CHAPTER 5
ANTENNA COMMUNICATION STRUCTURES

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5.1 General information about the operation of communication antenna structures under martial law

Wireless technologies have recently become not just a convenient means of communication and connection, but also a necessity of life. The majority of telecommunication service subscribers use only cellular communication, which imposes additional standards and requirements on the network, primarily as a critical infrastructure object. The presence of a developed cellular network contributes to business and economic activity in the region and is also a prerequisite for its further development. In today's world, with rapid digitalization and globalization, this criterion is almost indispensable for sustainable development, especially in regions that have suffered destruction and damage as a result of hostilities and require accelerated recovery.

The destruction of communication antenna structures can occur due to typical damage to supporting building structures [78] or as a result of installation or operation errors. In particular, [19] describes real events of a complete collapse during the installation of a 6-ton FM antenna on a new 1800-foot tower. 5 technicians died. The collapse was caused by undersized bolts on a makeshift extension of the lifting loop failing. Falling debris damaged one of the tower's cables, causing it to collapse.

The results of experimental studies on the load-bearing capacity of antenna structures have also been published. [52] describes experimental studies by measuring the energy losses during impact response and damage in conformal load-bearing antenna structures that consist of a faceplate, core, and ground plate. [51] reports the results of static indentation and impact tests on two CLAS antenna panels used in a wireless local area network system. The correlation between peak contact force, residual indentation, and delamination area was analyzed on a panel with an aluminum shielding plane. The work [76] presents research findings on the failure of antenna structures, considering additional loads during geometric nonlinearities that occur during destruction.

Deterioration of antenna structure foundations is also rapidly becoming a critical issue. A case study of 51 defective foundations of self-supporting and tensioned antenna structures is presented in [86]. Factors affecting the durability of tower anchors and foundations are discussed. These include corrosion of tower parts in direct contact with the ground, insufficient detailing of tower foundation reinforcement, and lack of maintenance of concrete foundations. Methods for repairing tower foundations are presented along with tower bracing systems used to maintain structural capacity during the repair process.

One of the main tasks of cellular mobile operators in wartime is to provide subscribers with high-quality and stable access to the network, which entails a prompt response to possible damage and destruction of communication antenna structures as a result of hostilities in order to eliminate the identified damage [43]. Unfortunately, in recent years, Ukraine has recorded cases of damage to communication antenna structures both as a result of military operations and as a result of combat clashes, where control and communication means of units are destroyed by drones and other enemy combat equipment [95]. Hitting cellular antennas or base stations disrupts coverage in their area, resulting in reduced or no mobile and Internet service. Antennas receive and transmit radio frequency signals from mobile phones, forming communication "cells." Damage to such an antenna renders the "cells" inoperable, creating "dead zones" for subscribers within them [68].

Faced with the consequences of missile and bomb strikes on the civilian infrastructure of Ukrainian cities, the telecommunications network of cellular operators was no exception. Not only telecommunications equipment and cable feeder routes are damaged and destroyed, but also the supporting structures of antenna structures. While it is quite possible to replace equipment in a short time, the situation with restoring the supporting structures of communication antenna systems is much more complicated and requires a long-term restoration or reinforcement process. At the same time, practice shows that mobile communications are critically important for the coordination of repair teams, the logistics of construction materials and communication with emergency services, particularly in areas where the infrastructure is damaged [92].

The accelerated restoration of cellular base station operability is of the utmost priority, as it is a key condition for building a strategy to counter the enemy's armed aggression and restore economic activity, especially in frontline regions and near the combat zone.

When examining the state of mobile communication availability in combat zones, it should be noted that since the beginning of the full-scale invasion, more than 3,500 base stations have been damaged. At the same time, operators have already restored more than 1,200 of them and built more than 1,500 new ones [1] (see Figure 5.1). In particular: Kyivstar in Kharkiv region restored 90% of the network, in Kherson region – 15%, Zaporizhia region – 50%, Donetsk region – 30%; Vodafone Ukraine in Kherson region restored communication in 45 settlements, in particular thanks to demining of territories; Lifecell reports over 800 destroyed or damaged base stations, 80-90 repair teams make 2-3 trips every day to restore equipment.

