Degradation and Reinforcement of Industrial Gas Tank Support Structures. Thirty-Year Long Monitoring

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Abstract. An analysis of reinforced concrete supporting structures of more than a dozen liquid gas tanks mounted on tower support structures located at different sites on Poland's territory is presented. Stability testing of the degraded structures was carried out over a period of 30 years and pointed out significant defects that prevented safe operation of the tanks containing hazardous medium. Analysing complex stress states, as well as displacements of shell structure components, the authors developed a concept of strengthening the structures. Initial repair works, which had been carried out without proper supervision, failed to meet the mandatory requirements and were not compatible with the original design solutions. After several years of operation of the reinforced structures, their degradation states were assessed again. The next stage of repair works was carried out under the supervision of the authors together with authorized representatives of the investors.

1. Introduction
In order to maintain the durability of a building structure without degrading its performance within the expected time of its operation, it has to comply with the defined design requirements concerning its usability (serviceability limit state - SLS), load carrying capacity (ultimate limit state - ULS) and stability [1]. The basic elements determining the safety of a building structure should reliably perform the technological functions of the tank in the expected period of its use. A stationary spherical gas container consists of a pressure storage vessel, i.e. a tank, and its supporting structure. The safety of storage and distribution of industrial gases is ensured in conditions of limited deformations and displacements of the gas tank's shell and bar structural elements. Safety risk typically involves degraded construction of reinforced concrete support towers, as their deformation process results in the disruption of the tank's shell. In case of a disaster or structural failure, the liquefied medium stored in the tank can not only lead to the destruction of infrastructure, but also risk the safety of people. The risk is increased by the fact that the explosive substance is often stored in several tanks, which creates the possibility of the spread of the disaster [2].

2. General requirements
Gas tanks as building structures should comply with certain required standards concerning the calculation, design, construction and operation of engineering structures [3, 4]. Examples of the tested spherical tanks with their damaged supporting elements are shown in figure 1. It is necessary to carry

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out correct verification of the required standards on the ULS and SLS concerning safe bearing capacity and transfer of loads (such as the structure's own weight along with its insulation, fittings and accessories, as well as the load and temperature of the stored medium, pressure and wind suction and the weight of snow) onto the foundations. Account should also be taken of the loads with water fill during technological tests, the effect of both external and merge temperatures and dynamic loads resulting from the flow of the medium, as well as the loads resulting from assembly inaccuracies. Additionally, in the analysis of the ULS, a possibility of the tank's shell deformation under the influence of variable operational loads, such as pressure or temperature, should be taken into consideration.

Figure 1. Examples of examined gas tanks with a capacity of 600m^3 in 1987 and 1991

Complex support structure elements should be designed and formed in order to ensure free access to serviceable joints, and both ring and block foundations must be shaped in such a way as to enable correction and rectification of the coordinates to eliminate local processes of shell degradation. The outer surface of the tank and its support structures are designed to provide the required stability. Protection against corrosion of the tank's internal surfaces is provided by taking into account the aggressiveness of stored media. In the case of storing combustible substances, tanks should be protected against fire by making protective coatings and installing automatic sprinklers or complex fire extinguishing systems.

In view of potential threat, during its operation both the tank's shell and supporting structures must be subjected to continuous inspection. During the authors' research work both measurements and analysis in terms of safety and durability of complex shell and bar structures were carried out. Particular attention was paid to the assessment of structural materials of the supports. When examining the degraded elements of the supporting structures, it was essential to evaluate the actual complex stress states and compare them with their design values defined as the limit ones. In cases of threats, it was indispensable to develop safety or strengthening measures to ensure further trouble-free operation of the tanks. Independently, the reliability of the technological infrastructure and its operation must be checked by technical supervision teams of distribution companies.

3. General requirements

Storage of propane-butane gas in spherical pressure vessels supported on reinforced concrete structures is a solution commonly used in Poland. The authors conducted research work on a dozen spherical tanks with a capacity of 195 m^3 and 600 m^3, located throughout the country.

