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The full-scale test of bearing structures of the shelter to assess the possibility of its further operation

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Abstract:
Today, military operations continue in Ukraine, and the need for protective structures is increasing. The scientific work describes the structural scheme of the existing shelter, including the determination of cross-sectional dimensions, thicknesses, concrete strength, and reinforcement strength of the shelter frame, as well as the external reinforced concrete walls. To achieve this, both mechanical openings, various ultrasonic and other measuring devices were used. The type and dimensions of the foundations for the columns and the outer walls of the shelter were determined by digging. The general technical condition of the shelter's bearing structures and their damage levels have been determined based on research findings. The control calculation of the bearing capacity of the shelter structures allowed us to determine the required payload, which would simulate the load from the blast wave. At the same time, the maximum bearing capacity of all shelter structures and the values of averaged (redistributed) moments, obtained from the static calculation of a multi-span continuous roof slab, were determined. A proposed strengthened option for the roof structures of the shelter is presented. Based on this, conclusions were drawn that will enable future improvements in the durability and service life of protective structures, and during new construction, to take into account the shortcomings identified in the last century when constructing the shelter under study.

Keywords:
shelter, columns, crossbars, precast reinforced concrete roof slab, soil backfill, strength quality of concrete, strength quality of reinforcement, bearing capacity, mechanical opening, ultrasonic study

1. Introduction

The rapid and unpredictable changes in global circumstances influence the design and reconstruction of building structures. Achieving an adequate level of protection against military threats requires the creation of specialised facilities, including warehouses, anti-radiation shelters, rapidly constructed civil defence structures, dual-purpose buildings, and basic shelters [1]. It is important to remember that reconstructing existing shelters or building new protective structures requires incorporating civil defence needs into urban planning [2]. Moreover, in the face of military and non-military threats, appropriately maintained and managed defence structures, including bunkers, shelters, and temporary shelters, are an effective way to protect the lives and health of the population [3].

Given the ongoing war in Ukraine and the generally unstable political situation worldwide, civil defence protective structures have once again become essential. These buildings are designed to protect and promote the health and well-being of individuals.

In Ukraine, many of these defence and protective structures were built in the last century and may not meet contemporary standards [4,5]. Therefore, it is crucial to reconstruct these shelters. This reconstruction should be informed by various studies on the renovation of structures for buildings with different purposes [6–13], with a mandatory focus on the design features and calculations specific to protective structures [5,14].

The reconstruction of shelters should be based on recent scientific research in this area. It is mainly to plan the choice of civilian shelters for protection against ballistic missiles and unmanned aerial vehicle attacks in urban areas that have not been affected by hostilities [15] and to understand the impact of different damages in existing structures that cause a determined stress-strain state that cannot be predicted by calculation [16].

However, in our opinion, the principal consideration when designing new shelters or reconstructing existing shelters is the impact of the blast wave on the supporting structures. Some studies are interesting in this regard. Firstly, a study was conducted on a ground-based reinforced concrete shelter featuring a new internal cylindrical configuration. This design features vertical and inclined walls, topped with a flat roof constructed from M40 concrete and Fe500 steel. This research was conducted under two explosion scenarios: spherical air detonation (SAD) and hemispherical surface detonation (HSD). The results showed that the proposed reinforced concrete shelter can withstand blast loads of 4.98 MPa (SAD) and 0.93 MPa (HSD) [17]. Secondly, studies of the impact of blast loading on corroded and non-corroded reinforced concrete buildings have shown that blast distance and concrete strength are key parameters for determining the effectiveness of structures against blast loading [18]. Finally, the results of mathematical modelling of the behaviour of protective shelters under explosion conditions allow us to investigate the mechanisms of destruction or loss of integrity of shelter structures and establish the connection of these aspects with ensuring the performance of its protective functions under the influence of an explosion [19] and empirical formulas for blast overpressure, which are validated against experimental data, ensure accurate predictions for protective structures [23].

Based on various studies, proposals, and current standards, a comprehensive assessment of the shelter's supporting structures was conducted to validate its continued operation.

2. Materials and methods

The shelter building being examined (Fig. 1 and Fig. 2) was constructed in the 1980s. Conventionally, the shelter can be divided into three parts. The first part of the shelter is directly a protective structure in axes "1"-"6" "A"-"E". The second and third parts of the shelter are an underground passage and a gallery. These parts are located to the left and right of axes "1" and "6" (Fig. 1).

The gallery, located to the left of axis "1", provides access to and exit from the surface. The underpass adjacent to axis "6" between axes "A" and "A/1" allows access to and from the hospital basement. The floor level of the hospital basement and the paving surface are significantly higher than the floor level of the shelter, so a concrete ramp has been installed for entry to and exit from the protective structure.

