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Repair of the inner steel shell of an underground liquid fuel tank with a polyester-glass laminate

Naprawa wewnętrznego płaszcza stalowego zbiornika podziemnego na paliwo płynne laminatem poliestrowo-szklanym

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Abstract. The article presents the results of numerical analyses and experimental tests, the aim of which was to evaluate the method of repairing the inner shell of a double-walled underground tank with a laminate coating made of polyester resin and glass mat, in the context of the impact of this coating on the strength parameters of the inner shell as well as the properties of the laminate during its long-term use contact with fuel. The results of experimental tests, including the determination of porosity and absorption, as well as the assessment of flammability of laminate samples, indicated important features of the laminate coating in the context of the fire hazard of the tank. The results obtained also indicated the need to continue work on the development of effective and safe repair technologies using composite coatings.

Keywords: fuel tank; laminate; composite; corrosion; strength; flammability; porosity; FEM analysis.

Streszczenie. W artykule przedstawiono rezultaty analiz numerycznych i badań doświadczalnych, których celem była ocena metody naprawy płaszcza wewnętrznego dwuścianowego zbiornika podziemnego powłoką laminatową, wykonaną z żywicy poliestrowej i maty szklanej. Ocena ta dokonana została w kontekście wpływu powłoki laminatowej na parametry wytrzymałościowe płaszcza wewnętrznego oraz właściwości laminatu przy jego długotrwałym kontakcie z paliwem. Wyniki badań doświadczalnych, obejmujących określenie porowatości, oznaczenie chłonności oraz ocenę palności próbek laminatu wskazały na cechy powłoki laminatowej, istotne w kontekście zagrożenia ogniowego zbiornika. Otrzymane rezultaty wskazały również na potrzebę kontynuacji prac nad rozwojem skutecznych i bezpiecznych technologii naprawy z wykorzystaniem powłok kompozytowych.

Słowa kluczowe: zbiornik paliwowy; laminat; kompozyt; korozja; wytrzymałość; palność; porowatość; analiza MES.

When the regulations [1, 2] on monitoring leaks of tanks for storing flammable liquid materials entered into force, parts of tanks for liquid fuel required modernization or replacement. The introduced changes were aimed to minimize the risk of soil contamination with fuel leakage from the tanks. Leakage was very often caused by leaks due to corrosion of the tank shell. This problem was identified particularly in steel underground tanks commonly used at fuel filling stations and distribution depots. Two shells (instead of one) and the continuous monitoring of the space between them to identify potential leakage of the inner shell were considered as the solution to guarantee the relevant safety level of such tanks. However, the operational experience of such tanks shows that corrosion processes observed on the surface of both shells still pose a serious risk that can result in fuel leakage into soil.

Corrosion losses on the surface of the outer shell in double-wall tanks are usually caused by improperly applied bitumen protection on the shell or damaged protection as the result of placing the tank. Corrosion rate of steel in soil is estimated to be 0.1 ÷ 0.2 mm/year, and this process can accelerate in the presence of additional factors, such as stray currents or microorganism, e.g. anaerobic sulfate-reducing bacteria. These factors are not constant, and their rate depends on many circumstances, such as the level of groundwater, a season, or the presence of road infrastructure in the vicinity of the tank. For example, in winter a significant quantity of chlorides from deicing agents enters soil near the tank (transported there by vehicles), which increases soil conductivity and stimulates the development of pitting corrosion [3]. The repair of the outer shell, agreed with the Polish Office of Technical Inspection, usually requires the removal of backfill and a layer of bitumen protection, the welding repair of the shell, and then the restoration of a bitumen layer and the backfill. The repair of the inner shell damaged by corrosion is also problematic. Corrosion losses observed on the inner surface of the shell are the result of an aggressive effect of both chemical compounds from the stored fuel and water condensate deposited on the inner surface of the shell (Photo 1). It should be also mentioned that this surface is

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usually protected only by oil coating at the stage of the tank construction. However, this type of treatment does not provide the long-term and effective protection of the shell. Therefore, the inner steel surface of the shell is likely to corrode within a few years. The repair of the shell should lead to the full or partial restoration of its mechanical properties, mainly its load-carrying capacity, and successfully provide its protection against further corrosion processes, which occur on the inner surface. Repairing the tank prevents bearing high costs of the tank exchange into the new one. The tank exchange is connected with the closure of a fuel filling station for the time required for performing construction works. Also, the network of underground technological installation can be damaged.

