Strengthening of the reinforced concrete tank of anaerobic purification plants with the manufacture of biogas, damaged as a result of design and construction errors

A Kramarchuk¹, B Ilnytskyy¹, D Hladyshev² and O Lytvyniak³, ⁴

¹ Department of Building Constructions and Bridges, Institute of Civil Engineering and Building System, Lviv Polytechnic National University, S. Bandera str., 12 79013 Lviv, Ukraine
² Lviv Polytechnic National University, Institute of Architecture and Design, Department of Architectural Design and Engineering, S. Bandera str., 12 79013 Lviv, Ukraine
³ Department of Civil Safety, Viacheslav Chornovil Institute of Sustainable Development, Lviv Polytechnic National University, S. Bandera str., 12 79013 Lviv, Ukraine
⁴ E-mail: lytvyniak.oksana@gmail.com

Abstract. The defects and damages of bearing structures (walls, covering) of the solid-cast reinforced concrete tank were identified and detected using visual and instrumental testing. The actual reinforcement of the tank was determined and coordinated with designed reinforcement. Furthermore, the deformations were measured, the cracks opening in the walls and its depth in the concrete were detected and was also the strength quality of concrete was defined.

During the year of the operation, the tank developed a considerable system of cracks in all lateral walls from technological loadings. At the same time, the width of the crack opening exceeded the limit values for reinforced capacitive structures (w=k), which is equal to 0.1 mm. The walls lost tightness, the use of the structure in the technological process was suspended. Checking calculations of the design solutions was carried out for the elements of the tank on technological loadings in the software package LIRA to find the causes of the cracks opening and water penetration in the walls of the reinforced concrete tank. It was determined that the existing design solutions did not ensure the bearing capacity and the fracture strength of bearing reinforced elements of the tank and its spatial rigidity from technological loadings.

Necessary reinforcement was defined by ensuring the strength and possible limitation of the width of the cracks opening.

This article presents the technical solutions concerning the strengthening of repair bearing elements of reinforced concrete spatial frame of the existing structure. The external bandages (reinforcing steel 4d32А400С) and inner tension bars (stainless steel round pipes 168 x 5 mm) were used as the strengthening of the reinforced concrete tank.

1. Introduction

During the operation of all types of buildings, a lot of the factors arise, which lead to the necessity of reinforcing the bearing structures that work on different types of loads. The main causes of the emergency technical situation of the structure include the increase of loading on bearing structures as a result of the change of their design map during the reconstruction and the modernization of technological processes [1 - 6], physical deterioration of materials and structures during intense and long operation, the aggressive impact of temperature and humidity on the concrete and reinforcement, and accidents at the enterprises [7 - 10]. In our case, two main factors lead to the emergency technical situation of the solid-cast reinforced concrete tank: carelessness during the development of working design documentation and considerable
defects and damages at the time of its erection. Therefore, only after years of the operation, the tank developed considerable operational abnormal damages, in the form of cracks of its lateral walls [5]. The considerable number of measured cracks with considerable depth in the concrete (some cracks went through the entire thickness) only confirms the work of the lateral walls of the tank as eccentric tension elements. The operation of a completely thick tank became impossible due to the insufficient reinforcement of its lateral walls and the errors of the design solutions about the reinforcement of its corners. Further operation of this structure is only possible after its reinforcing. Nowadays, a lot of reinforcements for the structures developed by the Department of Building Constructions and Bridges of Lviv Polytechnic National University are considered to be flexural elements and was presented in detail in scientific articles [11 - 16]. The strengthening methods for flexural and eccentric tension elements are similar and must ensure the necessary sectional area and the rigidity of strengthened bearing elements for the perception of necessary loadings. The scientific articles [11 - 16] present the strengthening of flexural elements with and without their unloading, depending on the operating conditions, a possibility of ensuring a joint action for the existing and additional elements of the strengthening taking into account the loss of physical-mechanical properties of concrete and reinforcement of the structures, which needed strengthening. In our case, the strengthening was necessary for all lateral walls that got considerable damages (cracks) along all their area. This strengthening was carried out with an empty tank, in other words with unloading that permits to use maximum existent physical-mechanical properties of concrete and reinforcement of the tank. The executed necessary instrumental tests and the calculations for the cross-section of the solid-cast reinforced concrete tank permit to use the most acceptable design arrangement and design diagram for the strengthening. The accepted steel elements of strengthening, such as inner tension bars and external bandages ensure the necessary spatial rigidity and tightness of the structure during the use of existent reinforcement that had a considerable negative reserve of bearing capacity at the moment of investigation. The introduced strengthening has to ensure the perception of all present loadings on the tank and it permits to use this structure in the future [1].

