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# STRENGTHENING OF THE REINFORCED CONCRETE TANK AFTER FAILURE



**The paper describe an interesting case of rectangular reinforced concrete tank strengthening. Due to errors in reinforcement design, the long walls of the tank were seriously cracked and starts to leak during the water test. As alternative to total tank demolition, a simple and effective strengthening method was developed and applied. Because the basic defects occurred in long walls of structure, the tie system was designed and constructed. The group of precisely located bar ties anchored on the strengthened walls outer surfaces reduced the stresses in these walls to the level, which could be carried by structure with existing reinforcement. The ties and their anchorages were made of stainless steel, and during design special attention was paid to actual technical state of the tank structure and its environmental conditions. The successful strengthening allow the tank to start the operation with only small time delay and any problems actually noticed.**

**Key words: reinforced concrete tanks, strengthening with tie.**

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# ПІДСИЛЕННЯ ЗАЛІЗОБЕТОННИХ РЕЗЕРВУАРІВ ПІСЛЯ РУЙНУВАННЯ



**У статті описано цікавий випадок підсилення прямокутного залізобетонного резервуару. Через помилки в розрахунку армування, довгі стіни резервуара серйозно тріснули і починали протікати під час випробування водою. Як альтернатива повному демонтажу резервуара, було розроблено та застосовано простий та ефективний метод посилення. Оскільки основні дефекти виникли в довгих стінах конструкції, система тяжів була спроектована і побудована. Група точно розташованих тяжів, закріплених на зовнішніх поверхнях стінок, зменшила напруження в цих стінах до рівня, який може сприймати конструкція з існуючим армуванням. Тяжі та їх кріплення були зроблені з нержавіючої сталі, і під час проектування особливу увагу було приділено фактичному технічному стану конструкції резервуара та його навколишнім умовам. Успішне підсилення дає резервуару змогу експлуатуватися лише з невеликою затримкою часу без видимих проблем.**

**Ключові слова: залізобетонний резервуар, підсилення тяжами.**

## Description of the tank and its failure

**The case tank structure description.** The digester tank was constructed in 2015 year as overground, monolithic reinforced concrete structure, shaped as closed rectangular box. Liquid sewage with working temperature 38°C reach the service level of 8.5 m. Maximum gas overpressure was 2.5 kN/m$^2$. The tank size in plan was 11.0x17.0 m, and total height 9.0 m. From two long sides and one short it was adjacent to new similar structures and one old building. This group of objects create sewage treatment plant for brewery, with biogas production.

The tank was founded with flat raft 50 cm thick on blind concrete and compacted sand. The walls with thickness 40 cm support the top slab 25 cm thick with two inverted beams spanning between long walls. Inside the tank there was built RC frame supporting equipment settled on the raft.

Reinforcing steel grade 500 and concrete C35/35 were used for construction. Considering tightness, only the vapor barrier membrane was put on ceiling and extended on walls reaching from top 50 cm below sewage level.