3.1. Tanks with a capacity of 195 m^3

This type of vessel support structure is shaped in the form of six reinforced concrete vertical columns bound by a horizontal reinforced concrete ring located at a height of about 3.0 m. The foundation under

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the columns is made of a reinforced concrete slab in the shape of an equilateral hexagon. The supporting columns are positioned on the perimeter of a circle with a radius of approx. 3.60 m. The connections between the tank's supporting columns in the column head zones have been formed as articulated ones in order to allow for interactive mutual displacements caused, for example, by thermal load. The lower segments of the columns are anchored to the foundation whereas the upper part remains free at the top end. The thrust plates of the tank shell are placed on the column heads in a sliding manner and stability of the contact zones is assured by using the friction forces (figure 2).

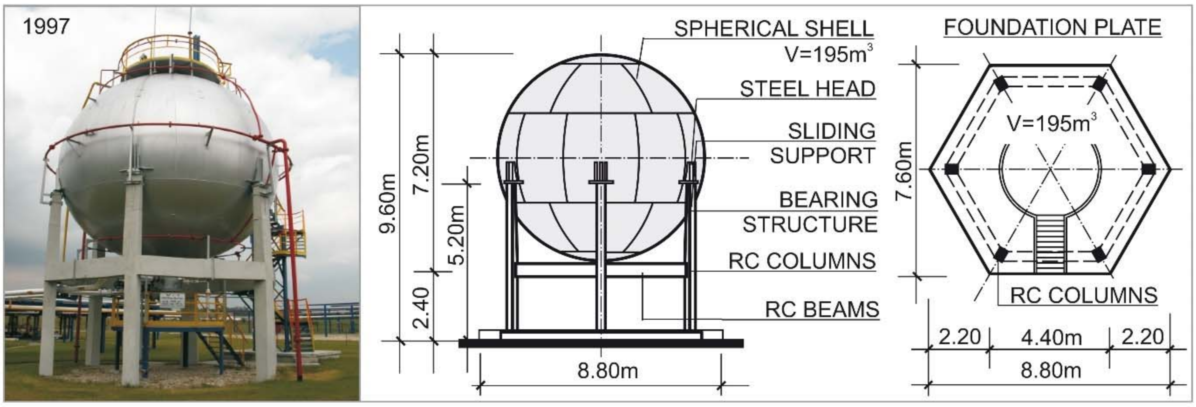

Figure 2. Construction details of the gas tank with a capacity of 195 m^3

3.2. Tanks with a capacity of 600 m^3

Spherical tanks of 600 m^3 capacity are placed on structures in the form of six supporting trestles inclined at an angle of about 6° relative to the vertical axis, resembling an inverted letter "Y" (figure 3). The branches of the support trestles are positioned at the vertices of the reinforced concrete base constructed as a ring-shaped regular dodecahedron situated at ground level. The lower parts of the trestle are connected to the ring in an articulated manner. The ring is supported with twelve columns anchored in the lower foundation ring, transferring the load to the subsoil. The thrust plates of the tank shell are placed on the column heads in a sliding manner.

