# CHAPTER 7
# STEEL SILO STRUCTURES

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## 7.1 Structural diagrams of steel silo structures

Steel silos (silo tanks) are large-sized vertical cylindrical or prismatic structures designed for long-term storage of grain crops, oilseeds and other bulk materials [66]. They are made of flat or corrugated thin-sheet steel panels, which provide sufficient strength and rigidity of the structure with a relatively small mass. Silos are widely used as part of elevator complexes, grain processing enterprises and agro-industrial farms.

Thanks to industrialised production, the main components of silos are manufactured with high precision in a factory and then transported to the construction site as individual parts, structures, or larger modules. The installation of these structures is carried out using specialised jacking or crane systems. Building silos demonstrates that using steel structures can significantly reduce installation time compared to concrete storage, as well as cut construction costs by approximately 20–25%. However, steel silos typically have a service life of 25 to 40 years, which is considerably shorter than that of concrete silos.

Steel silos are classified by shape, type of bottom, wall and cover [8; 60; 75]. According to the shape, there are rectangular and round silos. In modern Ukraine, most silo structures being built and operated are round. According to the type of bottom, silos are divided into flat and conical.

According to the manufacturing method, steel silos are divided into continuous welded, prefabricated and spiral (Figure 7.1). Continuously welded silos are made from separate sheets, which are connected by a weld directly at the construction site or are assembled (welded) from rolled blanks manufactured in the factory. The main disadvantages of these silos are their high cost, due to excessive material consumption, and the complexity of manufacture resulting from the large number of welds, which are arranged directly during construction.

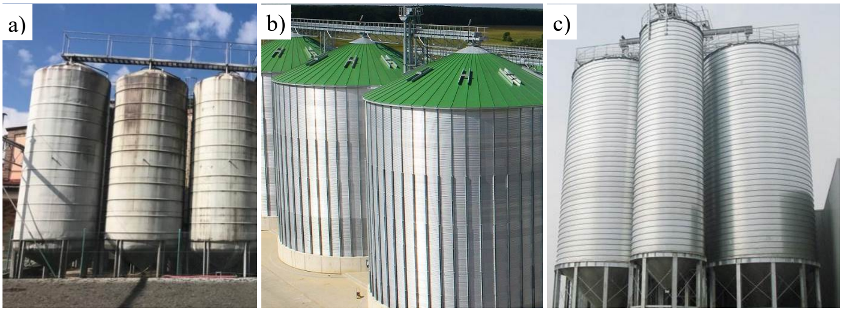



**Figure 7.1 – Types of steel silos by different manufacturing methods: a) welded; b) prefabricated from corrugated sheets; c) spiral**

Prefabricated steel silos come in three types:

– panel, characterized by a cylindrical body made of corrugated (smooth) sheets, fastened together by bolted joints. To ensure the stability of the shape, vertical stiffeners are installed at equal intervals. The general appearance and list of main structures are shown in Figure 7.2. The advantages of this design are high strength and high speed of installation without the use of heavy construction equipment. This design is most common in Ukraine and European countries;

– panel-frame silos, similar to panel silos, but instead of vertical stiffeners, they have an additional frame of posts installed outside the shell and serving to support the covering structure. The disadvantages of both frame and frame-panel silos are the complexity of installation, a large number of atypical structural elements, the lack of complete tightness and a large number of bolted connections;

– membrane-frame, characterized by shells made of one long tape that is spirally connected. Almost not used in Ukraine due to the specificity and complexity of installation.

Spiral silos also come in three types: spiral-bolted, spiral-seamed, and spiral-welded. All of them are characterized by cylindrical shells made of steel elements that are spirally connected by bolts, welding, or seam joints. Their advantages and disadvantages are similar to prefabricated and welded silo structures.