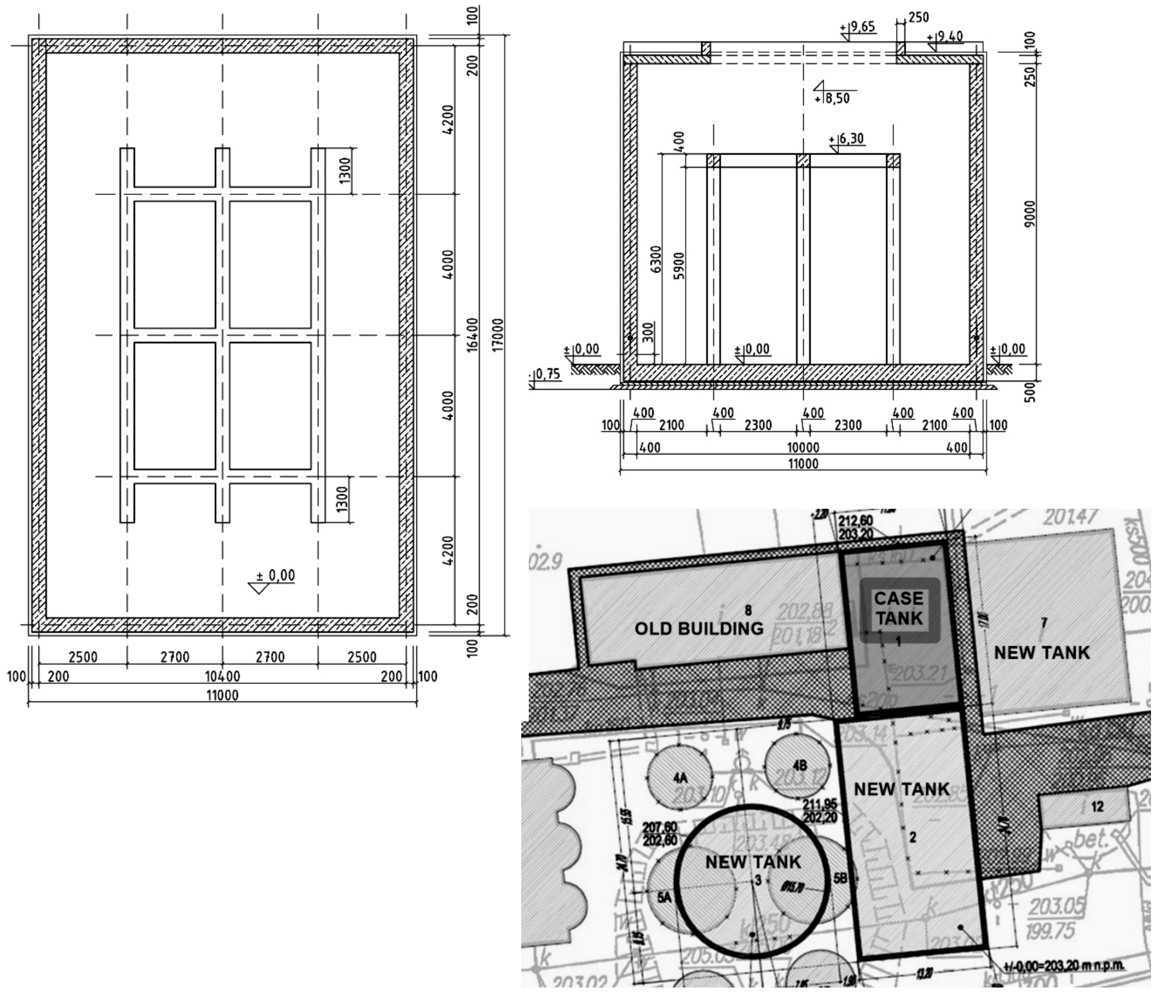


*Fig. 1. Tank plan and cross section. Site Development Plan (right bottom)*

**The failure course.** Directly after completing construction of tank structure, the leak test was performed. During filling the tank, the long walls starts to leak and deform outside to more than 30 mm in the center.