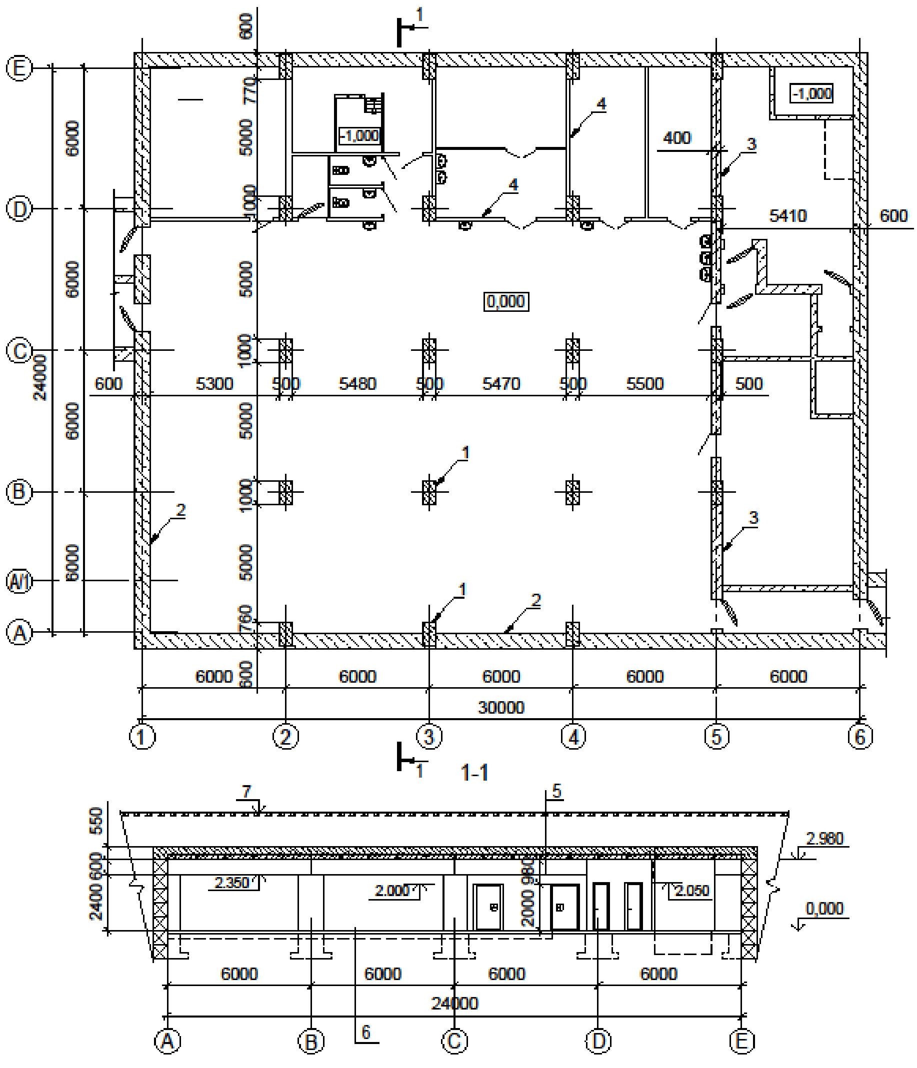

Fig. 1. The plan of shelter and cross-section 1-1:
1 – column (its size is 500 x 1000 mm);
2 – external precast-monolithic reinforced concrete walls (its thickness is 600 mm);
3 – inner monolithic reinforced concrete walls;
4 – brick partitions;
5 – roof structure (it consists of soil compaction (its thickness is 2000-3000 mm), waterproofing asphalt concrete (its thickness is 35-45 mm), precast-monolithic reinforced concrete slab (its thickness is 550 mm), precast-monolithic reinforced concrete crossbar (its size is 800 x 630 (h));
6 – floor structure (it consists of concrete floor, screeded with "Topping" type, concrete on compacted soil (its thickness is 120 mm);
7 – ground surface

The shelter has a rectangular shape with dimensions of 30 x 24 m, measured along axes "1"-"6" "A"-"E" (Fig. 1 and Fig. 2). A vestibule gateway with a corridor is provided to the left of axis "3". It is arranged in front of the underground passage for exit to the surface (Fig. 1). The main room in the shelter, where the population is located in the event of an air alarm, is provided in axes "1"-"6" "A"-"E". Its area is 404.3 m^2. Its total shelter area is 874.6 m^2. Auxiliary and medical (specialised) rooms are arranged in axes "5"-"6" "A"-"E" and "1"-"5" "D"-"E". The height of the shelter room is 2.98 m.

Fig. 2. Total view of the precast-monolithic frame of shelter

Foundations under the precast-monolithic walls of the shelter are strip monolithic reinforced concrete. Foundations for columns of the frame of axes "2"-"5" "A"-" E" are separate monolithic reinforced concrete columns.