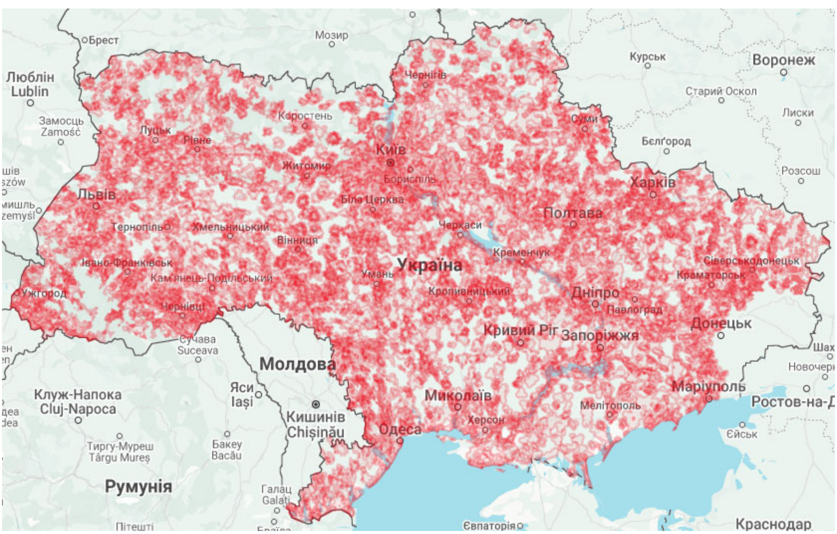

Figure 5.1 – 4G coverage by mobile operators in Ukraine [1]

5.2 Classification of mobile communication antenna structures

Antenna structures for cellular communications are a broad class of structures designed to house technological and radio equipment. According to their structural design, antenna structures are divided into towers, masts, and combined supports [36]. A distinctive feature of antenna structures is their high height (compared to the dimensions of their cross-sections), so the supporting structures and assemblies are designed mainly for atmospheric loads - wind, ice and temperature. However, this type of structure is very sensitive to explosive loads and damage to metal structures from shrapnel from shells.

To a large extent, the technical condition of antenna structures depends on the characteristics and stages of communication development in Ukraine. The process of establishing the technical condition of a particular structure is significantly simplified when data on the design features, operation, durability and reliability of such structures are known.

Based on our own statistics of the technical surveys results for the period 2017-2023, out of more than 1,600 mobile communication antenna structures, masts account for 41%, towers for 27%, combined supports for 9%, tubular towers for 3%, masts and large pipe supports on the roof for 20% of the total number of network objects. Depending on the characteristics of the region and the density of development, the ratio of structure types may vary slightly.

Location. The possibility of placing mobile communication antenna structures is primarily determined by urban planning restrictions, existing high-rise buildings and the possibility of potential land lease. Based on the characteristics of the area and the request of radio planning engineers for the need to expand the network, a decision is made on the feasibility of using a certain type of structure. Antenna structures can be placed on their own free-standing foundations, on the roofs of buildings, on other high-rise structures (chimneys, water towers, etc.), on a technological container using a support frame.

In the absence of restrictions on land lease, in rural areas, preference is usually given to structures on their own foundations. This allows flexibility in selecting the structural scheme and enables choosing the most cost-effective option. In the presence of urban high-rise buildings, it is more expedient to effectively use the existing height to place antenna structures on the roofs of buildings, minimizing the required height of antenna structures and solving the potential problem of radio shadowing of adjacent buildings (reduction in signal quality due to building density). In addition, in dense urban development, it is sometimes extremely difficult to find a potential site for the construction of structures on their own foundations, and if it is available, the cost may not be economically feasible for construction.

The use of other high-rise structures (chimneys, water towers) is rational in industrial development, using the existing height of the structures to install the necessary equipment with virtually no additional requirements for maximum wind area or weight.

Structural diagrams. Antenna structures are divided into towers, masts, combined supports, pipe supports on buildings, and chimneys (see Figure 5.2).

A tower is a cantilever-type support rigidly mounted on a foundation. Depending on the type of cross-section, towers are divided into through (lattice or lattice) and solid (tubular, conical) towers. The use of towers has an advantage for construction in mountainous conditions when it is difficult to place anchor foundations for mast stays. The most common is the tower design, the geometric scheme of which fits into the figure formed by rotating a broken line around a vertical axis. Due to the folds of the belts in height, the shape of the tower approaches that which follows the diagram of moments from wind load. Lattice towers, as a rule, have a triangular or square, rarely polygonal cross-section. In the absence of restrictions on geometric parameters, preference is given to towers with a minimum number of faces. When moving from a 3-sided tower to a 4-sided one, its weight increases by 10%, and the difference in the number of main elements can be up to 35%.