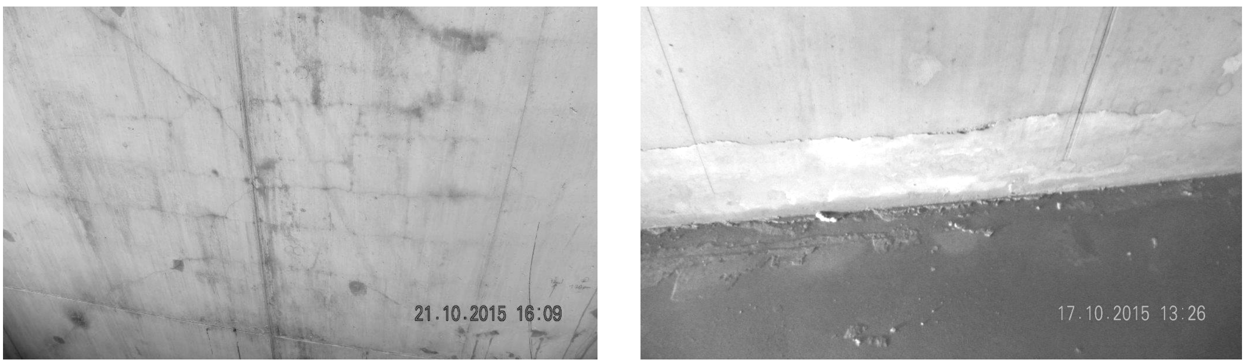


*Fig. 2. Cracks on the long walls: outside left) and inside (right) the tank*

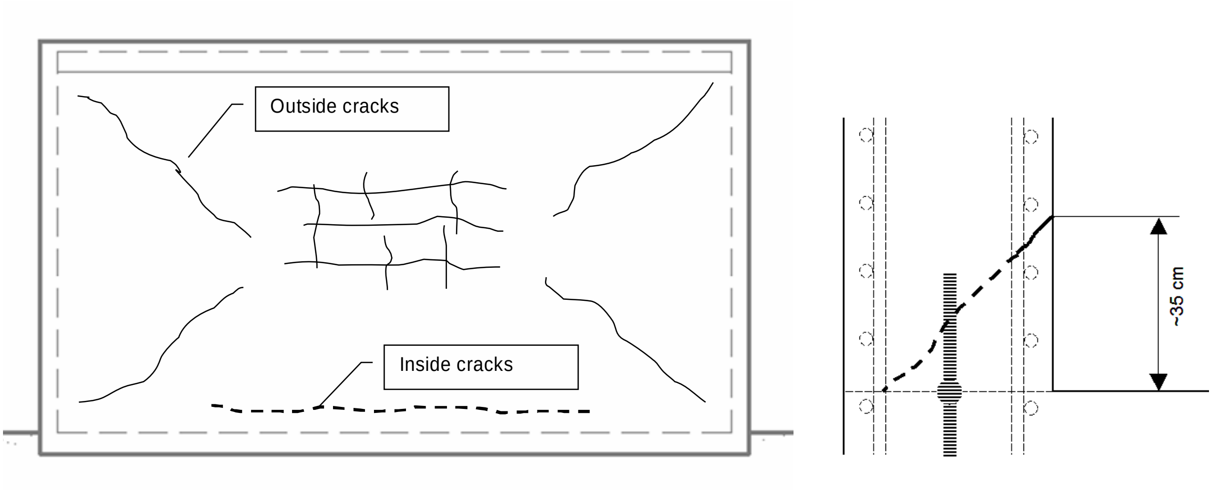


*Fig. 3. Left: sketch of outside cracking. Right: probable progress of the inside crack*

The test was immediately stopped and the tank was empted. The review of the structure shows characteristic crack pattern on both long side walls area. Additionally, there was a single horizontal crack noticed along the long walls located 30 cm above foundation raft.

### Analysis of the failure and original structural design and construction

**The failure analysis.** Observed cracking is typical for overload of the tank structure, particularly for the longside wall panels. The cracking distribution is characteristic for yield line mechanism of failure of slab supported on all edges [1].