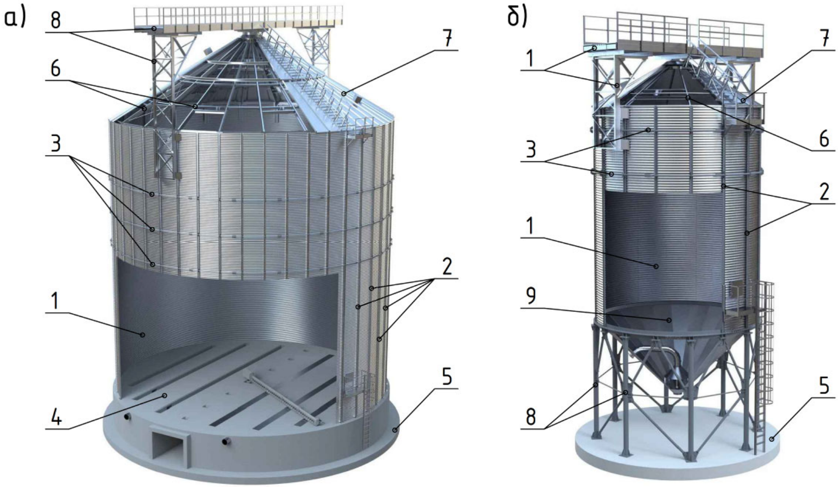



**Figure 7.2 – Structural elements of a panel-type steel silo:**
**a) with a flat bottom; b) silo with a conical bottom;**
**1) body made of corrugated sheets; 2) vertical stiffeners;**
**3) annular stiffening diaphragm; 4) flat reinforced concrete bottom;**
**5) foundation; 6) roof support system; 7) corrugated sheet covering;**
**8) conical bottom posts; 9) conical steel bottom**

The main causes of failures and destruction of steel silos are a combination of structural, technological and operational factors. Most often, they arise due to uneven distribution of load on the walls during loading and unloading, which can cause local loss of the lining stability. Also, design and manufacturing errors play a significant role, in particular, underestimation of operational, wind or snow loads [7; 9; 17; 101].

Common factors include the effects of corrosion and material fatigue in individual sections of the structure [7; 9; 28], as well as foundation defects – settlements or uneven deformations, which can cause skewing and additional stresses in the hull. Another important factor is seismic effects, which create dynamic loads that can provoke a loss of stability of the silo shell [77]. Shock waves from explosions have a similar effect, which acts impulsively, exceeding the design loads on the walls and joints of structures [101]. In addition, frequent causes of failures are violations of operating rules: overloading, untimely cleaning of grain residues, lack of regular inspections and maintenance [49].

### 7.2 Analysis of damage to silo structures caused by off-design impacts

The analysis of damage to steel silos caused by off-design impacts was performed using the example of a grain elevator, which consists of 11 silos of the same type that were exposed to the shock wave, fragments and elements of an explosive device (OKR "Caliber"), as well as fragments of neighboring buildings structures and structures that were destroyed as a result of the explosion. The location of the silo tanks is shown in Figure 7.3. The place of impact of the explosive device was located at a distance of 25...30 m opposite silos No. 7 and 8.

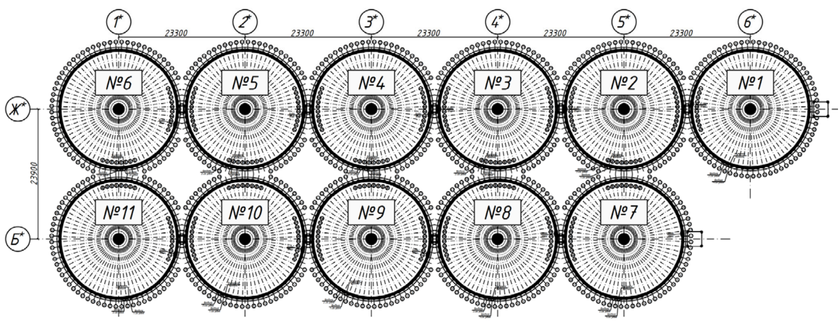



**Figure 7.3 – Layout of silo tanks in the damaged grain elevator**

Grain storage silos No. 1–11 are designed as cylindrical structures with a diameter of 21.5 m and a height of 24.8 m, with a construction volume of over 7,400 m³ each. The foundation consists of prefabricated reinforced concrete piles and a monolithic circular grillage with a diameter of 22.7 m and a height of 0.8 m. The vertical walls are formed from 20 metal belts made of 3.5 mm thick steel with a corrugated profile, reinforced with U-shaped stiffeners. The roof has a conical shape with a slope of more than 30°, made of radial girders and profiled flooring. The silos are equipped with ring stiffeners, external and internal stairs with platforms, as well as technological openings (doors, hatches, ventilation deflectors).