The height of lattice towers varies in a very wide range – from 40 to 500 m. Lattice towers are usually made of angles or tubular elements. The tower belts are supported on free-standing reinforced concrete foundations that work in compression, in pull-out force and in shear force.

Tower designs are more convenient for installation and operation of antenna and feeder equipment, as well as for maintenance of the structure itself, as there is no need to periodically adjust the tension and replace guy ropes, unlike masts.

A mast is a rigidly or hingedly mounted support on a foundation, which is supported in height by a system of elastic supports guy wires, placed in one or more tiers. The cross-section of the mast shaft is most often lattice, triangular or square, in some cases solid round. The cross-section of the mast trunk is most often lattice triangular or square, in some cases solid round. In plan, the stays are placed in three or four directions. The number of tiers in height is from one to seven tiers. The optimal angle of the guy wires inclination is 45-60°, with a further increase in the angle of inclination of the guy wires, the forces in the mast shaft belts increase. For each direction of the guy wires, either one foundation for all tiers or separate foundations for each tier of guy wires can be installed. The optimal angle of the guy wires inclination is 45-60°, with a further increase in the angle of inclination of the guy wires, the forces in the mast shaft belts increase. For each direction of the guy wires, either one foundation for all tiers or separate foundations for each tier of guy wires can be installed.

The calculation scheme of the mast is a continuous multi-span beam, in which the elastic supports are the junction nodes of the guy wires. Guy wires are flexible threads that are loaded by their own weight, the weight of ice and the action of the wind, the ends of which are fixed at different levels. Such a cable-rod system has a complex behavior under load and pre-tensioning of the ropes, which is associated with the work of guy wires as flexible threads and the calculation scheme can change when the load changes. Calculations of such a system are performed according to a deformed scheme using methods of gradual approximation.

The reliability of antenna mast structures primarily depends on the technical condition of the guy wires, which are made of steel ropes. The situation is complicated by the widespread use of ropes with an organic (hemp, sisal) or synthetic (polypropylene) core as guy wires, which have increased flexibility and are used for their intended purpose in pulleys, winches, elevators and are not intended for use in guy wires of antenna mast structures, have a significantly lower (by 20-30%) breaking force compared to ropes with a steel core.

In the baseline scenario, masts are more economical than towers, but their installation requires a much larger area (for masts, the approximate building area can be 400-800 m^2, for towers of similar height – 20-40 m^2). In addition, masts can perceive much less useful antenna load, unlike lattice towers.

A tubular tower is a cantilever support of a solid cross-section, consisting, as a rule, of several separate tubular sections with a height of 6-12 m, the sections are connected on flanges using high-strength bolts. The height of tubular towers is most often in the range of 30–50 m. The construction of tubular towers of a greater height is not implemented, since the design solution completely loses its economic feasibility. The main advantage of this type of structure is the minimum requirements for building area and relative invisibility in the architectural ensemble of the city, however, the cost of construction is significantly higher than other structures of similar height.

a) b) c) d)

Figure 5.2 – General view of communication antenna structures: a) tower; b) mast; c) combined support; d) tubular tower

A combined support (a combination of a tower and a mast) is a conical reinforced concrete support (type SK-26) rigidly embedded in the ground, on top of which a lattice steel extension is installed, supported by additional elastic supports – guy wires, which are attached to horizontal elements (beams). The emergence of combined towers was due to high competition for the subscriber base and increased demand from mobile operators for rapid and mass construction, that is, to put into operation the maximum possible number of antenna structures in the shortest possible time, to unify structures at an economically acceptable price and with minimal requirements for land allocation for development. This type of structure generally met the above requirements and played a significant role in the rapid deployment of the cellular network throughout Ukraine. However, it also had its own design shortcomings, namely the limited load-bearing capacity of the conical reinforced concrete SK-26 pole, which in turn imposed quite strong restrictions on operation in various windy areas and the installation of the maximum possible amount of antenna and feeder equipment.