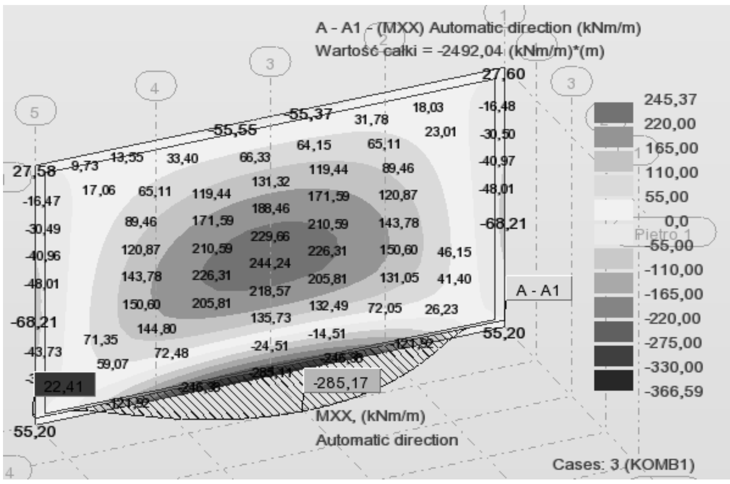


*Fig. 4. Vertical ULS moments for long wall and bottom edge*

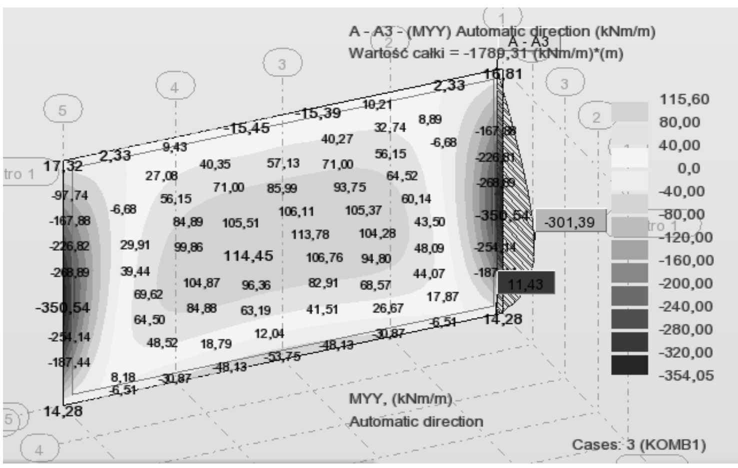


*Fig. 5. Horizontal ULS moments for long wall and side edge*

According to typical behavior under increasing hydraulic inside pressure, the initial yielding started on bottom edges (inside, horizontal crack), and spread through the slab as moments were redistributed from yielded regions to areas that still remain elastic (panel span), yielding them at least (outside "envelope" cracking).

The stresses in tank structure due to hydraulic pressure was obtained modeling the structure with FEM commercial software. The results for long walls are presented on Fig. 4 to 5 above.

**The design and constructed reinforcement capacity.** According to design, the typical reinforcement for wall panels used in span was mesh on both faces with ∅16 mm bars spaced 15 cm in each direction. The vertical edges were reinforced with horizontal bars ∅20 and 22 mm on both faces spaced 15 cm. The outer vertical layers of rebars have 3 cm cover.

Check calculations show, that for leak test conditions the stress in bottom edge vertical tensioned bars reach 536 MPa exceeding yield strength of steel (500 MPa). For other critical locations in the long walls, the service stresses were in the range between 250 and 330 MPa.

Checking the bending ultimate capacity of the wall structure, the obtained values for bottom edge was 80 % below required, and for span 54 % below.

### Strengthening of the tank

**The concepts considered. Taking into account the current state of the defective structure, four options of further actions were analyses:**

Option 1 Strengthening of walls with CFRP strips

Option 2 Integrated build-up of walls from inside with additional reinforcement,

Option 3 The mutual cross tying of the long walls,

Option 4 Tank demolition (including foundation raft) and rebuilt with improved structure.

Option 1 was rejected due to aggressive environment inside the tank, and no possibility of strengthening the bottom edges of the walls in this technology. Option 2 was deeply discussed considering required scope of repair action, access to the tank inner space, time schedule and costs. But the critical factor was the significant reduction of the tank capacity with big negative impact on operational performance. Option 3 was found as reasonable alternative to others, including the complete tank demolition and rebuilt.

**Basic assumption for tying.** The tie-bars run perpendicularly to the long walls planes, and passing through the drilled holes in walls are anchored outside. Because the sewage pressure acts identically to the opposite walls of the tank, so the ties give no unbalance effect on the walls, to which will be attached. For temporary support during installation and further tank maintenance operations, tie-bars were supported on the columns of the inner RC frame.