Underground transport galleries are located at the level of the foundations and serve to accommodate conveyor equipment. They are a corridor room 1.5 m wide and 1.9 m high, with walls and ceilings made of monolithic reinforced concrete 0.5 m thick. The upper transport galleries are supported by racks located between the silo structures and are structurally connected to the technological process of grain supply between individual containers and auxiliary structures.

During the inspection after the off-design impact, several damages to the load-bearing and enclosing structures of the silos were detected. The determination of the technical condition of the silos load-bearing structures was carried out taking into account the instructions of Appendix B “Determination and assessment of the condition of the foundations and technical condition of the facilities structures” (in particular, Appendixes B.2 “Concrete and reinforced concrete structures” and B.4 “Metal structures”) and Section 5 “Categories of the building structures and facilities technical condition” of DSTU 9273:2024 “Guidelines for the inspection of buildings and structures to determine and assess their technical condition” [24]. The identified defects and damages are presented in the form of photographs of the damages (see Figure 7.4 – 7.12). The identified significant damages to the building structures, in most cases, arose precisely because of the shock wave impact. To a lesser extent, the damage was affected by fragments of the explosive device, as well as fragments of the structures of neighboring buildings and structures that were destroyed because of the explosion. Also, some of the damage accumulated during the operation of the grain elevator structures.

During the survey, it was found that the structures’ geometric dimensions vary within the permissible values of the standards DBN V.2.6-221:2021 “Constructions of steel silos with corrugated walls for grain: Basic provisions” [65] and DSTU-N B EN 1993-4-1:2012. “Eurocode 3. Design of steel structures. Part 4-1: Silos” [25].

The main structural damages of grain elevator buildings after exposure to the shock wave, fragments and elements of an explosive device are:

– formation of cracks on the horizontal and lateral planes of the above-ground part of the silo structure grillage, in areas near the locations of foundation anchor bolts;

– massive detachment of anchor bolts (studs) along the perimeter of the lower belt of the structure's cylindrical part, which occurred because of deformations and displacements of the silo body (see Figure 7.6);

– formation of transverse and longitudinal cracks in the protective additional concrete layer at the top level of the foundation grillage, which protrudes beyond the silo building body;

– point damage to the sheets of the silo body belts in the form of various shapes of external dents, notches, through holes and cracks (see Figure 7.4, 7.7);

– loss of the design position (appearance of roundness) of the silo body (see Figure 7.5);

– deviation from the vertical straightness of the wall and individual elements of vertical stiffeners along its height by an amount exceeding the maximum permissible value according to the standards;

– the appearance of gaps between the upper plane of the grillage and the lower edge of the 1st belt of the structure sheets by the amount: vertically up to 50 mm; horizontally up to 20 mm (see Figure 7.6);

– destruction of the concrete floor along the perimeter of the supporting section of the 1st belt of the structure as a result of its deformation, displacement and movement (see Figure 7.8);

– destruction (deformation) of the spans of the structure's covering due to the crushing of cross-sectional shape and loss of stability of the design position (Figure 7.9);

– destruction of the pavement covering up to 65% of the total area;

– separation of the roof cone sheets from the supporting frame elements and convexity and deviation of the shape of the covering decking by up to 1600 mm inside the structure (see Figure 7.10);

– formation because of the roof destruction structures and coverings of through openings and cracks with an area of up to 8 $m^2$ (excluding the mass destruction of silos No. 7 and 8, (see Figure 7.9a);

– separation (destruction) of connections from self-tapping screws in the fastening elements of the ring stiffener at the roof level (see Figure 7.11);

– loss of the initial design position (curvature, crumpling and bending) of elements of stairs, platforms and fences of silo structures (Figure 7.4 a, c);

– damage to the elements of the transport gallery racks between the silos (see Figure 7.12).