As a result, during operation with an increase in the number of antenna-feeder equipment on the antenna structure – the maximum moment in the rack may exceed the permissible moment for bearing capacity. The destruction of the reinforced concrete rack occurs in a characteristic area at an elevation of +2,000…+3,000 m relative to the ground level – a combination of the maximum moment and a decrease in the number of prestressed reinforcement bars in the rack cross-section.

5.3 Analysis of damage to supporting structures of communication antenna structures caused by military operations

An analysis of the types of damage and destruction experienced by communication antenna structures due to hostilities and targeted attempts to disable telecommunications equipment was conducted using surveys involving the designers of communication antenna structures for mobile operator networks in Ukraine [34], as well as data from open sources collected between 2022 and 2025 [16].

Figure 5.3 shows the damage to the tower with a height of H = 60 m. The tower is a spatial lattice structure in the form of a truncated pyramid with a triangular cross-section. The faces of the tower are flat trusses with a rhombic and triangular lattice with struts, the elements of which are made of different diameters steel pipes. The tower consists of 11 sections; the sections are connected by flanges.

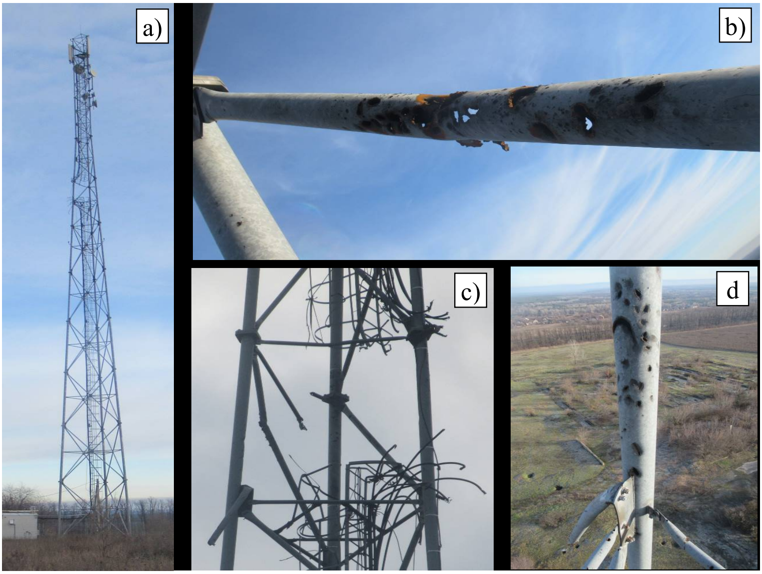

Figure 5.3 – Damage to the tower with a height of H = 60 m: a) general view of the tower; c) view of damage to sections C7-C8; b, d) through holes in the tower elements

Damage to the belts and destruction of the lattice elements of the tower sections C7-C8 at an altitude of +36,000…+48,000 m due to a hit by an FPV drone. There are numerous through holes (Ø20-50 mm) in the belts, struts and braces of the tower, destruction (rupture of pipes Ø89×4 mm and Ø76×4 mm) of struts and braces. General deformations of the tower shaft and abnormal deviations of the shaft axis from the vertical were detected. Figure 5.4 shows a combined support H = 42 m. In the lower part, a conical reinforced concrete column SK26.2-1.1 with a height of 26 m is used, which is buried in the ground by 6 m. At a height of 20 m from the ground surface, a spatial lattice quadrangular prism with 4 sections with a total height of 22 m is installed on it, the elements of which are made of pipes and round steel. The impact of the projectile fragments resulted in the severing of two out of four belts of the steel extension. Deformation of the lattice elements, multiple through holes in the tubular belts of the steel extension, and damage to the concrete protective layer exposing the reinforcement of the reinforced concrete column were also observed.