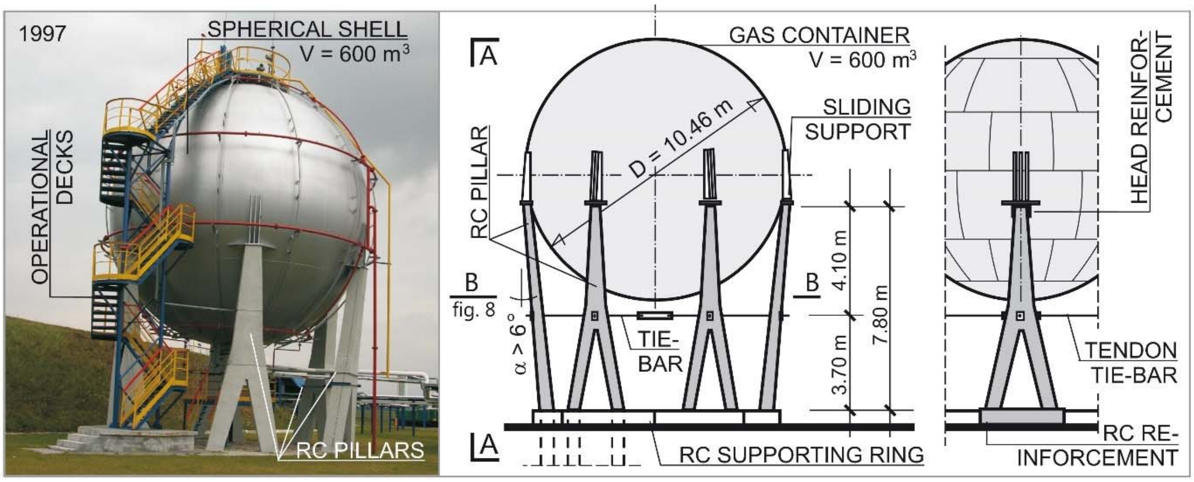

Figure 3. Construction details of the gas tank with a capacity of 600 m^3

4. Damage to reinforced concrete elements of the supporting structures

During several dozen years of operation, the investigated reinforced concrete supporting structures have been subjected to degradation and finally destruction process. The degree of the damage was dependent primarily on the initial state of the manufactured elements and the way the concrete surface was protected, as well as the aggressiveness of the environment. A significant role in the extent of the degradation process was played by the methods and quality of ongoing maintenance, which differed significantly among different users. In the examined structures concrete of strength grade of C16/20 or even C12/15 was found, which undoubtedly had an impact on accelerating the process of degradation and reduction of concrete's durability.

The expected durability of reinforced concrete structures used in specialist constructions operating in destructive industrial environment is reduced by corrosion processes known as selective leaching and carbonate corrosion. Selective leaching is caused by soft rainwater deprived of calcium salts. The aggressiveness of soft water increases at lower temperatures. Progressive process of binding atmospheric carbon dioxide by concrete, known as carbonation process, leads to a lowering of concrete's pH. The pH in the vicinity of the examined reinforcement bars was reduced to 8 ÷ 9 units.

Figure 4. Structural faults of the support structures of tanks with a capacity of 195 m^3

The corrosion process in properly implemented and used concrete structures (figure 4), working in environments defined as class XF1, XF3 according to aggressiveness standards, is expected to be initiated only after about 50 years. However, in an environment polluted with aggressive substances such as SO_2, NO_x, Cl belonging to classes XA1 and XA2, the corrosion process is significantly accelerated. This was found to be the case practically in all of the assessed structures. The above destructive phenomenon with the highest degree of deterioration was found in the parts of the supporting structures buried in the ground.

During the operation of the carbonized elements, the corrosion products increased their volume and generated tensile stresses, which resulted in concrete cracks and loosening of the large parts of coating surfaces [5]. These damaged parts made it easier for the aggressive environment factors to penetrate into the structure and, as a result, intensify the corrosion processes, while corrosion losses diminished the bearing capacity of reinforced concrete elements. The diversified inclination of the 600 m^3 tank's columns (>6°, cf. figure 3) constituted the main cause for the weakening of the lower column zones. The cross-section of the trestle support zone, including the losses produced during the long years of operation, turned out to be particularly dangerous and insufficient for safe transfer of the operating loads. Faulty support zones of the column heads failed to provide correct load transfer onto the supporting elements. Degraded supporting structures posed a threat to the safety of the tanks, and deformation processes were the cause of asymmetry in the shape of the balanced membrane structure of the tank steel shells.