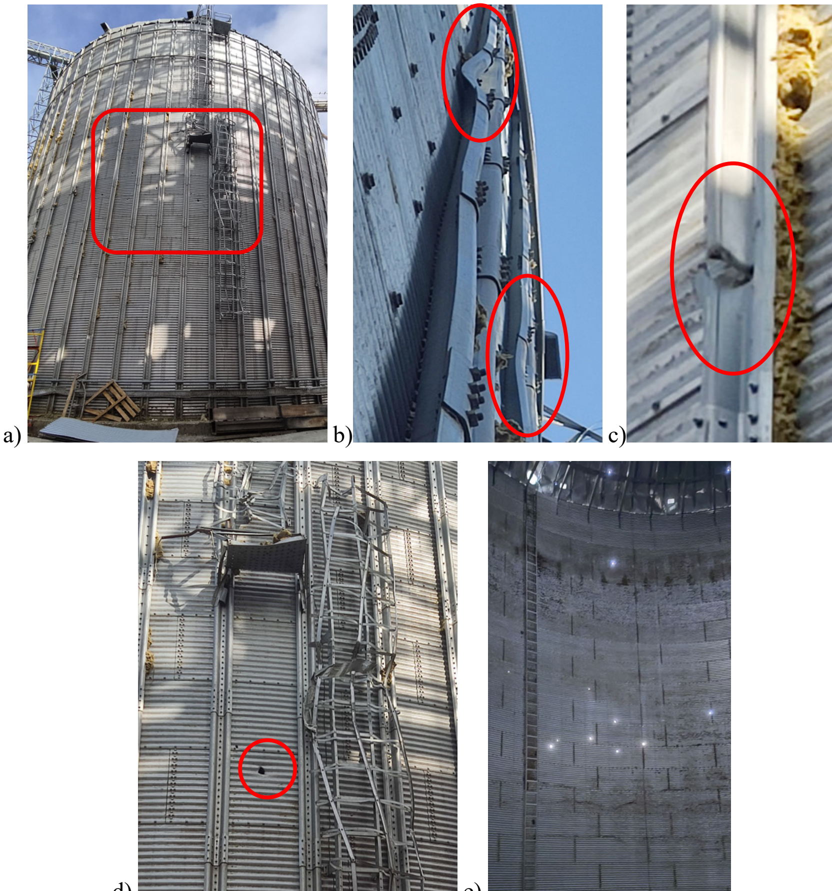
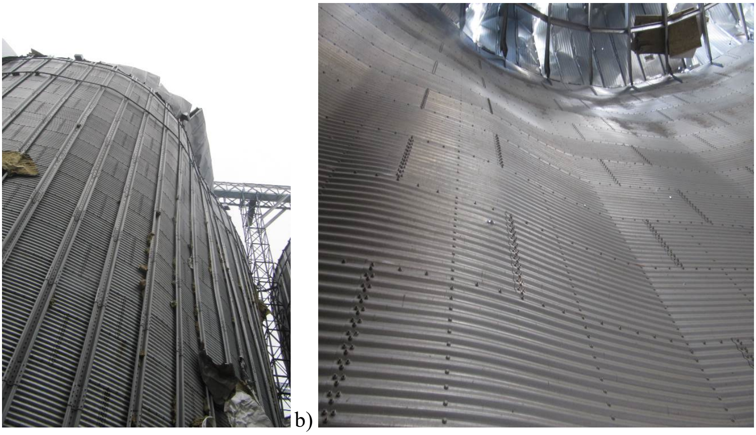