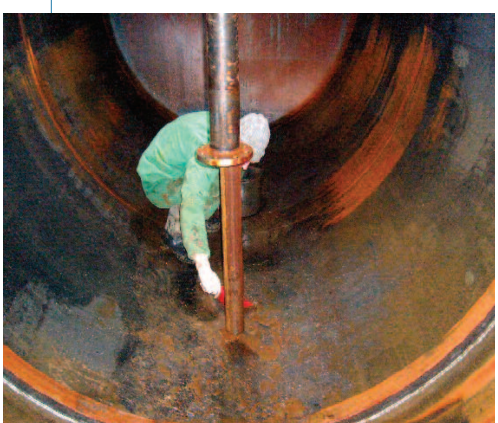

Photo 1. Corrosion on the surface of the inner jacket of the fuel tank
Fot. 1. Korozja na powierzchni płaszcza wewnętrznego zbiornika paliwowego

One of the repair methods consists in the application of the composite coat on the inner surface of the inner shell, made of hardened unsaturated polyester or epoxy resins, and fibreglass. This paper presents the results of numerical analyses and experimental tests, the aim of which was to evaluate the repair method with reference to the impact of laminate on improving strength parameters of the inner shell in the double-wall underground tanks (Photo 2), and to evaluate parameters of the applied laminate with regard to a long-term contact with fuel, which are crucial for fire risk assessment of the tank.

Photo 2. The analysed underground tank
Fot. 2. Analizowany zbiornik podziemny

Repair technique with laminate coating

The discussed method of repair is classified into the so called **laminate techniques** characterized by laminate coats easily formed on the large area of cylindrical steel elements. The repair layer is usually applied over the whole surface of the inner shell of the tank. This repair method can be considered as an alternative for methods using specials pastes, which are only used to repair the shell locally, where major corrosion losses are observed [5]. The laminate is composed of one or more layers of glass fabric in the resin matrix. The layers are applied to the inner surface of the shell, previously treated with the blast cleaning method. The first layer applied to the steel surface is a resin layer, which levels the surface (as there are some losses), primes it, and also protects against corrosion. Fibreglass layers soaked with polyester resin with hardener are manually placed on the first layer. Then, the layers are pressed with a roller to uniformly distribute resin on the surface of fibreglass (Photo 3). The fibreglass layer is intended to improve the shell strength, mainly because of tensile stresses in the meridonal and circumferential direction. Finally, the laminate is coated with electrostatic dissipative paint.

Numerical analysis

The first stage of tests included numerical analysis to evaluate effectiveness of strengthening the inner shell of the one-chamber, double-well tank with polyester glass laminate. This evaluation was performed in the context of possible restoration of original mechanical properties of the shell. The Ansys Workbench software was used to performing these analyses.

The analysis was conducted for the double-wall underground tank for storing flammable liquid materials, with a nominal capacity of 20 m^3 and an (inside) diameter of the inner shell of 2500 mm. A wall thickness of the inner and outer shell were 6 and 4 mm respectively. Both shells were made of carbon steel S235JR. The constant distance between the shells was provided with circumferential distribution bars with a diameter of 4 mm, at the spacing of approx. 1500 mm over a length of the cylindrical part of the tank. The load, the source of which was inside the tank, was assumed to be transferred only through the inner shell. Therefore, the model for numerical analysis included only the inner shell and the fill pipe with the cover. The shell was under the self weight and subjected to inside (excess)

Photo 3. Applying a polyester-glass laminate to the inner surface of the tank shell
Fot. 3. Nakładanie laminatu poliestrowo-szklanego na wewnętrzną powierzchnię płaszcza zbiornika

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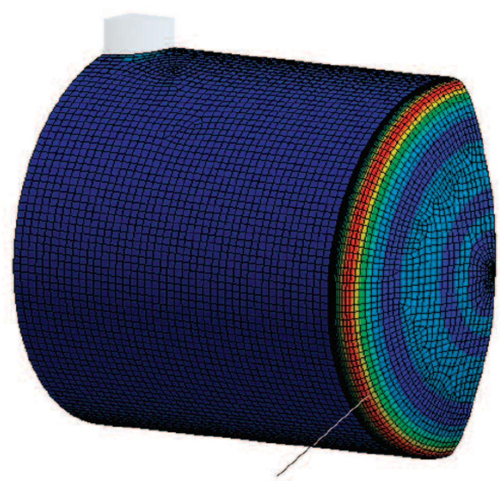
pressure of 75 kPa. Such a pressure is applied during the pressure test required by the Polish Office of Technical Inspection prior to the issue of the operation permit. The pressure of 75 kPa slightly contributed to 187% of the working pressure of the analysed tank, and was the most favourable case of loading the inner shell. It should be mentioned that nowadays double-wall tanks have to meet requirements of the standard PN-EN 12285-1 [4], and they are manufactured in accordance with documentation approved by the Polish Office of Technical Inspection.