The height of the foundation under the column is 980 mm. The foundation dimensions in the plan are 2.6 x 3.6 m. Furthermore, the foundation features one ledge and a cantilevered protrusion. The height of the ledge is 300 mm, and the size of the cantilever protrusion is 600 mm.

The precast-monolithic external wall of axis "E" rests on a strip foundation. The width of the foundation bearer is 1900 mm. The cantilever protrusions from the wall edge are 650 mm, and the height of the strip is 300 mm (Fig. 3).

Fig. 3. Digging of foundations at the intersection of axes "2"-"E"

The foundation depth from the clean shelter floor is 1100 mm. Reinforcement of the columnar foundation is a reinforcing mesh of rods. The diameter of these rods is Ø32AIII (A400C). The spacing of these rods is 200 x 200 mm. Reinforcement of the strip foundation is a reinforcing mesh of rods. The diameter of these rods is Ø16AIII (A400C). The spacing of these rods is 200 x 200 mm.

The technical condition of all foundations is normal (serviceable) (category "1") according to [20]. Measurements have established minor deviations in the axes of the load-bearing columns, with spacing variations increasing or decreasing by up to 60 mm.

The column spacing is 6000 mm. This distance is located between the centres of the columns and the centre of the external walls of axes "A", "E", "1", and "6". The extreme columns along axes "A" and "E" are sunk into the precast monolithic walls. The depth of this sink is 330-340 mm. The cross-sectional dimensions of all columns are identical, measuring 500 x 1000 mm. Each column is rigidly fixed in a precast monolithic columnar foundation. The height of the column, measured from floor level to the underside of the precast crossbar, is 2350 mm. The cantilever extensions are not provided at the support points of precast-monolithic reinforced concrete crossbars in columns.

An instrumental survey conducted with an electronic total station, Trimble M3 (serial number 131612), found no evidence of curvature in the columns, no deviations from verticality, and no discrepancies between the column's geometric axes and the shelter's actual axes.

According to the results of ultrasonic and instrumental studies with the removal of soil embankment and mechanical opening both from the outside and from the inside, the crossbars and the roof slab above the shelter of axes "1"-"6" "A"-"E" are precast-monolithic. Precast solid slabs are supported on the crossbar of axis "2" and the precast monolithic wall of axis "1". The width of these slabs is 1200 mm. The lower part of the roof structure is made in a prefabricated version by installing solid slabs and T-beams with shelves in the tension zone. The precast solid slabs installed in the centre of the premises can be identified by the visible seams between them on the ceiling. The seams are particularly noticeable in areas with no repair work or where the slabs were installed with significant discrepancies (Fig. 4).

Fig. 4. Roof's fragment of axes "1"-"2" "A"-"B"

Also, the seams between the slabs were recorded based on the results of the mechanical opening of the roof. The slab is reinforced with longitudinal rods 8 Ø 22AII (A300C, "spiral"). The protective layer of these slabs is 6-27 mm. The concrete strength is C30/35. The width of precast solid floor slabs is 800 and 1200 mm. Only 1200 mm slabs (20 slabs) are provided between spans "1"-"2" and "2"-"3" of axes "A"-"E". In other spans, two standard slab sizes were used without any specific sequence regarding their widths (Fig. 4, Fig. 5). The slabs rest on the shelves of the crossbars of axes "2", "3", "4", "5", and the external load-bearing walls of axes "1" and "6".

Fig. 5. Roof structure's fragment in axes "1"-"2" "D"-"E"

The monolithic component of the roof (slabs and crossbars) was determined by digging with the removal of the soil embankment (Fig. 6). The height of the soil backfill is 2 m. The thickness of the precast concrete roof is 550 mm. The thickness of asphalt concrete is 35-45 mm. The height from the floor level to the bottom of the slabs is 3 m. Walls are made of blocks with monolithic reinforced concrete inclusions.

Fig. 6. The embankment removals above the shelter roof at the intersection of axes "2"-"E"

The crossbars and slabs from the middle of the premises are precast, with reinforcement outlets into the monolithic reinforced concrete part of the slab. The total thickness is not less than 550 mm. The transition line from precast to monolithic reinforced concrete in the shelter roof was difficult to determine. The study site was always filled with water, which was accumulated under a waterproofing layer of asphalt concrete (its thickness is 35-45 mm) and moved to the opening site (Fig. 6).