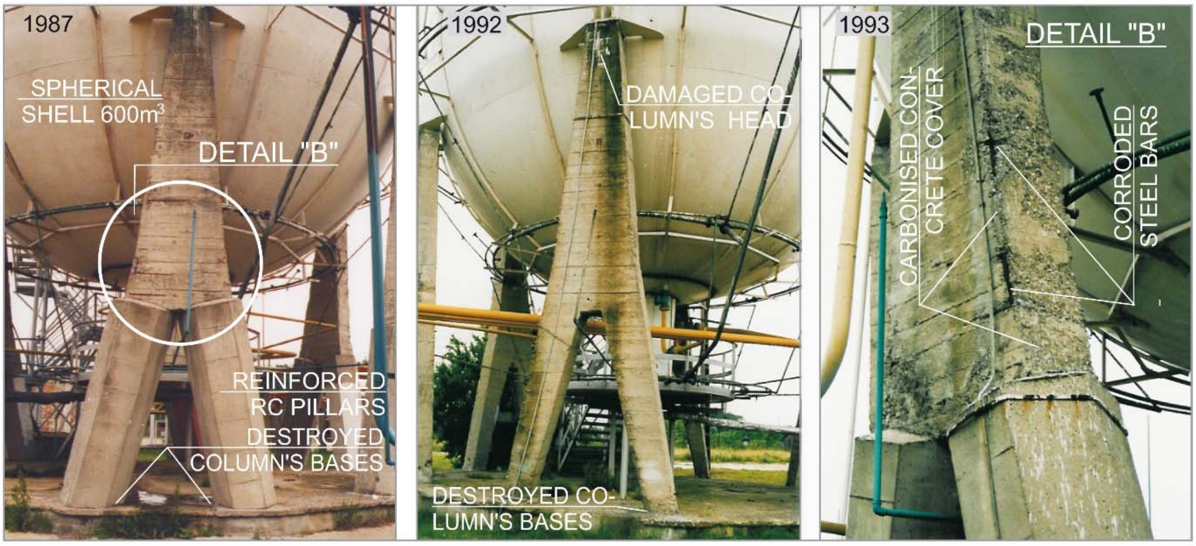

Figure 5. Structural faults of the support structures of tanks with a capacity of 600 m^3

Considering solutions protecting the degraded structures, it was necessary to inform the user about the period in which the support structure was able to fulfill the conditions of the limit states in order to adapt the solutions to the planned time of the tank's operation.

5. Chronology of destruction process elimination

The structural state and quality of the repair work of a dozen tanks were subjected to monitoring in a period longer than 25-30 years. In the analyzed cases, typical defects and damage to the supporting structures, described in Section 4, were reported by users of the facilities. The users, however, had no qualifications for independent and reliable assessment of the structures. Plants for the storage of liquefied industrial gases are naturally located outside large agglomerations. The lack of proper supervision contributed to the fact that in many cases the state of the damage was so significant that, after the authors' inspection, the structure was immediately excluded from operation, due to imminent disaster threat. Strengthening works to ensure reliable and sustainable use of the endangered structures were carried out immediately after detailed assessment of their technical condition and outlining the scope of repair work and producing relevant design documentation.

The economic situation of Poland in the last century and the state of technological advancement of local construction companies a few decades ago were so weak that it was necessary to design the strengthening works in such a way as to take into account local conditions and technological possibilities of their implementation. Hence, the strengthening and repair of reinforced concrete structural elements were designed using concrete with a maximum strength corresponding to the current class C20/25. Strengthening works involved removal of the carbonized layer of concrete covers, cleaning the reinforcement bars of corrosion products, inserting additional reinforcement bars into uncorroded zones, as well as making ferroconcrete "shirts" around columns, beams or brackets.

In places with limited access, reinforcements in the form of so-called "cages" made of steel angle sections located in the corners of the pylons and connected by welding flat bar battens were used. Additionally, steel elements were protected against corrosion and column surfaces were covered with a layer of cement and lime plaster. On completion and formal approval of the repair work, the structures were granted a five-year operation period on the condition of being subjected to periodic inspections at intervals of one year. The repair works were carried out without proper supervision by the investor. The quality of the repairs was very low, design requirements for the concrete grade were not met – the highest concrete strengths amounted to C16/20. All this resulted in low durability of reinforcements leading to

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losses of concrete cover on the surface of several dozen square centimeters. On the exposed surfaces of steel elements subjected to aggressive atmospheric environment, effects of advanced corrosive processes were observed.