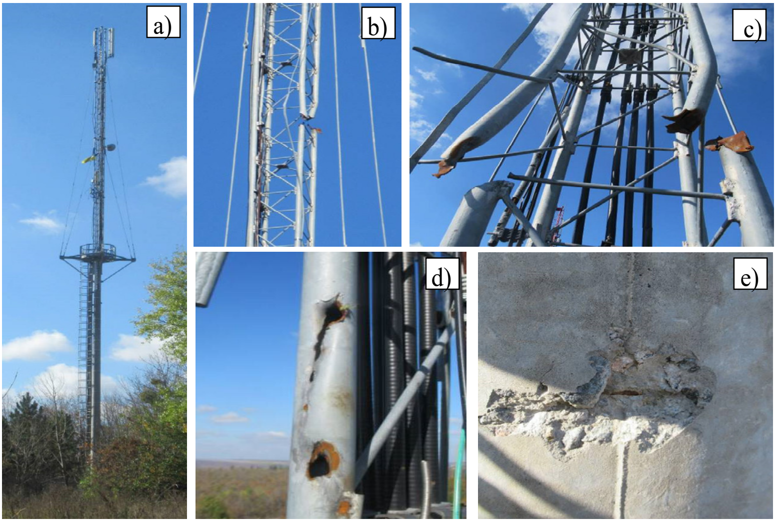

Figure 5.4 – Damage to the combined support H = 42 m: a) general view of the support; b, c) two of the 4 belts are broken; d) holes in the elements; e) damage to the reinforced concrete column

Figure 5.5 shows the damage to a tower with a height of H = 60 m. The tower is a spatial lattice structure in the form of a truncated pyramid with a triangular cross-section. The faces of the tower are flat trusses with a semi-oblique lattice, the elements of which are made of steel angles.

The shell hit led to the destruction of the antenna-feeder equipment located in the upper part of the tower. Deformation of the upper section belts due to the action of the shock wave, destruction (rupture) of the lattice elements was noted. Destruction of the flange connections of the tower upper sections due to the impact of the shock-explosive load.

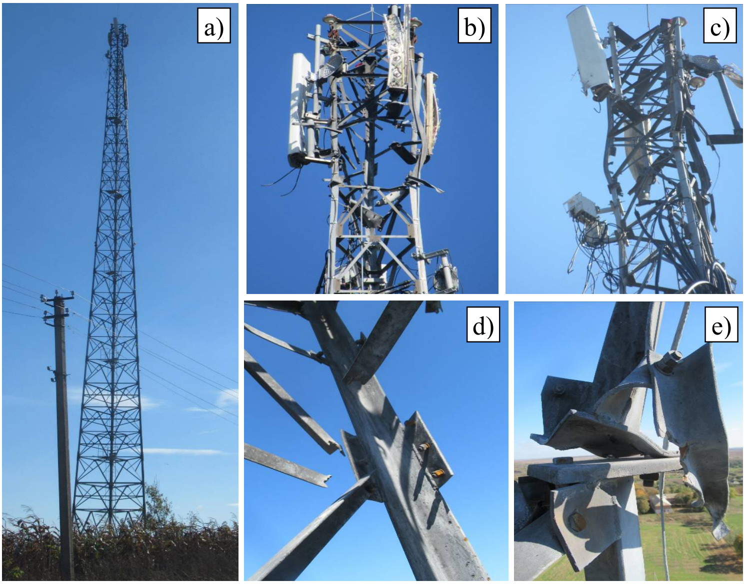

Figure 5.5 – Damage to a tower with a height of H = 60 m:
a) general view of the tower; b, c) view of damage to the antenna-feeder equipment, deformation of the upper section belts;
d) destruction (rupture) of the lattice elements made of angle steel;
e) destruction of flange joints due to shock-explosive loading

Figure 5.6 shows the damage to the tower with a height of H = 70 m. The tower is a spatial lattice structure in the form of a truncated pyramid with a triangular cross-section. The faces of the tower are flat trusses with a rhombic and triangular lattice with struts, the elements of which are made of different diameters of steel pipes. The tower consists of 12 sections; the sections are connected by flanges.

As a result of the shell fragments hitting the belt, deformations and dents occurred, as well as destruction and rupture of the struts of the tower sections.

To restore the elements, part of the tower sections were dismantled, followed by the replacement of damaged elements and the installation of the tower in the design position.