2. Materials and methods
The design map of the solid-cast reinforced concrete tank is a three-dimensional wall with the bearing slab roofs and foundation and four external reinforced concrete lateral walls, which are included in spatial work in different ways (figure 1). The thickness of the reinforced concrete walls is 400 mm, the thickness of the foundation plate is 500 mm, the thickness of the slab roof is 250 mm and the height of the tank from the bottom is 9000 mm. The barrier brick walls are foreseen from the contour of the structure above the mark +7.450. The reference mark ±0.000 m has accepted as the mark of the bearing floor of the workroom adjacent to the tank. At the time of the study, the tank was not used because of the emergency operational condition. [17]. The need for visual and instrumental investigations of the solid-cast reinforced concrete tank arisen due to the formation of multiple abnormal cracks and deformations of the lateral walls with the loss of their tightness, which is necessary for the capacitive structures. To conduct calculations for the structural elements of the tank with the determination of its prospects for the bearing capacity and the fracture strength, the investigations of the physical-mechanical properties of concrete and the defects and damages of the tank during the construction were carried out. During the investigation, the tank was not filled and the results of measurement for the deflections of three walls were as follows (in the central part of the walls): within axes A - E - f = 7.5 to 35 mm; within axes 1 - 3 - f = 9.3 to 22.3 mm; within axes E - A - f = 4.9 to 20 mm. The uncovered deformations along the walls of the tank from their tension at the height 3 m from the tank bottom were: +7.1 mm corner in axes 3/A along the axis 3; +8.3 mm – corner in axes 1/A along the axis 1; +8.7 mm - corner in axes 3/A along the axis A; +10.3 mm - corner in axes 3/EA along the axis E. The deflections for walls of the empty tank at the other levels are shown in figure 2.
Figure 1. The scheme of the tank, the crosscut 1-1, and the total view of the structure on the crossing of axes 3 - А: 1 – existent supports for the covering of tank; 2 – existent precast reinforced concrete walls with thickness 400 mm, reinforced symmetrically by two mesh reinforcements d12A400C with step 150 x 150 mm; 3 – retaining wall under flotator; 4 – existent reinforced concrete foundation plate of the tank with reinforcement for the floor d14A400C with step 120 x 120 mm; 5 – sewage level at the time of investigation; 6 – existent reinforced concrete slab roof of the tank; 7 – contours of the foundation for tank.

The deflections of the empty tank showed the values, which were less than their limit values fu=L/200=10000/200=50 mm [9] (figure 2, 3). However, the width of cracks opening and the depth of their permeation played a primary role in the decrease of capacity for the work of the investigated tank. The developed system of cracks for two lateral walls of the tank was detected after moistening by the water of the concrete surface. The cracks for front of axes E to A for the wall at the axis 1 are shown in the figure 4. When the tank is filled only to 300 mm, the measured width for the formation of the cracks varied in the range from 0.1 to 0.6 mm.

Figure 2. The results of deflection measurements for wall at the axis 3 for front axes А - Е

Figure 3. The results of deflection measurements for wall at the axis 1 for front axes Е - А

Figure 4. The cracks of front axes Е - А for wall of axis 1 after the moistening by water of the concrete surface.

It is worth noting that the width of cracks opening exceeded their limit values for reinforced concrete capacitive structures. The depth of cracks passing into the concrete walls of the tank is shown in figure 5. The step of cracks measurement was 120 mm (base of ultrasonic comparator UK-14PM). Because of that, the lateral walls of tank work as tension reinforced concrete elements with the flexure, accordingly most detected cracks formation are through the entire thickness in the central part on the outside lateral walls and near the corners of these walls. It indicates insufficient reinforcement for the lateral walls of the tank.