The presence of atmospheric water on the surface of the roof slabs and traces of waterlogging of the ceiling and external walls are associated with the use of sandy soils for the embankment of the shelter. Determined soils, by geological surveys and drilling, are well-permeable and have a low cohesion coefficient. The embankment of these types of premises must be made using clay soils. These soils must be limited to the passage of atmospheric water. Damaged protective waterproofing coating contributes to the waterlogging of walls and ceilings. The waterproofing coating was made using hot bitumen for foundation walls. The waterproofing coating was made of asphalt concrete for the roof construction. For this type of waterproofing, a service life of 50 years is considered critical, as it marks the point at which the material loses its protective properties.

The protective layer of monolithic concrete to the supporting reinforcement is at least 200 mm. The cross-section of the precast part of the crossbar is 800 x 630 (h) mm. Its total height is about 1000 mm. The total height of the roof was determined by drilling and measuring with a Trimble M3 tacheometer. It is 1180 mm. From axis "E" to axis "A", the embankment thickness is 2-3 m. So, the load from the backfill will be within 36…54 kN/m^2. Due to the substantial thickness of the soil backfill, no microcracks were observed at the joints of the prefabricated slabs following the repair work. This situation indicates that the roof has sufficient rigidity.

The external walls of the shelter of axes "1"-"6" "A"-"E" are precast monolithic (Fig. 7). They include typical precast concrete blocks (600 x 600 x 2400 mm) and monolithic reinforced concrete inclusions. The width of these inclusions is at least 600 mm. These inclusions are reinforced with six longitudinal rods connected by transverse reinforcement. Monolithic reinforced concrete inclusions ensure stability to the walls and take on the entire load from soil pressure.

Fig. 7. External wall's fragment of the "E" axis

Internal walls (partitions) in axes "5"-"6" "A"-"E" are monolithic reinforced concrete. Its thickness is 200, 400, and 500 mm. The internal walls in axes "2"-"5" "D"-"E" are brick. The thickness of these internal walls is 120 mm, excluding any decorative elements. No damage to the external walls or frame structures was found during the visual and instrumental study. It is worth noting that complete exposure, displacement, reaching the yield point reinforcement, reinforcement ruptures, and violations of the adhesion of the reinforcement to the concrete were also not detected. The walls and frame structures under study also do not have any concrete damage associated with alternating wetting-drying and freezing-thawing. The technical condition of all bearing structures of the shelter is normal (serviceable) (category "1") according to [20]. The shelter stability (rigidity) of axes "1"-"6" "A"-"E" is ensured by the frame nodes in the fastening places of the columns to the columnar foundations and by the roof of the precast monolithic slab.

3. Research results

Using the ultrasonic device "POISK", the location of the reinforcement and its diameter for the columns at the intersection of the axes "2"-"C" and "2"-"B" were determined.

The number and diameter of the column reinforcement were checked by mechanical opening using a perforator. The shelter was operational during the study, so the number of mechanical openings was limited. The longitudinal reinforcement bars were fixed at the intersection of the axes "2"-"C". There are 10 pieces in total. The column reinforcement is symmetrical. Four middle reinforcement rods were Ø20 class AII (A300C), and six extreme reinforcement rods were Ø22 class AIII (A400C) (Fig. 8, Fig. 9).

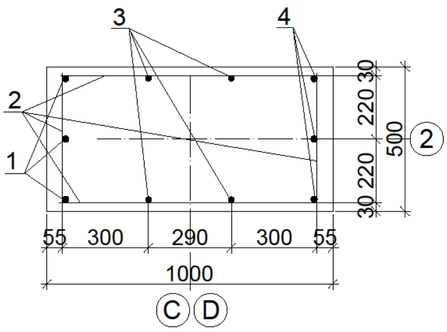

Fig. 8. Column reinforcement at the intersection of axes "2"-"C" and "2"-"D": for column "2"-"C": 1, 4 - Ø22 AIII (A400C), 3 - Ø20 AII (A400C); for column "2"-"D": 1, 3, 4 - Ø20 AII (A300C), 2 - Ø8 AI (A240C) spacing of reinforcement is 300 mm

Fig. 9. Mechanical opening of column reinforcement at the intersection of axes "2"-"C"

The total area of the longitudinal reinforcement is 12.56 + 22.81 = 35.37 cm^2. The transverse reinforcement is Ø8 class AI (A240C). The rod spacing is 300 mm. Four welded flat column frames were assembled to create a single spatial frame. At the intersection of the axes "2"-"D", the number of longitudinal rods is 10 Ø20 class AII (A300C). Its total area is 31.42 cm^2. The transverse reinforcement is similar to the column at the intersection of the axes "2"-"C".

For further control calculations, the design steel resistance of the working non-stressed reinforcement for columns and the remaining supporting structures of the frame is taken f_{yd} (R_s)=365 MPa and f_{yd} (R_s)=280 MPa.