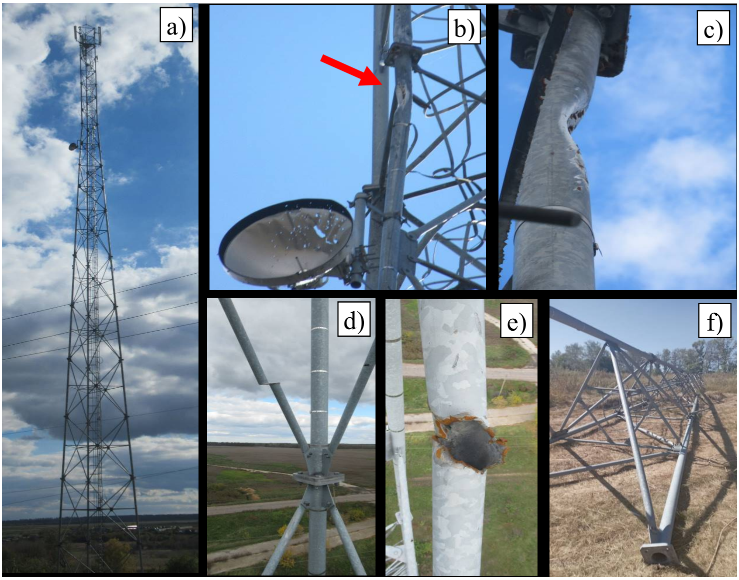

Figure 5.6 – Damage to a tower with a height of H = 70 m: a) general view of the tower; b, c) formation of deformations and dents in the belt; d, e) destruction (rupture) of lattice elements; e) process of dismantling part of the damaged sections for their restoration

Figure 5.7 shows the damage to the tower with a height of H = 60 m. The tower is a spatial lattice structure of a quadrangular cross-section with a rhombic lattice with additional truss elements up to the mark +20,000, with a rhombic lattice from the mark +20,000 to the mark +48,000, a cross lattice from the mark. 48,000 m, the elements of which are made of steel angles. The tower consists of 11 sections, which are bolted together through belt plates.

Through-going destruction of almost all elements of the tower sections' lattice C8-C11 was noted. Deformation (bending) of the belt of the C7 section and the formation of a dent in the belt. The presence of through-going holes in the elements of the lattice of the tower, destruction and rupture of the braces of the elements as a result of being hit by a kamikaze attack drone.

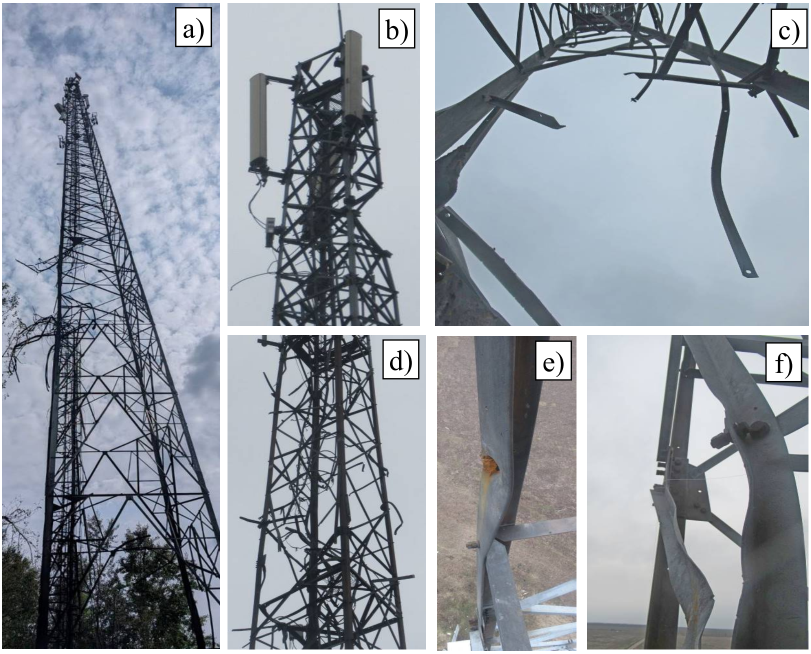

Figure 5.7 – Damage to the tower with a height of H = 60 m: a) general view of the tower; b) damage to the tower belt; c, d, e) through-the-wall destruction of almost all elements of the tower lattice of sections C8-C11; e) deformation and dents of the section C7

Figure 5.8 shows the damage to a tower with a height of H = 12 m on the roof of a one-story administrative building. The tower is a spatial lattice structure of triangular cross-section with a semi-oblique and oblique lattice, the elements of which are made of steel pipes (belts) and angles (lattice elements). The tower consists of 6 sections, the sections are connected by flanges. The tower rests on a supporting frame of channels, fixed to the coating with the help of traverses and M20 studs.