During the instrumental investigation of reinforced concrete structures of the tank, the determination of the concrete strength was carried out the non-destructive method using spring automatic machine A-1 by «Chmelnithprombud». At that, we discovered the porosity of concrete that was concerned with possible topping-up water and insufficient vibrocompaction of concrete, on which the smooth walls of air emptiness with diameter 2÷3÷4 mm indicate. The considerable height of the casing (over 3 m), two mesh reinforcement with small cells, which overflowed over the casing height, could influence on insufficient
vibrocompaction of concrete. The age of reinforced concrete of the tank was approximately one year at the
time of the investigation. IZS-10N machine was used for the determination of the location of the main
reinforcement, the thickness of concrete cover and diameters of the main reinforcement for walls. By the
results of researches was determined the actual guaranteeing strength quality of concrete with its 95 %
ensuring. Also, the strength quality of concrete for lateral walls of axis front 1 - 3, A - E, E - A along the
axes A, 3 and 3 was C12/15. The defined value of strength quality of concrete is in two times lower than
the design strength quality of concrete, which must be equal to C25/30. The values W8 were not reached.
The total coefficient of variation for the concrete strength (V = 11.89 %) does not exceed the normative
coefficient of variation (Vn = 13.5 %) [5]. The insignificant variations of strength property of the concrete
along all inspected area of the external surface of tank is evidence of stability for concrete strength.

![Figure 5. The depth of cracks passing into the concrete walls of the tank for axes 1 - 3 along
the axis A](image)

The level of through cracks formation

The depth of cracks, mm

The distance from boundary of the wall, m

3. Results and discussions

The impossibility of operation of the tank by the purpose gave birth to the necessity to carry out the
verifying calculations of its design solution as such that did not ensure the guaranteeing bearing capacity
and fracture strength of bearing reinforced concrete elements. There were executed the verifying
calculations of the tank as a spatial system in the software package LIRA on the design and technological
loads for the possibility of the analysis of the main design solutions, accepted in the execution plan of the
tank.

By the calculation the necessary reinforcement were determined according to the ensuring of the
strength and possible limitation for the width of cracks opening till \( w_k \leq 0.1 \) mm for the capacitive
structures. The comparison of the designed reinforcement of the tank elements and calculated
reinforcement by the verifying calculation on the technological loadings are shown in table 1. By the
calculation, the walls of the full tank were related to category 4 of technical state (hazardous) [17] by their
insufficient bearing capacity that was concerned with insufficient reinforced of the slabs for the wall
enclosure, the slab roofs and the bottom of the tank. Using the verifying calculations on the limit design
loadings, we determined the characteristic zones in the walls, in which the stresses in main reinforcement
of the meshes and inner girder greatly exceeded the conventional yield strength for the reinforcement that
was used in the tank. There were also determined that the corners of the solid-cast joining of the wall
elements of the tank between themselves and the joining the wall elements with the slab of the bottom
were insufficient reinforced for the perception of the active tensile loads and the bending moments, which
acted simultaneously.
Table 1. The comparison of the designed reinforcement of the elements of the tank with the received reinforcement by the verifying calculation

| The elements of the tank | The location in the axis | The location’s place of the area and the direction for the reinforcement | By the project Reinforcement А400С | By the verifying calculation | Comparison |
|--------------------------|--------------------------|---------------------------------------------------------------|---------------------------------|---------------------------------|------------|
|                          |                          |                                                               | Ǿ, mm  | S, mm  | Aₜ, running cm²/m | Ǿ, mm  | S, mm  | Aₜ, running cm²/m | Aₜ,с / Aₜ,p |
| Lateral walls            | 1 - 3 and 3 - 1          | Bottom of the wall, vertical                                 | 7.53   | 25     | 32.7             | 4.34   |
|                          |                         | The middle, vertical                                         | 7.53   | 28     | 41.1             | 5.46   |
|                          |                         | The middle, horizontal                                       | 7.53   | 28     | 41.1             | 5.46   |
|                          |                         | Near the corners, horizontal                                 | 7.53   | 28     | 41.1 to 67.9     | 7.24   |
|                          |                         | Bottom of the wall, vertical                                 | 7.53   | 32     | 53.6             | 7.12   |
|                          |                         | The middle, vertical                                          | 7.53   | 32     | 53.6             | 7.12   |
|                          | A - E and E - A         | The middle, horizontal                                       | 7.53   | 32     | 53.6             | 7.12   |
|                          |                         | The top of the wall, vertical                                 | 7.53   | 22     | 25.3 to 41.1     | 4.41   |
|                          |                         | Perpendicularly to axis 6 (middle support)                   | 10.26  | 22     | 150              | 2.46   |
|                          |                         | Along the axes from the borders: along axis 1, 3             | 12.83  | 20     | 120              | 2.42   |
|                          |                         | Perpendicularly to axis 2                                    | 12.83  | 32     | 120              | 4.18   |