Only 1/4 of the shell and the fill pipe were modelled for the numerical analyses to represent the symmetry conditions at their edges. These analyses concerned three computational configurations: S1 – with the reference model with a steel shell having a nominal thickness of 6 mm; S2 – with the model with a steel shell having a thickness of 4 mm; representing the situation in which the shell thickness was reduced by corrosion; S3 – with the model with a steel shell having a thickness of 4 mm, strengthened with a polyester glass laminate. This laminate was composed of two layers of glass fabric with a thickness of 1 mm each, separated by three layers of polyester resin with a thickness of 0.5 mm. The linear model of the material of both the shell and the laminate was sufficient for the analysis: The assumed elastic modulus and Poisson's ratio for steel were E = 210 GPa and 0.3. The following values of deformability of longitudinal and transverse layers of fibreglass (Glass) and polyester resin (Resin): E_{Glass} = 73 GPa, v_{Glass} = 0,22 and E_{Resin} = 3,78 GPa, v_{Resin} = 0,35.

Regarding the technology of manufacturing glass fibres, the analysed laminate was considered to be the isotropic material. The shell was modelled using the Ansys Composite Pre software, which allows to define laminate and layers of the composite element formed after strengthening the steel shell with this laminate. Moreover, the condition of displacement continuity was met on contact surfaces between individual layers of the laminate, and between the shell and the laminate.

Figure 1 illustrates the typical distribution of stresses (for each of three models) reduced on the outer surface of the steel shell, on which the highest stress values were recorded. In each case they were observed on the surface of the tank end, and were noticeably lower than yield strength of steel (235 MPa), from which the shell was made. As the shell thickness was reduced, the highest values of stress observed in the model S2 (including corrosion losses in the shell wall) contributed to approx. 163% of stresses observed in the reference model S1. When the laminate was applied to the model S3, then stresses were reduced to the level of 127% of stresses in the reference model S1. The obtained results indicated that strengthening with the polyester glass laminate led to the partial restoration of the original bearing capacity of the shell. However, bearing capacity of the shell strengthened as presented above, was not sufficient to transfer the inside pressure exerted on the shell both during the pressure test and the operation of the tank.



$\sigma_{max,S1}$ = 127,89 MPa (t_{stal} = 6 mm)
$\sigma_{max,S2}$ = 209,10 MPa (t_{stal} = 4 mm)
$\sigma_{max,S2}$ = 162,43 MPa (t_{stal} = 4 mm + t_{lam} = 3,5 mm)

Fig. 1. Huber-Mises equivalent stress distribution on the shell surface
Rys. 1. Rozkład naprężeń zredukowanych Hubera-Misesa na powierzchni płaszcza

Experimental test on the laminate

There are two fundamental methods of the penetration of liquid substances into the laminate, that is, osmosis determined by a molecular structure of cured resin, and the capillary infiltration through micro-cracks [6]. When the tank is filled with fuel, surface voids, voids, pores, and crevices in the laminate are likely to be filled during the diffusion with fractions of polycyclic hydrocarbons in gaseous state, and with the liquid fraction after a longer storage period of fuel. This may increase fire risk to the tank and weaken the structure of laminate. The experimental tests were performed on porosity, absorption, and flammability of the laminate being in contact with liquid fuel to verify the above thesis.

The tests covered **laminate coats made of glass fabric soaked with polyester resin**. The laminate tested was prepared in the laboratory conditions following precise principles of the manufacturing technology. Laminate samples were prepared using unsaturated polyester resin AROPOL M105 TB with a low emission of styrene, and the glass fabric EM 1002 with a weight of 150 and 225 g/m^2, joined with binder. The samples were subjected to ageing for six months without contact with fuel, and in the presence of Pb95 fuel and fuel oil ON (Photo 4).

Test on porosity

The laminates manually formed in fuel tanks had a certain number of voids in their inner structure, which were relatively small when compared to the size of laminate. Such voids, regardless of their shape and size, can be called as pores [7]. Connected to each other, these voids create porous space in the laminate, which is usually filled with the air and steam that can move in this space. The laminate samples, prepared in the laboratory conditions, were subjected to the macroscopic examination performed with a naked eye and the microscopic examination, which confirmed the presence of many pores having different shapes and the ability to store substances from fuel. It is expected that porosity can be greater as the conditions for laminate shaping inside the tank can

Photo 4. Laminate samples for testing
Fot. 4. Próbki laminatu do badań

considerably differ from those specified in the work method with respect to temperature, relative humidity or precision of applying resin with hardeners. A porous structure of the laminate demonstrated its tendency to absorb substances from the surrounding.