Weakening of the beam cross-section walls with numerous through holes (d = 10…30 mm), rupture of the support frame stud from damage by shrapnel fragments of the support frame attachment to the building's load-bearing structures were detected.

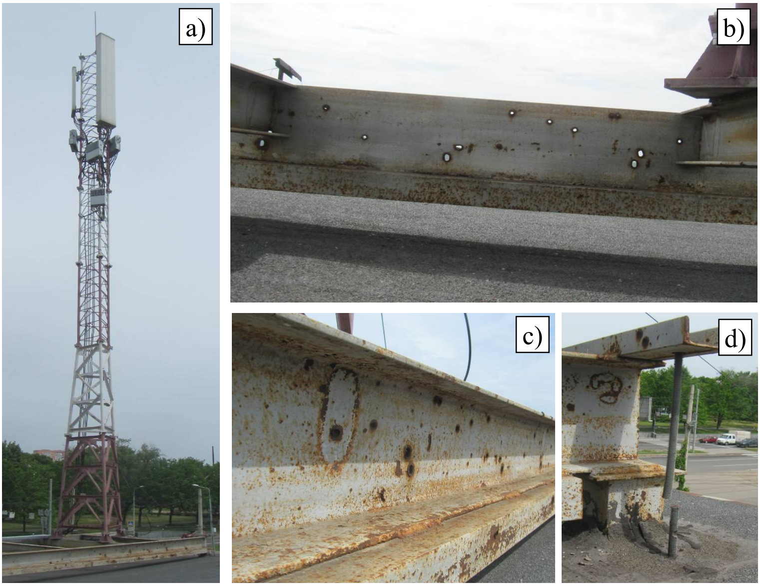

Figure 5.8 – Damage to a tower with a height of H = 12 m on the roof of a one-story administrative building: a) general view of the tower and the supporting frame; b, c) weakening of the walls cross-section of the channel beams with numerous through holes (d = 10…30 mm) from damage by shrapnel fragments; d) rupture of the supporting frame stud in the attachment to the building's load-bearing structures

Figure 5.9 shows a photo of the destruction of communication antenna structures as a result of air bombs or cruise missiles hitting the supporting elements in the lower part of the structures. The antenna structures were spatial lattice structures built according to standard designs.

Figure 5.9, a shows the destruction of a 155-meter-high tower, which is a pyramid with fractures of the belts at the marks +32,000 m and +64,000 m;

further, the tower is a prism with a base of 1.75×1.75 m and a height of 25 m. The tower was hit by high-explosive FAB-500 air bombs, which caused the destruction of the lower section lattice elements of the tower (support braces) and the general collapse of the structure.

Figure 5.9, b shows the destruction of the tower as a result of an air bomb hitting the supporting elements of the tower at an altitude of +5,000…+8,000 m. The destruction of one strut and the adjacent braces also led to the general collapse of the structure.

Figure 5.9 – General collapse of communication antenna structures as a result of air bombs hitting the load-bearing elements of their lower part: a) destruction of elements of the lower section of the tower; b) destruction of one post and adjacent braces

5.4 Summary of damage to communication antenna structures caused by military operations

Based on the analysis of the most common types of damage and destruction suffered by communication antenna structures as a result of hostilities, targeted attempts to destroy and disable telecommunications equipment, it was found that the most common damage is local sabotage damage (local cuts) of belt elements, fragmentary bending and ruptures of antenna structure grid elements as a result of an FPV drone hitting the structure, local weakening of the cross-section of the rod elements of antenna structures with numerous through holes with a diameter of 10…30 mm or rupture of the support frame pins from being hit by shrapnel fragments, etc.

It should be noted that the vast majority of defects and damages caused by military operations pose an immediate danger of structure destruction even without reaching the calculated value of the wind load and cause an emergency condition of structures – technical condition category 4 (emergency) [24]. Structural elements with such defects and damage require complete replacement (restoration) of sections with observance of spatial geometry and partial dismantling of the upper sections, since strengthening individual nodes and elements is an ineffective and temporary solution and does not systematically solve the problem of reliability and durability of the structure as a whole. At the same time, the estimated degree of damage to the structure as a whole is less than 20%, which, according to the Methodology for the Examination of Buildings and Structures Damaged as a Result of Emergency Situations [64], corresponds to Category I damage.