The anchorage length for the reinforcement of the inner meshes for the wall enclosure in rigid joints of their connections on the combined action of the tensile loads and the negative bending moments were insufficient and the additional corner reinforcing elements were not effective enough. During calculation, the junction point for the wall elements of the tank with the slab roof must be accepted as a hinged joint due to insufficient length of the reinforcement dowels from the wall slabs.

For the possibility of further safe operation for the solid-cast reinforced concrete tank, it is necessary to carry out its strengthening for the prevention of further cracks opening and the ensuring of its spatial rigidity. Similarly to the calculation of the bearing capacity, we carried out the verifying calculations in the software package LIRA with regard to the design solution of the tank with technological loadings and accepted elements of the strengthening. The dead, changing, continuous, and variable changing loads were accepted similarly to the calculation of the design solution of the tank. Inasmuch as it is completely impossible to close the considerable formation of cracks even with the elements of the strengthening (through the cracks will act the hydrostatic pressure), then it is necessary to ensure the tightness for the reinforced concrete elements of the tank.

By the realized investigation, all walls of the solid-cast reinforced concrete tank (their thickness is 400 mm) are symmetrically reinforced by two meshes d12А400С (their step is 150 x 150 mm; the area of reinforcement is Aₜ = 7.53 cm²/m; the design resistance for the reinforcement is fₚ = 365 MPa). The distance between the axes of the bars of the reinforcement meshes is 250 mm. Taking into account the recommended deviation for the reinforcements meshes that is equal to 10 mm, the calculated distance between the axes of the reinforcement bars is 250 – 2 · 10 = 230 mm. We considered the reinforcement
meshes as displaced to one of the walls. The linkage to one border was accepted 40 mm and the linkage to other border was accepted 400 – 230 – 40 = 130 mm.

The thickness of the tank’s bottom was 500 mm. The protective layer was 50 mm that corresponded to the linkage of the bars for the reinforcement’s diameter 14 mm: \(50 + 2 \cdot 14 + 2 \cdot 10 = 98\) mm. We accepted the linkage of the bars 115 mm as for the walls. The reinforcement for the bottom was \(d_{14A400C}\) (the step is \(120 \times 120\) mm; the area of reinforcement is \(A_e = 12.82\) cm\(^2\)/m; the design resistance for the reinforcement is \(f_{yd} = 365\) MPa). By the realized measurements, the concrete strength corresponds to the quality of the concrete C12/15. The cracks were in the walls of the tank with the residual opening after the unloading of the tank till 0.6 mm (more information in Materials and methods) which is evidence of the yield of the reinforcement during the filling of the tank.

The strengthening of the tank (figure 6, 7) was realized by means of the outer bandages (reinforcing steel \(4d_{32A400C}\) with \(A_s = 32\) cm\(^2\)) and inner tension bars (stainless steel round pipes \(168 \times 5\) mm). We accepted that the outer bandages had prestress \(50\) t and the inner tension bars without the prestress (table 2).