**Figure 7.4 (a-e) – Damage to silo No. 7:
vertical stiffeners because of the blast wave
and mechanical action of debris, external ladders
and the wall of the body made of corrugated galvanized steel sheets**

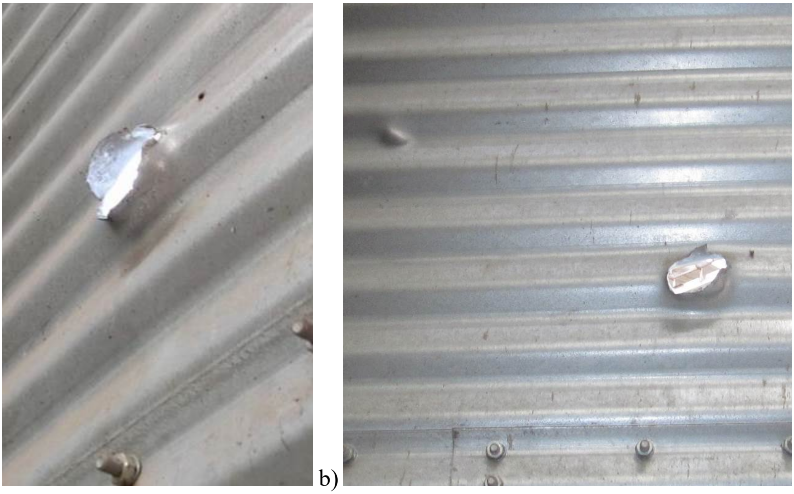


a) b)

**Figure 7.5 (a-b) – Loss of design position (appearance of roundness) of the wall of the cylindrical part of the silo structure No. 8 by up to 200 mm (external and internal view)**

a) b)

**Figure 7.6 (a-b) – Separation of anchor bolts (studs) along the perimeter of the lower belt of the structure's cylindrical part, which occurred because of deformations and movements of the silo body**

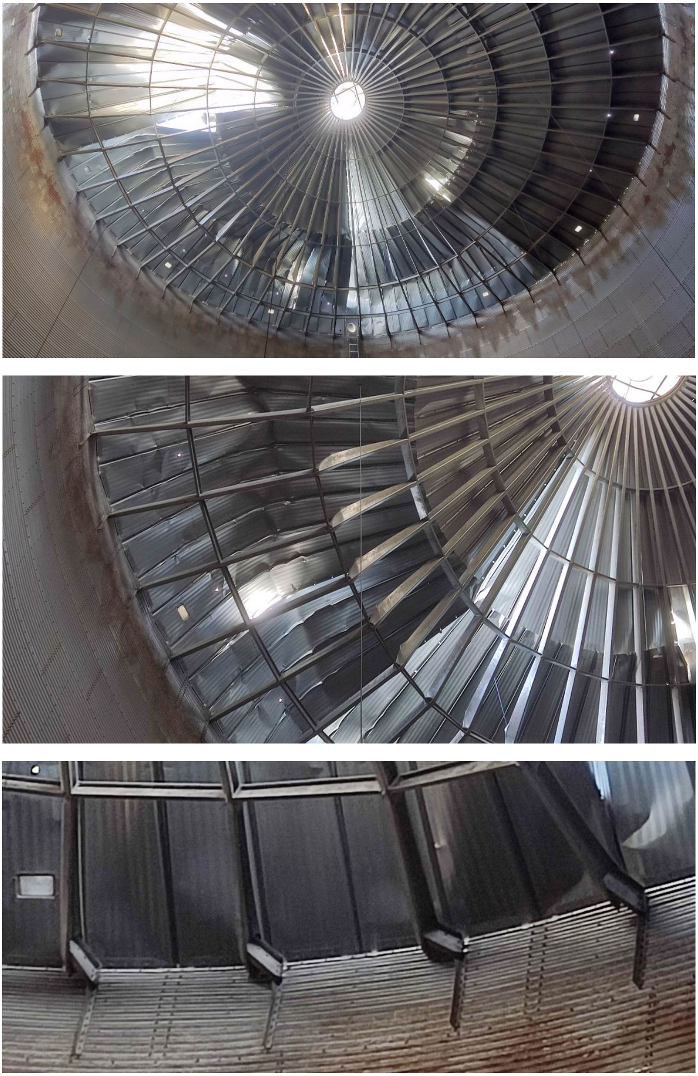


a) b)