Absorption tests

The next step was to determine moisture absorption by samples prepared in accordance with PN-EN ISO 62:2008 [8], that is, in the direction through the *thickness laye*r of flat and bent solid materials. The laminate samples were weighed before and after ageing in fuel to determine the percentage difference in their weight. The analysis was conducted on 11 laminate samples prepared without any additional layer of conductive material. The samples were dried in the drying oven at a temperature of 50°C, and – when cooled down to teh room temperature, they were weighed using the validated laboratory scale Mettler AJ100 with an accuracy of measurement of 10^{-4} g. The samples were aged in fuel for six months, and then dried with absorbent paper, and weighed again. The percentage difference in weight of each sample with reference to the initial weight was determined from the following equation:

$$Cp = \frac{m_2 - m_1}{m_1} \cdot 100\%$$

where:
m_1 – laminate weight before ageing in fuel, after drying in a drying oven and cooling;
m_2 – laminate weight after ageing in fuel.

The obtained results are shown in Figure 2. They indicate absorption of Pb95 and ON fuels through laminate at the level not exceeding 2.79 and 3.18% respectively.

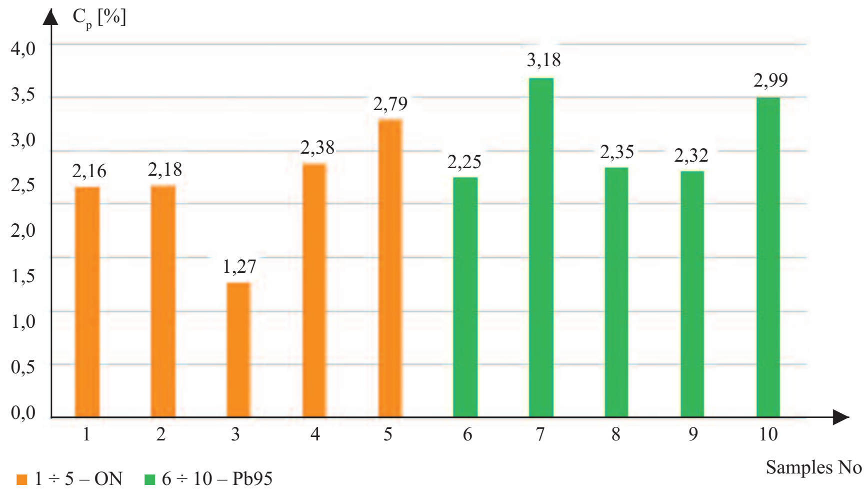


Fig. 2. Absorption of laminates after 6 months of conditioning in ON and Pb95
Rys. 2. Chłonność laminatów po sześciu miesiącach kondycjonowania w ON i Pb95

Flammability test

The ability of the examined laminate to absorb liquid fuels can indicate its flammability increasing over time, and consequently a greater fire risk to tanks subjected to the discussed repair method.

These predictions were verified by testing flammability of the laminate using the glow wire method according to PN-EN 60695-2-11:2015 [9] and the needle flame method according to PN-EN 60695-11-5:2017 [10]. The tests were performed on the laminate samples having the same structure as in case of the absorption tests, and subjected to the ageing process in the drying oven at a temperature of 70°C, and then stabilized at the room temperature for 48 h. The samples were aged in the presence of fuel, and without fuel (reference samples).

Glow wire test. In this procedure a temperature of the wire made of the alloy of nickel and chromium was recorded, at which the composite glowed or ignited for longer than 30 s from removing the wire from the sample. The time was measured after the contact between the wire and the laminate (Photo 5). The test was performed at the following temperatures of the wire: 500, 650, and 800°C. The test results are shown in Table 1. All samples aged in fuel were considered as flammable at a temperature of the wire equal to 650°C and higher.

