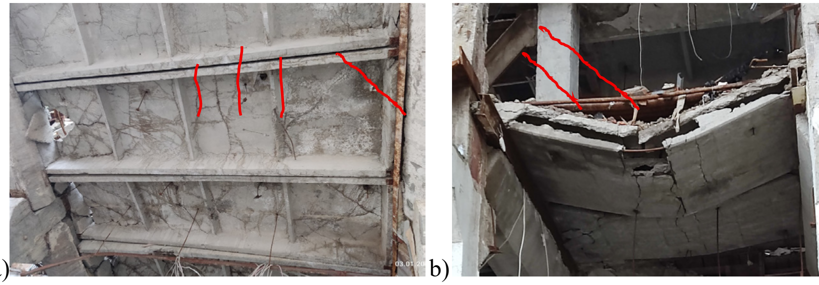


Figure 2.6 – Damage to columns of a multi-storey frame building: a) destruction of the 4th column; b, c) destruction of concrete over the entire cross-section of the column as a result of shear forces

Figure 2.7 – Cracks in the crossbar at the level of the 3rd floor ceiling

Technical condition of the load-bearing structures of a multi-storey frame building, according to the characteristic classification features of the reinforced concrete structures technical condition (Table B.2.1 DSTU 9273:2024 [24]) is assessed as emergency (technical condition category 4) and requires the introduction of measures to eliminate existing hazardous factors and urgent reinforcement of load-bearing structures (elements) and long-term restoration of structures that have been destroyed and damaged.



a) b)

Figure 2.8 – Damage and failure of floor slabs:
a) local failure of shelves and multiple cracks in ribbed slabs
b) failure of multi-hollow slabs

a) b)

Figure 2.9 – Damage to metal structures of a multi-storey frame building: a) bending from the plane of vertical cross-ties; b) loss of cross-sectional shape and design position of the metal truss


a)

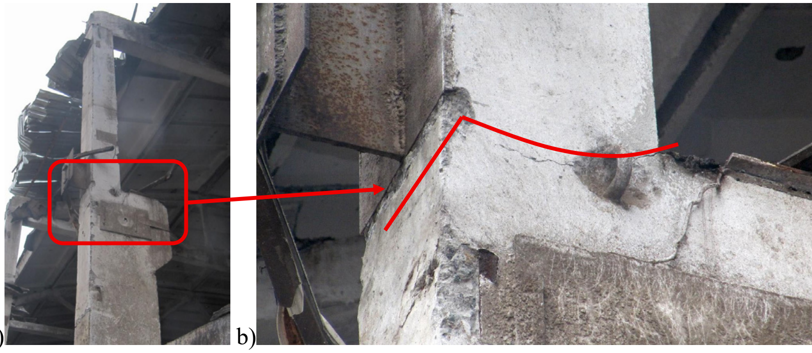

b)

Figure 2.10 – Destruction of prefabricated expanded clay concrete wall panels of a one-story frame building: a) destruction and collapse of wall panels; b) partial separation of embedded parts from the supporting elements of columns, loss of design position with a deviation of 150 mm and formation of cracks with an opening width of up to 30 mm


a)


b)

Figure 2.11 (a-b) – Collapse of crane beams and detachment of embedded parts of their attachment to columns



a) b)

Figure 2.12 (a-b) – Formation of transverse vertical cracks in the cross-section of the upper crane part of the column

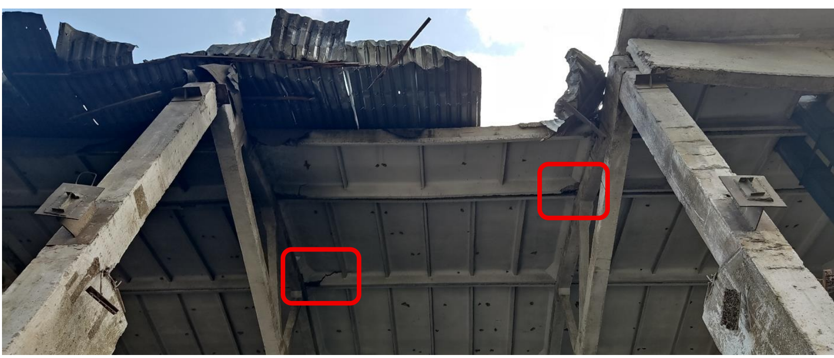
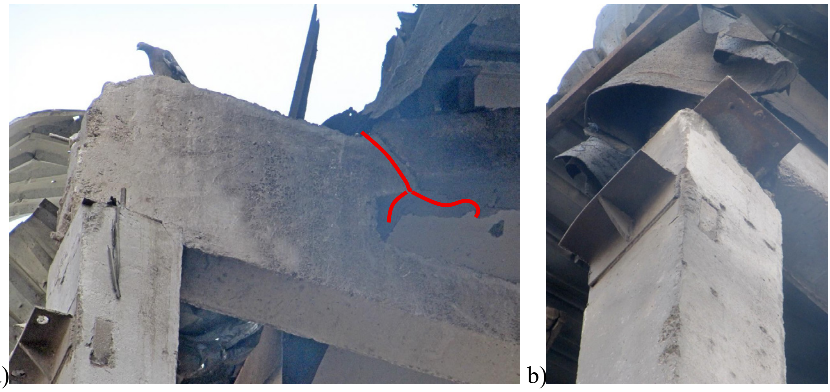