The authors' recommendations regarding the allowed operation period and the implementation of periodic inspections were ignored by the users. After several years of exploitation, subsequent repair work based on the same documentation was carried out, giving the same unsatisfactory effects in terms of quality and durability. The authors were asked to assess the structures and to supervise further operation only after random inspections of supervisory authorities, usually after about ten years, when the actual state of the structure demanded immediate shutdown of the object. After Poland's accession to the European Union in 2004, the legal situation was changed, obliging users to carry out annual inspections and to assess the state of the object by an approved engineering unit every five years. Construction companies gained access to modern technologies and it has become common to use higher concrete class. Due to the structural strength requirements concerning the design of reinforced concrete structures above the ground level, it was necessary to apply exposure classes XC4, XF1and XF3. For objects below ground level and constructions buried in the ground exposure class XA1 was adopted, which involved the use of C25/30 concrete grade as a minimum. However, for economic reasons specialized work using modern technology [6] could be performed only within a limited extent. In view of the above, the authors made the required documentation on reinforcement works using traditional technologies [7].

5.1. Tanks with a capacity of 195 m^3

Repair works, carried out in the years 2003 – 2007, and began with protecting the parts of the structure resting in the ground. Excavations were made around the columns to unearth the upper part of the foundation plate. The excavations were made secure with tight walls. The actual width of the excavated trenches was determined by the safety standards required for people carrying out this type of repair work. The degraded reinforced concrete structure was first made clean with water stream and then protected against the corrosion process by applying a reinforcing concrete layer of C25/30 class strengthened with rods of 8 mm in diameter made of ribbed steel. To attain the required conditions of adhesion, strength and tightness of the fillings, the shotcreting (concrete spraying) method was used. The concrete mixture was laid in layers to form a coating of final thickness of about 4.5 cm. To eliminate concrete shrinkage, special types of cement were used. The work involved reinforcement of two opposite side columns at the same time. The scope of the repair work is shown in figure 6.

The proposed method of strengthening could not be used in places where there was a high groundwater level making trench work impossible. In such cases, excavations were carried out near the columns to a depth of about 60 to 80 cm below ground level, and then prefabricated elements made of a steel pipe cut in half with an outer diameter adapted to the dimensions of the reinforced column were put in and stabilized. The outer surfaces of the tubes were cleaned by sanding and secured with corrosion-resistant coating. The bottom edge of the element had been made in a shape of a "blade" to facilitate its penetration into the soil. The side edges of the element had been also sharpened in order to make it easier to join them with butt welds. The inner surfaces of the pipe were cleaned by sanding and left without any coating. The tube was inserted into the ground as deep as the upper foundation plate level. The gravel from the inside of the pipe found around the tank structure was removed by washing out and pumping. After cleaning the pipe, its interior was filled with class C25/30 concrete. The applied solution is shown in figure 7. The next stage of work was the repair of the damaged surface of the columns and girders, situated above ground level. The repair was done using shotcreting of the previously grilled surfaces of the damaged parts. The final stage of the strengthening activities was the protection of the sheet of the spherical tank supports and the surface of the column heads from reciprocal displacements in a situation of exceptional loads.

Figure 6. Details of the implemented tank reinforcement structure: a) underground zone, b), c) over-ground zone