*Fig. 6. Tie-bars installed and supported on the inner columns*

Tie number and tie group location was assumed considering the wall deformations due to inside pressure as well as available space limits of the inside tank process equipment, and accessibility to anchorage zones outside the tank. Then the location was optimized to minimize stresses and wall deformations obtained during FEM analysis.

The results of FEM analysis for final ties location are presented on Fig 7 and Fig. 8.

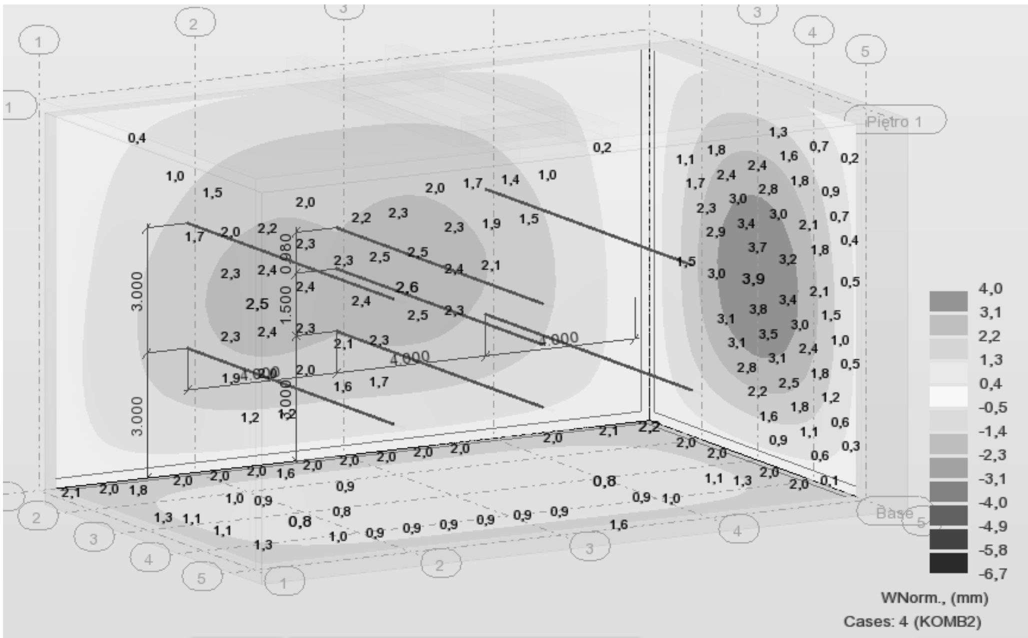


*Fig. 7. Tie-bars location and tank walls deformations under service load*

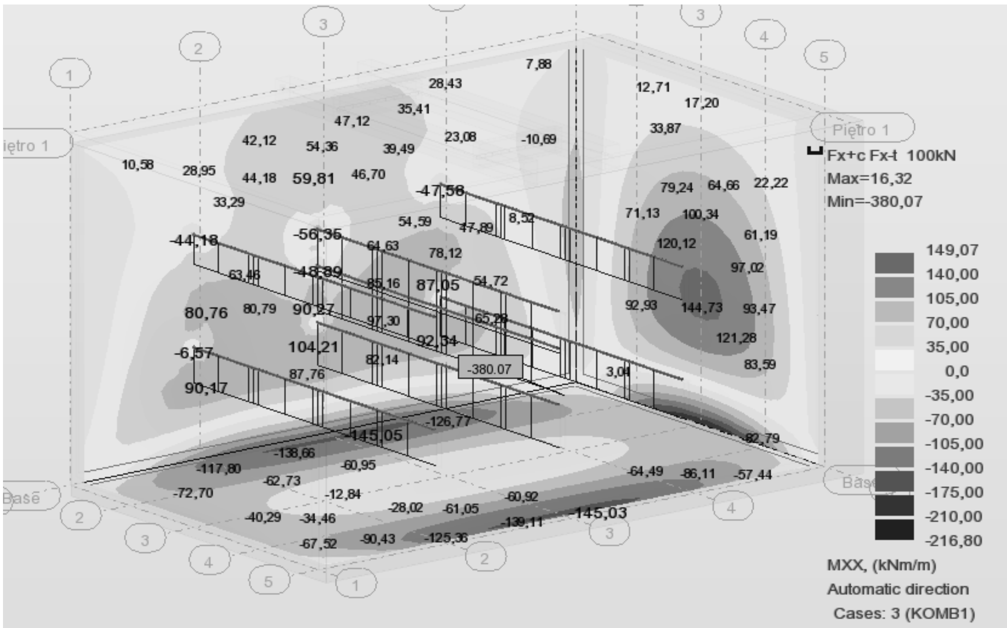


*Fig. 8. ULS moments for walls and the maximum tension force in ties*

**Tie construction: the design and basic calculations.** The primary assumption for the ties was to use typical prestressing bar or strand system. But in this case, some problems arise. First, is the material factor: the high strength prestressing steel is relatively sensitive to aggressive environment inside, so advance protection would be