Figure 2.13 – Collapse of the extreme reinforced concrete ribbed slabs of the cover and destruction of the longitudinal ribs in the supporting areas

The technical condition of the structures (elements) of the one-story warehouse building in axes 1-20, A-B is classified by most load-bearing structures (elements) as also in emergency, accordingly, technical condition category 4.



a) b)

Figure 2.14 – Damage to reinforced concrete roof trusses: a) the appearance and opening of vertical and inclined cracks with an opening width of up to 25 mm in the upper chord element of the truss in the area near its support on the column along the A axis; b) displacement of the support area from the design position in the horizontal direction in the support node of the truss

2.3 Summary of observed damage and guidelines for the restoration and reinforcement of damaged frame structures

Design features of the multi-storey frame building, as the presence of rigid nodes and a reduced pitch of the transverse frames at the site of the explosive device, made it possible to avoid complete destruction of the building. As for the single-storey frame building, the main factors were the insignificant total height (Htotal = 14.5 m), the distance from the site of the explosive device impact (23…25 m from the epicenter of the explosion) and the presence of additional obstacles in the path of the blast wave propagation, which minimized the amount of damage, affecting the overall integrity and technical condition.

The identified damage and defects of the elements of a frame multi-story public building can be classified as follows:

The detected structural damage after the action of dynamic non-projectile impacts significantly reduces the possibility of safe operation of frame buildings. The recorded destruction and deformations led to the loss of stability of individual sections of frames and fences, which require urgent repair and restoration work. The spatial rigidity of the buildings is only partially preserved. Several structural elements classified under responsibility categories A and B exhibit a technical condition of Category 4 (emergency). These include load-bearing frame components such as columns, beams, floor or roof slabs, and trusses located in the most severely damaged areas. The overall technical condition of the buildings is therefore assessed as emergency (Category 4). Consequently, the structures require immediate major repairs involving the dismantling of destroyed elements, their strengthening or replacement, and subsequent restoration. Continued operation of the buildings is not permissible until the complete set of restoration measures has been fully implemented.

Given the above results, to ensure further trouble-free and safe operation of the studied frame houses, some parts of which were damaged due to non-project impacts, it is advisable to formulate appropriate recommendations.

1. Perform emergency work:

1.1) prohibit access of personnel and unauthorized persons to the emergency fragments of buildings. Provide temporary fencing of dangerous areas;

1.2) fix the wall of the multi-storey frame, which deviated from the vertical position by up to 150 mm, with ropes to the staircase to allow safe access to the roof of the building;

1.3) dismantle the destroyed roof elements: roofing felt, screed, expanded clay. In a one-story building, additionally dismantle the roof made of steel profiled sheets;

1.4) dismantle ribbed and multi-hollow roofing slabs that have significant damage and deflections of more than 1/50. To do this, first disconnect the places where the slabs are welded to the trusses without damaging the belts;

1.5) dismantle the steel trusses of the roof of a multi-storey frame building, damaged as a result of the fire;

1.6) dismantle the reinforced concrete columns of a multi-storey frame building, which have significant deviations from straightness;

1.7) dismantle the expanded clay concrete wall panels of a single-storey frame building, which have lost their design position.

2. Recommended measures for strengthening and restoring the structures of a multi-storey frame building:

2.1) install vertical frame elements (columns) instead of those that are destroyed or will be dismantled. Install new cross-ties between rows of columns to ensure spatial rigidity;

2.2) install horizontal load-bearing floor elements (crossbeams, beams) and install floor slabs;

2.3) arrange steel roof trusses that were dismantled and reinforced or manufactured to replace damaged ones;

2.4) arrange prefabricated reinforced concrete roof slabs;

2.5) restore and strengthen external and internal brick walls that have lost their design position or are damaged by explosive loading;

2.6) arrange roofing carpet, window fillings, internal partitions and engineering networks.

3. Recommended measures for strengthening and restoring the structures of a single-story frame building:

3.1) perform continuous reinforcement of the sections of the above-crane and below-crane sections of reinforced concrete columns of a single-story frame building using steel clips and overlays;

3.2) arrange additional runs between the upper sections of the columns in the longitudinal direction to ensure the perception of horizontal forces;

3.3) restore the cross-ties that were dismantled during the reprofiling of the building;

3.4) reinforce the supporting sections of the truss trusses in places of damage, as well as arrange additional supporting chairs for trusses with a disturbed position of the supports;

3.5) reinforce the areas where the covering slabs rest on the trusses, considering the reduced support area;

3.6) arrange new covering runs from steel profiles in areas with missing slabs;

3.7) install the frames of the external fence and window filling.