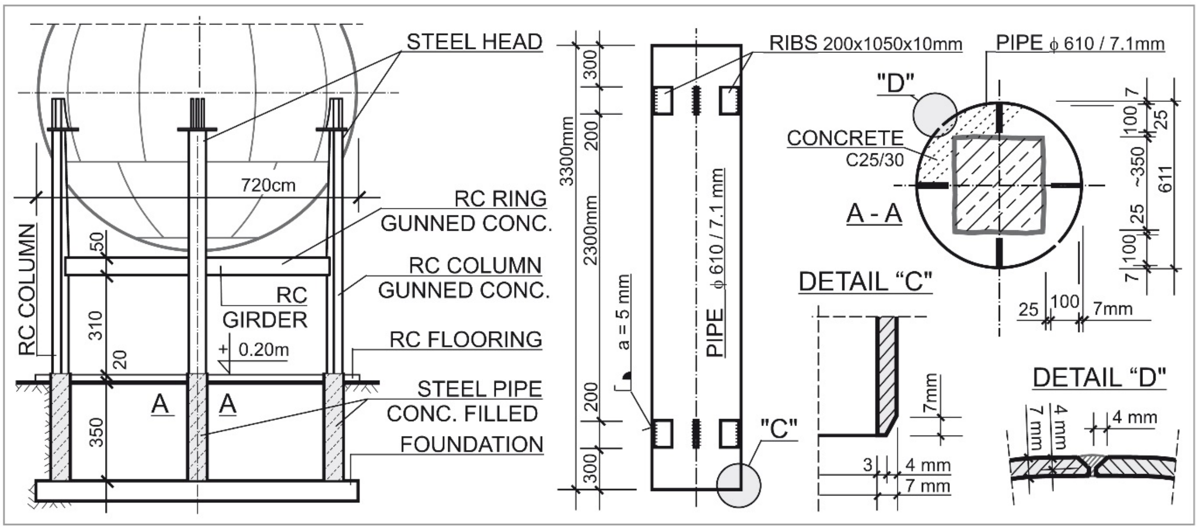

Figure 7. Reinforcement concept of the degraded elements of the 195 m^3 gas tank

5.2. Tanks with a capacity of 600 m^3

The authors' research conducted on several successive tank structures showed their pre-failure state, which made it necessary to put them immediately out of service. In the examined structures the connection of the supports with their foundations was made as articulated, which in the case of the inclined bar supports failed to ensure reliable equilibrium of the whole structure. As a result of progressing degradation processes of the structure, there was a possibility of its losing overall stability thus leading to imbalance and sudden uncontrolled disaster. As a result of repair activities, original concepts of strengthening the elements were implemented.

To strengthen the columns' base zones, it was necessary to create special reinforcements that would take over the peripheral forces. It was achieved by placing ring-shaped concrete supports stabilized by proper connections to the foundations, which eliminated mutual displacements of the structural elements and rotation of the columns' bases. In some cases, a customized solution using a centric steel ring to take over forces from tie rods was introduced. The ring was mounted below the bottom part of the spherical shell, as shown in figure 3 and 8. The horizontal tie system made of steel rods with a diameter of 30 mm provided redistribution of internal forces in all structural elements of the tanks' support, which resulted in the compensation of effort states caused by exceptional loadings. To adjust the tension and stability in the areas of surface anchoring, trestles with nuts with M30 metric threads were used.