**Figure 7.7 (a-b) – Point damage to the corrugated sheets of the silo building body No. 8 in the form of various shapes of external notches and through holes**

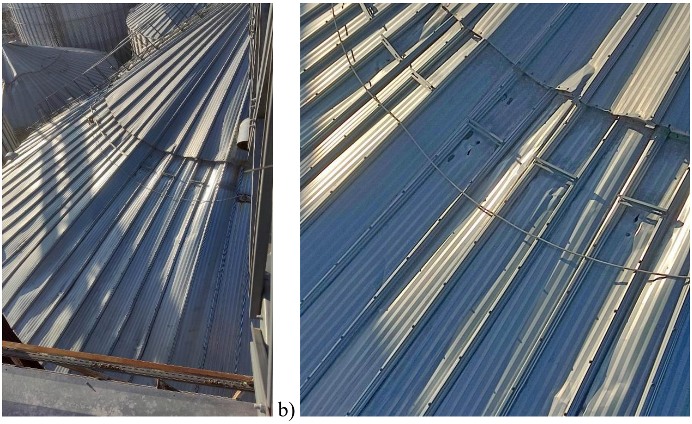
a) b)

**Figure 7.8 (a-b) – Formation of cracks and through holes at floor level due to displacement and movement of silo body No. 11 and local destruction of the concrete floor to a depth of h=10…50 mm**



a)
b)
c)

**Figure 7.9 (a-c) – Destruction of the covering and purlins of the roof supporting system of the silo building No. 9 and the formation of numerous openings and cracks**



a) b)

**Figure 7.10 (a, b) – Loss of the original design form and configuration of the roof and covering of silo No. 2, accompanied by the formation of numerous through-openings in the flooring at the points where individual dowels and self-tapping screws detach**

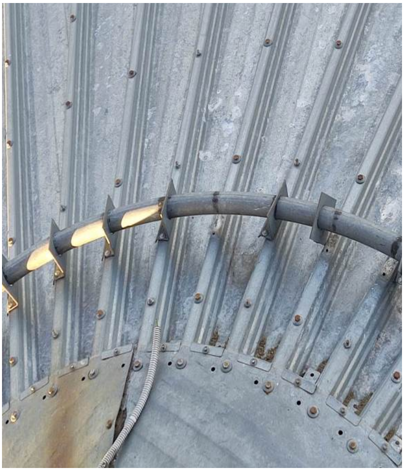


**Figure 7.11(a-b) – Loss of the initial spatial (shape and configuration of the roof and silo cover; complete (a) and partial (b) separation of connections from self-tapping dowels in the fastening elements of the ring stiffener at the roof level of building No. 9 (a) and building No. 2 (b)**

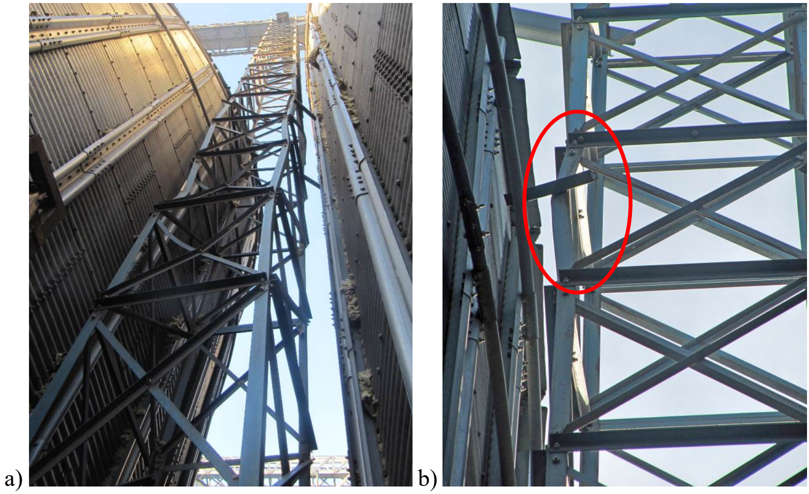


**Figure 7.12 (a, b) – Loss of vertical spatial stability, horizontal sections of the transport gallery racks between silo structures**