The type of reinforcement was determined by the distinct characteristics of the ridges. They were decisive for the rods during the construction years of the shelter. These ridges were “smooth”, “spiral”, or “herringbone”, which corresponded to AI, AII and AIII reinforcement classes (Fig. 9). The strength of the reinforcing steel was taken into account, of course. The strength of the reinforcing steel was assessed using the SHL-150 Hardness Tester, specifically employing the Brinell hardness test with reference tables.

The design resistances of longitudinal and transverse reinforcement for AI, AII, and AIII classes are specified according to the SNIP II-21-75 standard, which was in effect at the time of construction and is consistent with [21], which remains in force. The average thickness of the protective layer for longitudinal reinforcement does not exceed 30 mm. The average thickness of the protective layer for transverse reinforcement does not exceed 20 mm. A Silver Schmidt Type N sclerometer was used to non-destructively determine the compressive strength of reinforced concrete columns in the shelter frame using the elastic rebound method [7,12].

According to the research results, the average value of the calculated cubic strength $f_{cm,cube}$ for the examined columns is 42 MPa. So, the corresponding concrete grade is C25/30, and the calculated concrete compressive strength is f_{cd} = 17 MPa. The calculated concrete resistance is also given according to the SNIP II-21-75 standard, which was in force at the construction time and agreed with [22], which is still in force.

The bearing capacity calculation was performed for a column with a smaller cross-sectional area of longitudinal reinforcement – 10 Ø20 AII (A300C). The column is centrally compressed with a random eccentricity. The length of this eccentricity is 2350 mm. The bearing capacity of the column is N = 10 630 kN based on the determined physical and mechanical characteristics of concrete and reinforcement. Based on the bearing capacity of the column, the permissible useful load per 1 m^2 of the bearing roof structures without their own mass is g_k = 274 kN/m^2.

An external wall comprised reinforced concrete foundation blocks FB 24-6 and monolithic reinforced concrete inserts. The dimensions of these inserts are 600 x 600 mm (Fig. 10, Fig. 11). The blocks are installed one above the other to the entire height of the wall. The reinforced concrete inserts are arranged in the gaps between the blocks. The reinforcement of the monolithic insert is symmetrical (6Ø25 AII (A300C)). The total reinforcement area is 29.45 cm^2. The transverse reinforcement is Ø10 AII (A300C). The reinforcement spacing is 300 mm. The concrete grade of the monolithic insert is C20/25, and the calculated concrete compressive strength is f_{cd} = 14.5 MPa.

The calculation was performed for a wall reinforced with one reinforced concrete insert. The width of this wall is 3 m. Vertical and horizontal loads act on the wall fragment. Vertical loads consist of the load from its own weight, loads from the roof structures, and the blast wave (from the calculation – 100 kN/m^2). Horizontal loads will arise from the lateral pressure of the soil and the blast wave. A rod rigidly fixed at the floor level and hinged at the roof level was assumed for the calculation. The static calculation was performed in the SCAD Office software package. After performing the calculations, the following data were obtained: M = -406 kN·m, Q = - 651 kN, N = 1170 kN. Therefore, the cross-section and reinforcement of the precast-monolithic wall are sufficient.

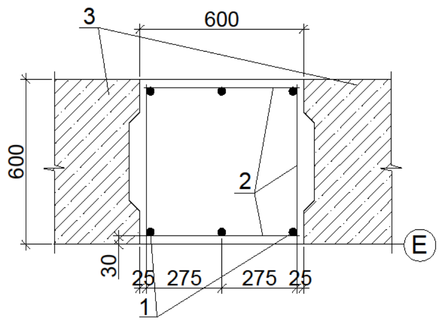

Fig. 10. Construction and reinforcement of the external wall of axis "E":
1 - Ø25 AII (A300S),
2 – Ø10 AII (A300C), reinforcement spacing is 300 mm;
3 - precast foundation concrete blocks FBL 24.6.6-t

Fig. 11. Disclosure of the external wall at the intersection of axes "2"-"E" (general view of the longitudinal rod Ø25 AII (A300C) and transverse reinforcement Ø10 AII (A300C))

The diameter of the longitudinal reinforcement for solid precast slabs was determined using the ultrasonic device "POISK" and mechanical opening (a total of eleven slabs were examined, and the reinforcement for seven was determined by mechanical opening).

Slabs with a width of 1200 mm have two types of reinforcement in the tension zone: 8 Ø28 AIII (A400C) and 8 Ø22 AII (A300C). Slabs with a width of 800 mm have one type of reinforcement in the tension zone – 7 Ø22 AII (A300C). The spacing of eight rods of the same diameter is 125-185 mm. The protective layer of concrete is within 6-30 mm. The total area of the reinforcement for Ø28 is 49.26 cm^2. The total area of the reinforcement for Ø22 is 30.41 cm^2. The spacing of seven rods is within 100-120 mm. The average thickness of the protective layer of concrete is 21 mm. The total area of the reinforcement is 26.61 cm^2. At the bottom, all longitudinal rods are connected using smooth reinforcement bars with a diameter of 8 mm (A240C).