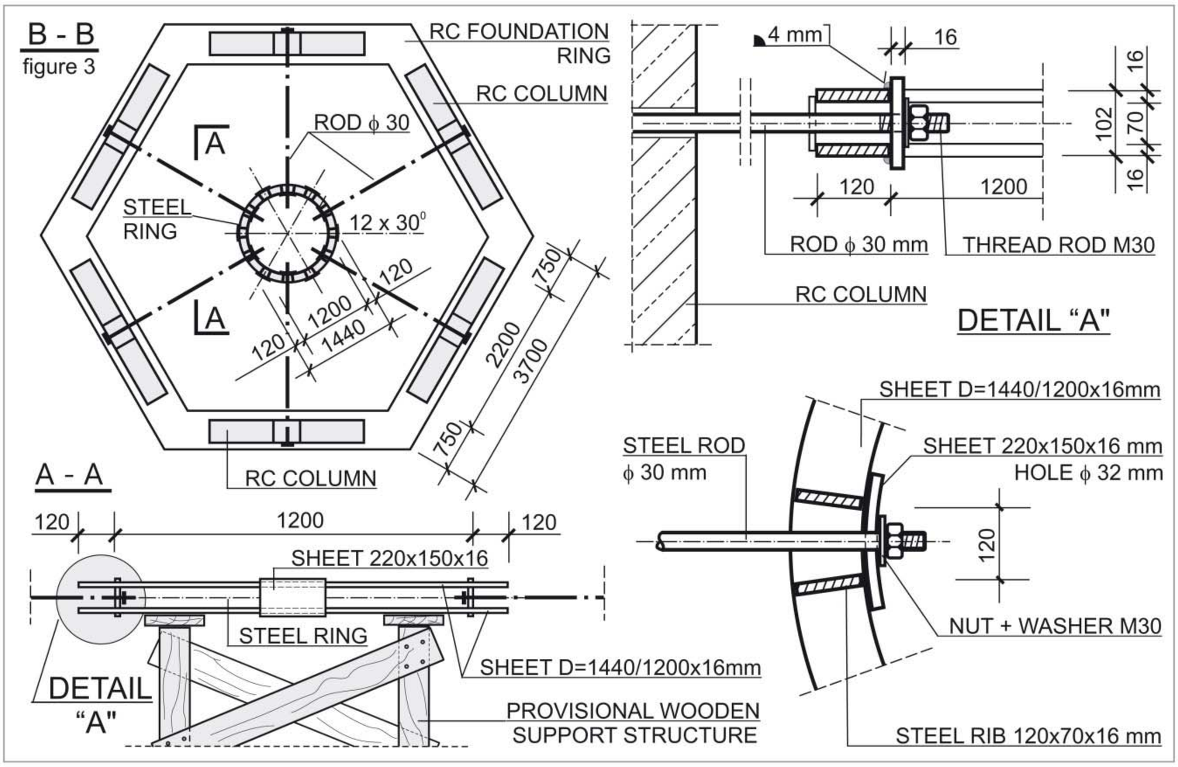

Figure 8. Stabilization concept of the degraded columns of the 600 m^3 gas tank

The whole structure shaped that way provided the suitable conditions for stable equilibrium. The steel containers' support plates resting on the columns' head surfaces were also protected against mutual displacements. The implemented stabilization solution provided proper overall stability, also eliminating the impact of temperature on the state of internal stress in spherical steel shells (see in bold in figure 9). The degraded reinforced concrete structure of the trestles was protected against corrosion processes with reinforcement layers about 40-50 mm thick. To attain the required conditions of adhesion, strength and tightness of the fillings, the shotcreting method was used. As a result, it was possible to secure and form a monolithic structure of existing carbonated concrete substances and exposed reinforcement bars. In the period of extended operation, the implemented surface reinforcement protected the coating against cracks caused by changes in outside temperatures. After shotcreting, it was possible to obtain a monolithic, rigid reinforced concrete structure taking over the bending moments produced by tilted columns (figure 10a).

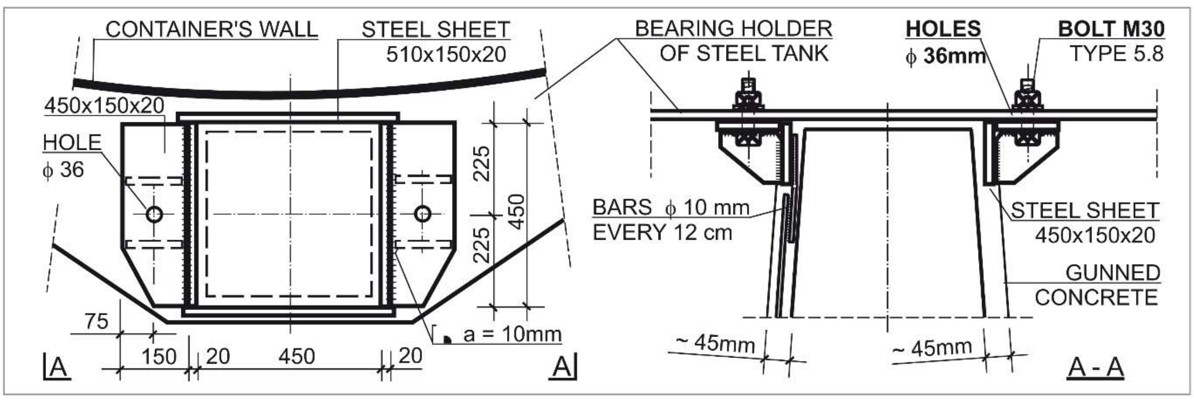

Figure 9. Stabilization concept of the support structure's head of the 600 m^3 gas tank