The technical condition of the structures (elements) of grain storage silos No. 7–11, according to the classification signs of defects and damage (Table B.1.1, B.2.1, B.7.1 DSTU-N B B.1.2-18:2016 and Table B.1 DSTU B B.2.6-210:2016), is assessed as unsuitable for normal operation (technical condition category 3), and individual structures and sections are assessed as emergency (category 4) and require urgent restoration and reinforcement of load-bearing elements. The technical condition of individual structures (elements) of silos No. 1–6 is assessed as unsuitable for normal operation (technical condition category 3).

The general technical condition of silo structures No. 1–6 is assessed as unsatisfactory (technical condition category 3), while silo structures No. 7–11 are assessed as emergency (technical condition category 4), since damage has been detected in the structures and elements (responsibility categories A and B), which may lead to failure in operation and the creation of an emergency.

## 7.3 Summary of damage and brief recommendations for restoration and damaged elements of steel silos

The general position of the silo structures during the formation of the grain elevator, the filling of each of them with grain within 50…70% of the volume, the distance from the point of impact of the explosive device and the presence of additional obstacles in the path of the blast wave propagation minimized the amount of damage that affected their integrity and technical condition. Due to the combination of these factors, none of the silo structures suffered destruction of hull.

The identified structural damage indicates the impossibility of further operation of the grain elevator structure as a whole and individual silo structures. The general technical condition of silo structures No. 1–6 is determined as unsatisfactory (technical condition category 3). At the same time, the technical condition of their individual structures and elements.

The structures and elements of silos No. 7–11 are in a condition unsuitable for normal operation (technical condition category 3). At the same time, individual structures and sections have signs of an emergency condition (category 4), which requires urgent restoration and strengthening of load-bearing elements. is also unsuitable for normal operation (category 3). The general technical condition of silos No. 7–11 belongs to category 4 (emergency).

Based on the above, the following recommendations can be made to enable further safe and trouble-free operation of the analyzed silo structures that were damaged because of non-projectile impact (explosive device detonation):

1. Stop the operation of the elevator and perform emergency work:

1.1 Urgently unload the silo containers of the grain to prevent the progression of damage and destruction of the silos.

1.2 Strengthen (unfasten) the racks of the technical galleries in places that have been damaged and have changed their geometric position.

2. Carry out complete dismantling of metal structures and elements of tanks No. 7-8, to sort and store them for decision-making on further use.

3. Replace deformed foundation bolts that have been damaged and lost their design functionality. The studs must have a diameter of M20–M24 and a minimum length of clamping in concrete ≥400 mm.

4. Carry out major repairs (replacement) of metal structures and elements of the tank that have lost their shape stability or design position: supporting and enclosing structures of the coating and roof, stairs, auxiliary platforms and fences at the level of the vertical part and roof of the tanks.

5. Carry out repairs of the concrete floor inside the tank after the installation of metal structures and elements.

6. Carry out repairs to the external concrete surfaces of the above-ground part of the foundation grillage: restoration of the protective concrete layer in damaged areas, sealing cracks with cement-sand mortar of the M150–M200 brand and installation of a protective anti-corrosion coating.

7. Carry out reinforcement or replacement of the vertical and horizontal elements of the supporting frame of the upper transport galleries. It is necessary to arrange an anti-corrosion coating on these elements.

8. Restore or replace elements of annular and horizontal stiffening elements at the roof level and along the height of the cylindrical part of the tanks.

9. Perform restoration or major repairs of structural elements of engineering systems that have been destroyed.