Table 5.1 summarizes the analysis of the most common types of damage and destruction experienced by the supporting structures of communication antenna structures [35]. The analyzed damage to antenna structures was collected based on surveys conducted with the participation of the authors [34] and on open-source data collected during 2022-2025 [16]. The conclusions from the analysis of damage to communication antenna structures are indicated in the last two columns of Table 5.1.

Table 5.1

General overview of damage to communication antenna structures caused by military actions

№	Architectural and structural solution of a communication antenna structure	Damage characteristics:			Technical condition category [24]	Recovery recommendations
		reason	place	description		
1	2	3	4	5	6	7
1	The 60 m high tower is a spatial lattice structure of 11 sections in the form of a truncated pyramid with a triangular cross-section. The faces of the tower are flat trusses with a rhombic and triangular lattice with struts made of steel pipes of different diameters.	hitting an FPV drone	elevation +36,00…+48,00 m (sections C7-C8)	through holes (Ø20-50 mm), rupture of tubes of belts, struts and tower braces	Most defects and damage resulting from military operations present an immediate risk of destruction to communication antenna structures, even when the calculated wind load threshold is not reached. Such conditions result in an emergency status for the structures, classified as technical condition category 4 (emergency).	Structural elements exhibiting these defects and damage necessitate complete replacement or restoration of affected sections, ensuring spatial geometry is maintained and partial dismantling of upper sections is performed. Strengthening individual nodes and elements is considered inefficient and temporary, as it does not address the overall reliability and durability of the communication antenna structure.
2	Combined support H = 42 m. In the lower part, a conical reinforced concrete column SK26.2-1.1 with a height of 26 m is used. At a height of 20 m from the ground surface, a spatial lattice quadrangular prism with a height of 22 m is installed on it, made of pipes and round steel.	hit by mortar shell fragments	elevation +35,000 m (section C3 of the extension)	two of the 4 belts are cut, numerous through holes in the tubular belts of the steel extension		
3	Tower H = 60 m in the form of a truncated pyramid with a triangular cross-section. The faces of the tower are flat trusses with a semi-oblique lattice, the elements of which are made of steel angles.	projectile impact	note +50,000…+60,000 m	belt deformations, destruction of flanges, gratings		

(End of Table 5.1)

1	2	3	4	5	6	7
4	Tower H = 70 m in the form of a truncated pyramid of triangular cross-section. The faces of the tower are flat trusses with a rhombic and triangular lattice with struts, made of steel pipes of different diameters. The tower consists of 12 sections; the connections of the sections are flanged.	hit by mortar shell fragments	elevation +60,000…+70,000 m-	deformations and dents in the belt, destruction and rupture of the braces of the tower sections	Most defects and damage resulting from military operations present an immediate risk of destroying communication antenna structures, even when the calculated wind load threshold is not reached. Such conditions result in an emergency status for the structures, classified as technical condition category 4 (emergency).	Structural elements exhibiting these defects and damage necessitate complete replacement or restoration of affected sections, ensuring spatial geometry is maintained and partial dismantling of upper sections is performed. Strengthening individual nodes and elements is considered inefficient and temporary, as it does not address the overall reliability and durability of the communication antenna structure.
5	Tower H = 60 m in the form of a truncated pyramid of a quadrangular cross-section with a rhombic lattice with splines up to the mark +20,000, with a rhombic lattice from the mark +20,000 to the mark +48,000, a cross lattice from the mark. 48,000, made of steel angles. The tower consists of 11 sections, the sections are bolted together.	Hitting 2 Shahed kamikaze drones	elevation +25,000…+70,000 m	through-the-wall failure of the C8-C11 lattice of the tower sections. Bending of the C7 section belt and dent formation		
6	Tower H = 12 m, installed on the roof of the building, triangular cross-section with a semi-oblique and oblique lattice, the elements of which are made of pipes and angles. The tower consists of 6 sections, the connections of the sections are flanged. The tower rests on a supporting frame made of channels.	shrapnel injuries	elevation +0.000…+3.000 m	weakening of beams with through holes (d=10-30 mm), breakage of the support frame stud		