**Table 2.** The efforts in the inner tension bars (pipe \(168 \times 5\) mm)

| Stage          | 1 (lower) | 2 (middle) | 3 (upper) |
|----------------|-----------|------------|-----------|
| Extreme bars   | +12.9     | +12.3      | +8.2      |
| Middle bars    | +22.1     | +22.9      | +16.2     |

The efforts in the wall:

\[
M_{x,\text{max}} = 80.61 \frac{kN \cdot m}{m}; \quad N_y = -138.27 \frac{kN}{m}; \quad (1)
\]

\[
M_{y,\text{max}} = 69.63 \frac{kN \cdot m}{m}; \quad N_y = -133.37 \frac{kN}{m}; \quad N_x = -358.92 \frac{kN}{m}; \quad (2)
\]

\[
M_x = 77.67 \frac{kN \cdot m}{m}; \quad M_y = 14.32 \frac{kN \cdot m}{m}; \quad N_{y,\text{max}} = -160.83 \frac{kN}{m}; \quad (3)
\]

\[
M_x = 80.22 \frac{kN \cdot m}{m}; \quad M_y = 15.1 \frac{kN \cdot m}{m}; \quad (4)
\]

The tensile efforts:

in corners of the conjunction for two walls with the bottom

\[
N_x = +161.81 \frac{kN}{m^2} \cdot 0.4 = +64.72 \frac{kN}{m}; \quad M_x = 22.65 \frac{kN \cdot m}{m}; \quad M_y = 16.48 \frac{kN \cdot m}{m}; \quad (5)
\]

\[
N_y = +84.37 \frac{kN}{m^2} \cdot 0.4 = +33.34 \frac{kN}{m}; \quad M_x = 23.05 \frac{kN \cdot m}{m}; \quad M_y = 16.08 \frac{kN \cdot m}{m}; \quad (6)
\]

in the middle of the wall’s height (in the direction X the wall is compressed)

\[
N_y = +23.05 \frac{kN}{m^2} \cdot 0.4 = +9.22 \frac{kN}{m}; \quad M_x = 22.85 \frac{kN \cdot m}{m}; \quad M_y = 9.61 \frac{kN \cdot m}{m}. \quad (7)
\]

The critical combination of the forces is the simultaneous action of the bending moments \(M\) and the forces \(N\). During the calculation of the strength of the tank by the normal sections, we took into consideration the arrangement of the mesh reinforcement with the displacement, the thicknesses of the protective coatings (40 mm and 130 mm), the length (the span) of the element 1000 mm, the height of the cross-section 400 mm, the width of the cross-section 1000 mm and the values of the bending moments.
M = 80.61 kN · m, the shear Q = 0 kN, the longitudinal force N = 138.3 kN. By the calculation the bearing capacity of the tank is ensured under the actual opening of the normal cracks in within 0.29 mm.

The scheme of the tank

![The scheme of the tank](image1)

The crosscut 2-2

![The crosscut 2-2](image2)

The front (axis A - D)

![The front (axis A - D)](image3)

The front (axis 1 - 3)

![The front (axis 1 - 3)](image4)

**Figure 6.** The scheme of the tank, the crosscut 2-2 with the arrangement of the inner tension bars and outer bandages of the strengthening, the front (axis A - D) and the front (axis 1 - 3):

1 – the existent supports for the covering of the tank; 2 – existent precast reinforced concrete walls with the thickness 400 mm, reinforced symmetrically by two reinforcement meshes d12A400C with the step 150 x 150 mm; 3 – outer bandages of the strengthening from the reinforcing steel 4d32A400C; 4, 5 – inner tension bars (steel round pipes 168 x 5 mm) in two directions; 6 – the support of the strengthening (pipe 168 x 5 mm); 7 – existent reinforced foundation slab of the tank (the reinforcement for the bottom d14A400C with the step 120 x 120 mm); 8 – existent reinforced concrete slab roof of the tank; 9 – supporting sheet of the inner tension bar with thickness t = 16 mm and with diameter d = 450 mm with the studs M24 (6 pieces). All elements are arranged inside of the tank and also the studs, which fix the inner tension bars, were executed of the stainless steel. Other elements of the strengthening was executed from the low-carbon steel C235.