The precast slabs are connected to the monolithic part of the roof by transverse reinforcement Ø7AI (A240C), which, together with the longitudinal reinforcement in the compressed monolithic part of the slab Ø12AIII (A400C), forms a frame (Fig. 12, Fig. 13, Fig. 14, Fig. 15). The number of longitudinal reinforcing bars corresponds to the number of frames in the precast-monolithic roof structure. The supporting connecting reinforcement of the monolithic roof slab is Ø25AIII (A300C). The concrete grade on the lower face of the slabs is C30/35, but the concrete grade in the monolithic part is C32/40.

During the experimental investigation, we found that all the shelter roof slabs along axes "1" to "6" and "A" to "E" were installed chaotically due to poor construction and installation quality. The cross-sectional area of the extreme span slabs "1"-"2" and "5"-"6" (their width is 1200 mm) is 30.41 cm^2 and 49.26 cm^2.

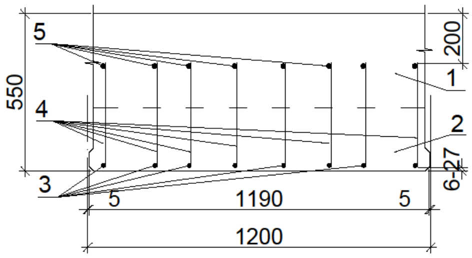

Fig. 12. Construction and reinforcement of a slab (its width is 1200 mm):
1 - monolithic reinforced concrete,
2 - precast reinforced concrete;
3 - Ø28AIII (A400C) or Ø22 AII (A300C);
4 - Ø7AI (A240C);
5 - Ø12AIII (A400C)

Fig. 13. Disclosure of a precast slab 1200 mm wide (a general view of three longitudinal rods Ø28 AIII (A400C))

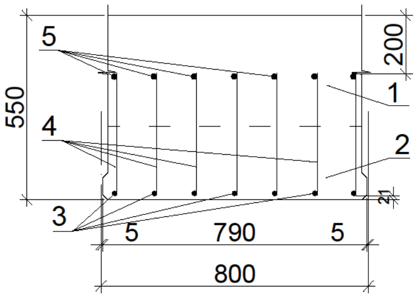

Fig. 14. Construction and reinforcement of a slab (its width is 800 mm):
1- monolithic reinforced concrete,
2 - precast reinforced concrete;
3 - Ø22AII (A300C);
4 - Ø7AI (A240C);
5 - Ø12AIII (A400C)

Fig. 15. Disclosure of a precast slab 800 mm wide

Considering the physical and mechanical properties of concrete and reinforcement, the maximum allowable bending moments for the cargo area have been determined. The cargo area width is 1 m.

The span moments for a roof made of prefabricated elements with a width of 800 mm are M_{11} = 462.9 kN·m. The span moments for a roof made of prefabricated elements with a width of 1200 mm with reinforcement 8Ø28AIII are M_{12} = 713.3 kN·m. The span moments for a roof made of prefabricated elements with a width of 1200 mm with reinforcement 8Ø22AII are M_{13} = 357.6 kN·m. The value of the moments on the support is M_{01} = 220 kN·m. For further analysis, we accept structures that meet the minimum bearing capacity required for the roof. The moment is M_{13} = 357.6 kN·m on the span sections. In the support sections, the moment is represented as M_{01} = 220 kN·m. The averaged redistributed moments will be:

- for extreme spans:

$$M_k = \frac{357.6 + 220}{2} = 288.8\ kN \cdot m$$

- and for medium spans:

$$M_c = \frac{357.6 + 220 + 220}{3} = 265.9\ kN \cdot m\,.$$

The longitudinal reinforcement for the crossbar between axes "D" and "E" along axis "3" and between axes "B" and "C" along axis "2" was determined through ultrasonic study and mechanical opening. Their number was 12 pieces. The reinforcement is symmetrical. The six rods Ø 32AIII (A400C) were arranged in two rows. The distance between the rods is 80 mm in height (see Fig. 16 and Fig. 17). The total area of the longitudinal tensile reinforcement is 96.5 cm^2. The protective layer of concrete for the longitudinal reinforcement is 30 mm. Transverse reinforcement was Ø 22AIIII (A400C). Flat welded frames were also used. The reinforcement spacing is 300 mm, while it is 150 mm near the supports (Fig. 16 and Fig. 17). In a study of a monolithic reinforced concrete slab, the soil embankment was removed. The transverse reinforcement of the crossbar was determined as Ø18AIII (A400C) with a consistent spacing. The longitudinal compressed reinforcement of the crossbar was of Ø18AIII (A400C). The supporting connecting reinforcement of the monolithic roof slab is Ø25AIII (A300C).