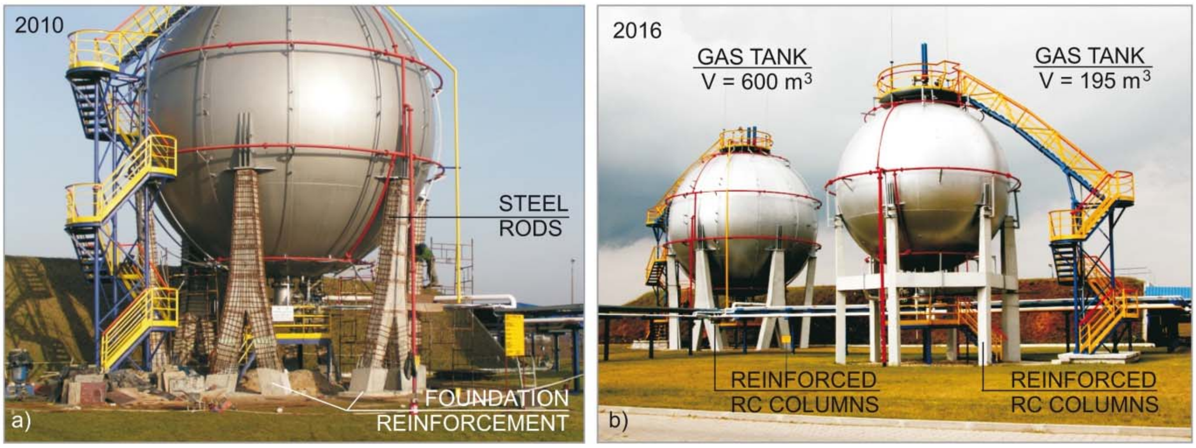

Figure 10. Details of the implemented tank reinforcement structure: a) view of the columns, b) view of the tanks after their structural reinforcement

After completion of repair works and strengthening of the supporting constructions, it was possible to commence reconstruction works on spherical steel tanks involving local removal of corrosion products followed by corrosion protection activities. Areas damaged by corrosion were found in the connection zones of 25 mm thick steel shells with elements of technological installations and in the support zones on the column heads.

The structures were allowed to be operated for a period of five years and subjected to annual inspections. During the visual and non-destructive examinations carried out after the expiry of the prescribed period, the authors observed, in all cases, only minor surface damage, evidence of proper choice of technologies and the correctness and effectiveness of the performed works. To determine the actual quality of the reinforced structures in the last three years, the authors conducted the following non-destructive tests:

- ultrasonic pulse velocity testing, using line and area scans for concrete uniformity assessment,
- the detection of rebar's diameter and their cover depth beneath the cover surface, by the use of electromagnetic pulse induction technology,
- testing of the electrical resistivity of concrete due to direct link between concrete resistivity and its corrosion rate,
- identification, control and on-going monitoring of moisture of both concrete surfaces and structure's inside,
- testing of the compressive strength of concrete with press and rebound hammer.

Resulting from the undertaken tests, the structures were allowed to operate for another five-year period, and the overview of the reinforced structures after the following several years is shown in figure 10b.

6. Results and discussion

As a result of the examinations of more than a dozen degraded concrete support structures of spherical industrial gases tanks, it was possible to develop the following guidelines concerning their supervision with due regard to the provisions of the construction law:

- in view of the repeatability of constructional solutions concerning support structures of gas tanks, it is possible to state that repair solutions using shotcrete should be taken into account by designers and users of this type of construction, as proven in terms of durability over a 10-year period of use;
- special attention should be paid to contact zones and connections of reinforcement elements with materials of reduced strength parameters;

• in the course of repair works, modern technologies using carbon fiber and polymers can be applied. However, due attention should be paid to life expectancy of the reinforced surfaces;
• an important issue, subject to verification, must be the qualifications of the repair works team [8]. All work should be carried out under the supervision of the authors of the reinforcement work documentation and the representative of the investor;
• in current assessment of bearing structure, the Building Information Modelling (BIM) method quality could be efficiently adopted [9],
• the designers and executive engineers dealing with structures endangered of combustion should pay particular attention to current mutual cooperation [10].

7. Conclusions
In the cases presented here, proper risk assessment and efficiently conducted reconstruction activities made it possible to eliminate danger and ensure the launching of the technological process as soon as possible, all in compliance with the conditions of safety for workers and the environment.

The designed and used materials and technologies, beside predicted durability, should take into account the requirements due to local possibilities for proper implementation. To avoid future instances of life threat or building disaster, support structures of industrial gas tanks should be under constant supervision of the user.

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