The strengthening of the tank was realized using the outer bandages and the inner tension bars, which ensured its spatial rigidity and, of course, the bearing capacity of all walls of the solid-cast reinforced concrete tank under the actual opening of the normal cracks in within 0.29 mm. Taking into consideration the limitation for the width of the opening cracks within 0.1 mm for this structure, the additional inner damp proofing to ensure the tightness of the wall enclosure and the bottom of the tank was realized after the executed strengthening. The material for the damp proofing must have considerable deformation features and good adhesion to the surface of the concrete. It is connected with the variation for the width of the cracks opening, which will not be bigger than the value 0.29 mm.
The verifying calculations in the software package LI RA showed the considerable insufficiency of the reinforcement of the wall slabs of the solid-cast reinforced concrete tank. In all corners of the tank and the places, where the walls join with the slab of bottom, the simultaneous perception of the active tensile loads and bending negative moments is impossible due to that the reinforcement in corner joints of the tank elements is not ensured. Existing detected additional corner elements are not sufficiently effective and they do not ensure the necessary length for the anchorage of the reinforcement in inner meshes of the wall enclosure in rigid joints. The identified design errors caused formation of the large quantity of the abnormal cracks with considerable depth of their passing in the concrete that rendered impossible the further operation of the tank due to the loss of the tightness in the walls. The strengthening for the structures in accordance with the outer bandages and the inner tension bars was ensured the spatial rigidity and the bearing capacity of all walls of the solid-cast reinforced concrete tank under the actual opening of the normal cracks in within 0.29 mm. The outer bandages were executed from the reinforcing steel in quantity 4d32A400C and the inner tension bars from the round pipes 168 x 5 mm of the stainless steel. The operation of the tank is possible when the width of the cracks openings is in within 0.1 mm, therefore the ensuring of the tightness for the wall enclosure and the bottom of the tank was carried out inner damp proofing, which has considerable deformation behaviors and good adhesion to the surface of the concrete.

**Conclusions**

The verifying calculations in the software package LI RA showed the considerable insufficiency of the reinforcement of the wall slabs of the solid-cast reinforced concrete tank. In all corners of the tank and the places, where the walls join with the slab of bottom, the simultaneous perception of the active tensile loads and bending negative moments is impossible due to that the reinforcement in corner joints of the tank elements is not ensured. Existing detected additional corner elements are not sufficiently effective and they do not ensure the necessary length for the anchorage of the reinforcement in inner meshes of the wall enclosure in rigid joints. The identified design errors caused formation of the large quantity of the abnormal cracks with considerable depth of their passing in the concrete that rendered impossible the further operation of the tank due to the loss of the tightness in the walls. The strengthening for the structures in accordance with the outer bandages and the inner tension bars was ensured the spatial rigidity and the bearing capacity of all walls of the solid-cast reinforced concrete tank under the actual opening of the normal cracks in within 0.29 mm. The outer bandages were executed from the reinforcing steel in quantity 4d32A400C and the inner tension bars from the round pipes 168 x 5 mm of the stainless steel. The operation of the tank is possible when the width of the cracks openings is in within 0.1 mm, therefore the ensuring of the tightness for the wall enclosure and the bottom of the tank was carried out inner damp proofing, which has considerable deformation behaviors and good adhesion to the surface of the concrete.

![Figure 7. Joint A (the arrangement of the outer bandages of the strengthening) and the joint B (the arrangement of the inner tension bars of the strengthening): 2 – present precast reinforced concrete wall of the tank with the thickness 400 mm; 3 – outer bandages of the strengthening of the reinforcing steel 4d32A400C; 4, 5 – inner tension bars in two directions (pipe 168 x 5 mm); 9 – outer supporting sheet of the inner tension bar with thickness t = 16 mm and with diameter d = 450 mm; 10 – angle bar 250 x 250 x 16 mm; 11 – thread M36; 12 – thread shanks (reinforcing steel 4d40A400C); 13 - mounting joint (reinforcement steel 8d32A400C); 14 – supporting sheet of the outer bandages 16 x 730 x 130 mm; 15 - stiffening bar 10 x 90 x 250 mm; 16 – hard cement-sand grout; 17 – inner supporting sheet of the inner tension bar with thickness t = 16 mm and with diameter d = 370 mm; 18 – studs M24; 19 - symmetry line; 20 - stiffening rib 8 x 100 x 330 mm. The bays between flanges and the wall of the tank from inner face and also the openings under the studs were filled up sealing mastic. There was used the welding seams with leg 6 mm besides mentioned welding seams.](image-url)
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