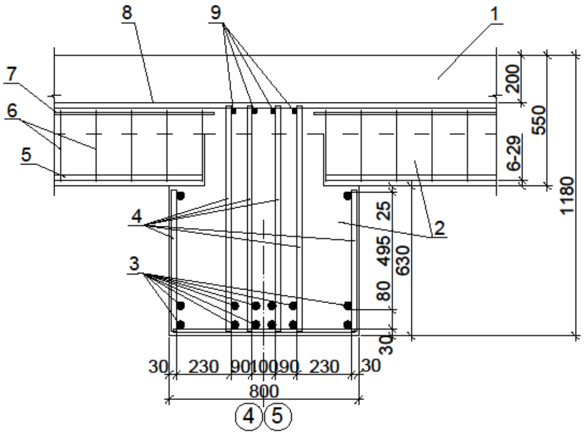

Fig. 16. Construction and reinforcement of the crossbar and the roof slab:
1 - monolithic reinforced concrete,
2 - precast reinforced concrete;
3 - 12Ø32AIII (A400C);
4 - Ø22AIII (A400C) or Ø18AIII (A400C) (its reinforcement spacing is 300 mm and near the supports its reinforcement spacing is 150 mm;
5 - Ø28AIII (A400C) or Ø22AII (A300C);
6 - Ø7AI (A240C);
7 - Ø12AIIII(A400C);
8 - Ø25AII (A300C);
9 - Ø18AIIII (A400C)

Fig. 17. Disclosure of the crossbar from the shelter room and mechanical opening of the monolithic section of the roof (extreme longitudinal reinforcement is 2Ø32 AIII (A400C), transverse reinforcement is Ø22 AIIII (A400C))

The opening of the supporting reinforcement of the crossbar in the span was not carried out due to the existing shelter and the complexity of the work. The calculation of the bearing capacity for the crossbar was conducted using a split-type scheme. The physical and mechanical characteristics of concrete and reinforcement were determined by experimental research. The maximum permissible bending moment for the crossbars of the roof is M_r = 3804.2 kN·m. Accordingly, the permissible useful load per 1 m^2 of the roof supporting structures, without taking into account the weight of the structures, based on the bearing capacity of the crossbar, is g_p = 163.1 kN/m^2. There was no need to open the supporting reinforcement of the crossbar, as the bearing capacity with the split-type scheme is significant, which is higher than that of the roof slabs. Moreover, under the non-split scheme, the bearing capacity is expected to increase.

The static calculation of the roof slab was conducted using the SCAD Office software package. The roof slab of a continuous structure hinges on the external walls and is rigidly connected to the crossbar through the reinforcement cage outlets. To simulate the width of the crossbar and the actual design span, the slab is divided into elements along the length with a step of 0.1 m. A 1-meter-wide fragment of the slab was taken for calculation. The calculation was performed for two loading options. For the first option, we consider the load from the slab's weight, the backfilling with soil (which has a thickness of 2 m), and a payload valued at 60 kN/m². In the second option, we change only the payload (its value is 100 kN/m²). The payload value corresponds to the shelter class – СПП A-IV, as noted in reference [5].

We conducted a static analysis of a multi-span roof slab using a continuous calculation scheme, which yielded the external bending moment values (Fig. 18 and Fig. 19).

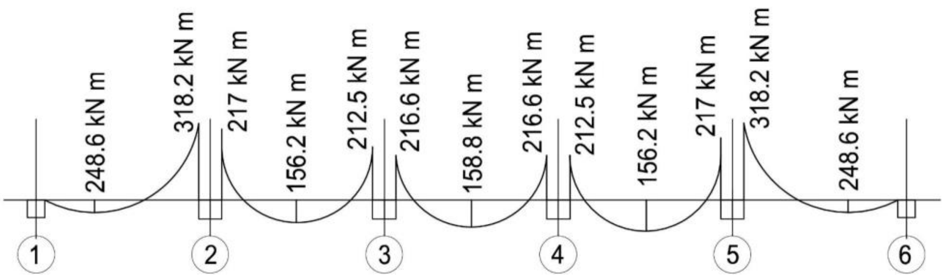

Fig. 18. External bending moment diagrams from the first loading option (load from own weight and backfilling with soil and useful load are 60 kN/m^2)