required. Second: the required pre-tensioning, which shall be applied to already defective wall structure. The third was the expected tendon elastic elongation due to service loads, inducing wall panels deformations resulting in further degradation of structure and its tightness.

For those reasons the stainless steel round bars were used for ties, with relatively large diameter of 65 mm, and with no significant pretension.

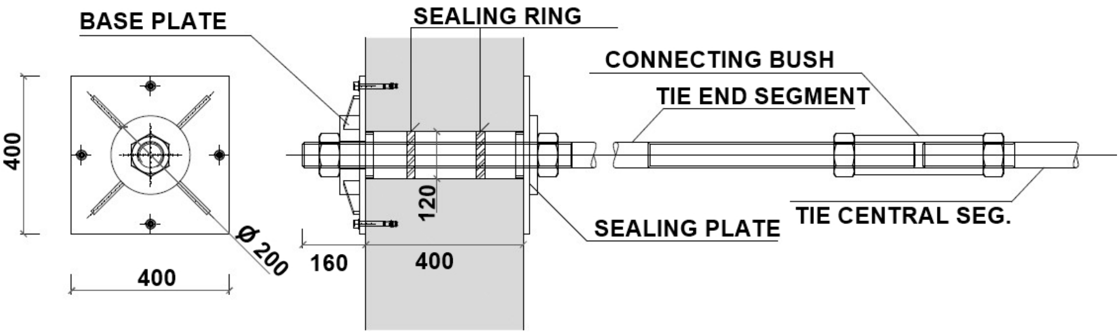


*Fig. 9. Construction of tie-bar and it's anchorage*

Large diameter reduce the stress level and elongation due to tying force. It also improve tie resistance to corrosion, so any additional protection is required. The steel grade A316L (1.4404) was choose for specified environment aggression and appropriate strength ($f_y/f_u$ = 200/500 MPa, in: [2], Tab. 2.1).

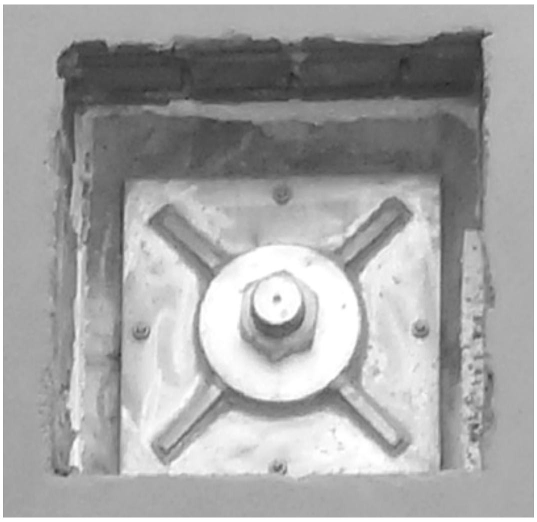

*Fig. 10. Tie anchorage, close view from inside of old building*

Maximum ULS tension force $N_{Ed}$ = 380.07 kN (Figure 8) for tie-bar shank cross-section area $A_0$ = 28.3 cm² results in stress:

$$s_{Ed} = \frac{N_{Ed}}{A_0} = \frac{380.07}{28.3} = 13.4 \ \textit{kN/cm}^2 = 134 \ \textit{MPa}$$

which is less than design yield strength [2]: $f_{yd} = \frac{f_y}{g_{M0}} = \frac{200}{1.1} = 182$ MPa

The ties will pass through holes drilled in the long walls, and are anchored outside this walls in the base plates. Due to space limits out and inside the tank, the tie bar was divided into two short end segments and inner longer one (see Fig. 9). The tie segments connections and end anchorage was made as threaded – for length adjusting and omitting welds as more sensitive to corrosion.

The base plate dimensions results in press to concrete with net stress 4.7 MPa. The stress in anchoring block ∅200 mm is presented on Fig. 9.

The maximum stresses calculated based on Huber-Mises's theory equal to 235.37 MPa locally exceed yield stress of steel equal 200 MPa, but found to be within safe limits referred to ultimate strength of 500 MPa.

**Summary.** Due to actual cracking of the walls, the strengthening action described above was supplemented by the crack injection and sealing of the entire surface of the tank interior with chemical resistant coatings (not included in the original design). For assuring maintenance and revision access to anchorages a small chambers were made. They are located in the wall of existing building attached to the tank and in tank thermal insulation on opposite wall.

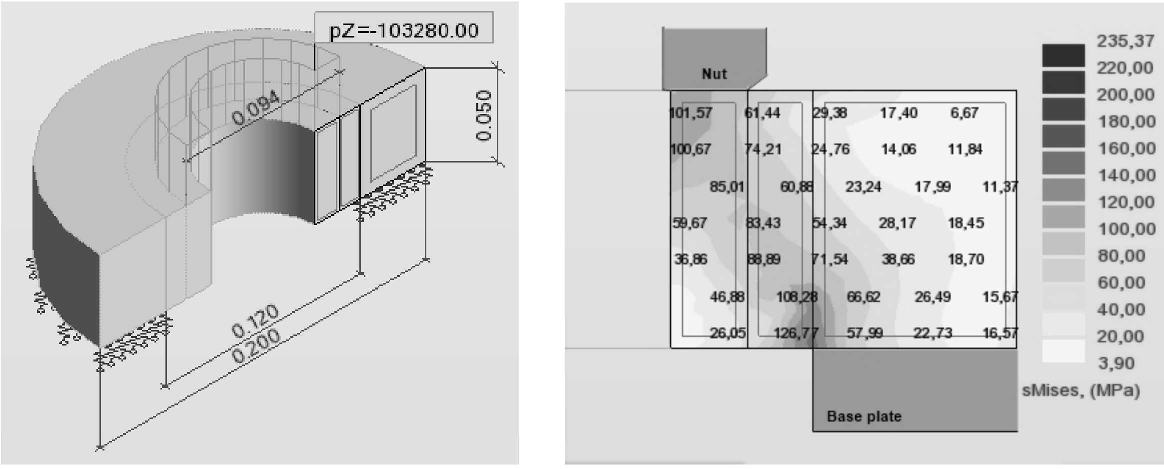


*Fig. 9. Stresses in anchoring block*

Presented strengthening solution allows the tank to work according to planned conditions with small completing time delay. To date, no problems have been reported with the tank structure and its operation.

Other remark shall be put on original design quality. The use of advanced software do not automatically assure good design.

*1. Wight J. K., MacGregor J. G. Reinforced concrete: mechanics and design 6th ed., .Pearson Education Ltd, New York 2012.2. EN 1993-1-4 (2006) (English): Eurocode 3: Design of steel structures – Part 1-4: General rules – Supplementary rules for stainless steels.*