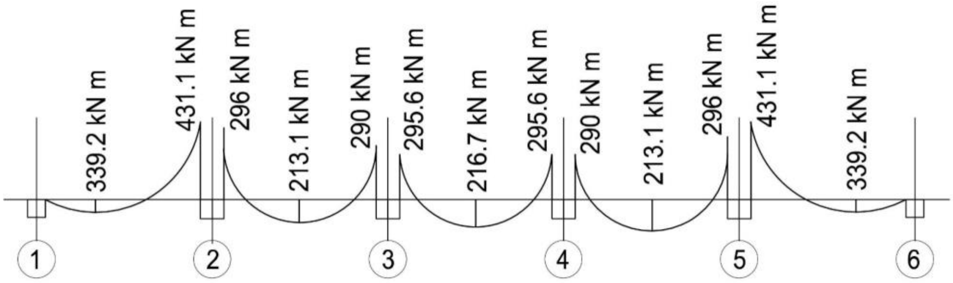

Fig. 19. External bending moment diagrams from the second loading option (load from own weight and backfilling with soil and useful load are 100 kN/m^2)

The averaged (redistributed) moments in the extreme spans of the slab of the axes "1"-"2" "A"-"E" and "5"-"6" "A"-"E" for the first loading option is

$$M_{ks} = \frac{248.6 + 318.2}{2} = 283.4\ kN \cdot m\ ,$$

and for the second option is

$$M_{ks} = \frac{339.2 + 431.1}{2} = 385.2\ kN \cdot m\ .$$

The averaged (redistributed) moments in the middle spans of the slab of the axes "2"-"3", "3"-"4", "4"-"5" "A"-"E for the first loading variant is

$$M_{cc} = \frac{217 + 215.5 + 156.2}{3} = 195.1\ kN \cdot m\ ,$$

and for the second option is

$$M_{cc} = \frac{296 + 290 + 213.1}{3} = 266.4\ kN \cdot m\,.$$

We also determined the limiting values of moments to ensure the bearing capacity of the precast-monolithic slab. For the extreme spans of the slab of axes "1"-"2" "A"-"E", and "5"-"6" "A"-"E" for the first loading option, we obtained

$$M_k = 288.8\ kN \cdot m \geq M_{ks} = 283.4\ kN \cdot m\,.$$

In the middle spans of the slab of axes "2"-"3", "3"-"4", "4"-"5" "A"-"E" for the second loading option, we obtained

$$M_s = 266\ kN \cdot m = M_{ss} = 266\ kN \cdot m\,.$$

4. Practical expediency of research

According to the State Building Standards enacted in 2024, all shelters in Ukraine must undergo a thorough visual and instrumental investigation to determine the load that simulates the impact of a blast wave. Many shelters lack design documentation because they were built secretly in the last century. The proposed studies enabled us to determine the maximum bearing capacity of all shelters' constructions and highlighted errors in their construction. The precast slabs with different cross-sectional areas of longitudinal tension reinforcement for the middle and extreme spans did not allow us to classify the shelter into the appropriate class without strengthening. The findings from this research can be used in the design of new protective structures.

5. Conclusion

According to the results of a visual and instrumental technical investigation of the shelter, it was found that it did not comply with the requirements [4] due to insufficient bearing capacity of the roof slabs in the extreme spans of the axes "A"-"E", "1"-"2" and "A"-"E", "5"-"6".

Control calculations indicate that the shelter does not correspond to the standards for the lowest class of СПП A-IV, as mentioned in [5]. The required useful load simulating the blast wave does not exceed 60 kN/m², although it should be equal to 100 kN/m² according to [5]. The ultimate static forces for columns, beams and external walls, and, accordingly, the useful loads per 1 m^2, exceed the load from the blast wave at the level of 100 kN/m^2. In a continuous scheme, the internal forces in the middle and extreme spans of the shelter floor slab differ due to the effect of a static uniformly distributed load.

Based on these considerations, precast slabs with different cross-sectional areas of longitudinal tension reinforcement must be provided in the precast monolithic roof for both middle and extreme spans.

For the extreme (first) spans of axes "1"-"2" "A"-"E", and "5"-"6" "A"-"E", the area of working tensile reinforcement should be bigger. The area of working tensile reinforcement for all middle spans must be smaller.

All the shelter roof slabs of axes "1"-"6" "A"-"E" were mounted chaotically due to poor construction and installation quality as determined by an instrumental investigation. For the slab with a width of 1200 mm, the cross-sectional areas for the extreme spans "1"-"2" and "5"-"6" were set at 30.41 cm² and 49.26 cm², respectively.

Given that the roof slabs are installed chaotically, the load-bearing capacity limitations were determined by precast slabs. These slabs have a minimum cross-sectional area of the working reinforcement. To comply with the class СПП A-IV according to [5] for shelter, the slabs of the extreme spans of axes "1"-"2" "A"-"E" and "5"-"6" "A"-"E" must be reinforced. We propose to arrange additional monolithic reinforced concrete beams on the existing roof, supported by existing walls and columns, as their bearing capacity is sufficient. The existing roof slab should be fixed to the strengthening structures using cables and plates while reducing its design span.

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