Needle flame test. This procedure consisted in exposing the samples to flame for the specified time (Photo 6). According to the standard [10], the sample is considered to be non-flammable when it does not glow or

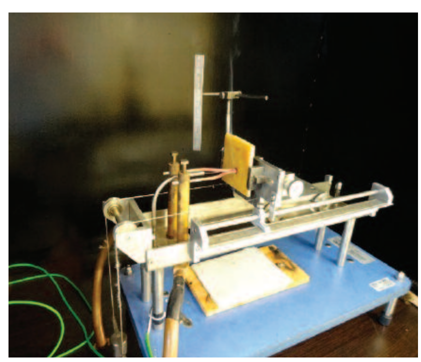


Photo 5. Determination of the ignition temperature of the laminate using the glowing wire method
Fot. 5. Oznaczenie temperatury zapalenia laminatu metodą rozżarzonego drutu

Table 1. Flammability test results using the glowing wire method
Tabela 1. Wyniki badania palności metodą rozżarzonego drutu

Sample symbol	Temperature of hot wire [°C] 500	650	800	Notes
	ignition or glowing within 30 s from removing the wire from the sample yes/no			
1 Z	no	no	yes	sample not aged in fuel (reference samples). Approx 2 mm depth of wire penetration into the sample
2 Z	no	no	yes	
1 ON	no	yes	yes	samples aged in ON; approx. 2 mm depth of wire penetration into the sample; samples at a temperature of 650° C or higher glow or burn emitting black smoke
2 ON	no	yes	yes	
1 Pb95	no	yes	yes	samples aged in Pb95; approx. 2 mm depth of wire penetration into the sample. Samples at a temperate of 650°C glow and emit slate-grey smoke, and at a temperature of 800°C they glow or burn emitting black smoke
2 Pb95	no	yes	yes	

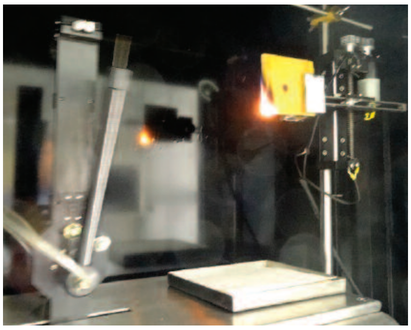


Photo 6. Flammability test using the needle flame method
Fot. 6. Badanie palności metodą płomienia igłowego

Table 2. Flammability test results using the needle flame method
Tabela 2. Wyniki badania palności metodą płomienia igłowego

Sample symbol	Exposure time to flame 15 s	30 s
	ignition or glowing within 30 s from extinguishing flame, yes/no	
1 Z	no	yes
2 Z	no	yes
1 ON	yes	yes
2 ON	yes	yes
1 Pb95	yes	yes
2 Pb95	yes	yes

ignite after the specified time of contact with the needle flame, or when the flame ignited on the element self extinguishes within 30 s after the needle flame is removed. The exposure time to flame was 15 and 30 s at the flame impact on the edge of the samples. The test results are presented in Table 2. All laminate samples conditioned in fuel did not show any signs of self--extinguishing within 30 s from removing them from the flame, which indicated that the laminate tested could be considered as flammable.

Conclusions

The ability of laminate coats to effectively protect steel surface against corrosion, which is based on experience of contractors who work such repairs, is their unquestionable advantage. The laminate application is intended to prolong the service life of fuel tanks.

The performed numerical analyses confirmed the potential of polyester--glass laminates in repairing corroded steel shells of underground double-wall tanks for liquid fuels. The application of the composite coat was demonstrated to improve strength parameters of the inner shell impaired by corrosion

The experimental tests, which involved the evaluation of porosity and absorption, showed that the laminate coat had a tendency ti absorb substances from fuel. The flammability tests conducted with two methods confirmed that the polyester-glass laminate should be classified into flammable materials propagating fire and smoke. The latter properties of the material tested is related to a serious fire risk to the tank after its strengthening. It should be also mentioned that the obtained results provide information only on flammability of the laminate. However, they cannot be considered as the base to evaluate the reaction of laminate strengthening in case of the tank fire. Such an evaluation requires further tests on the laminate coat with respect to changes in their properties after a long-term contact with fuel. The results from testing laminate coats from tanks operated for many years seem to be particularly useful. Such test results could also provide information concerning changes in the structure of laminates affecting parameters of mechanical strengthening with these laminates.

Owners of all Figures and Photos: Authors

Literature

[1] Rozporządzenie Ministra Gospodarki z 18 września 2001 r. w sprawie warunków technicznych dozoru technicznego, jakim powinny odpowiadać zbiorniki bezciśnieniowe i niskociśnieniowe przeznaczone do magazynowania materiałów ciekłych zapalnych (Dz.U. nr 113, poz. 1211).

[2] Rozporządzenie Ministra Gospodarki z 21 listopada 2005 r. w sprawie warunków technicznych, jakim powinny odpowiadać bazy i stacje paliw płynnych, rurociągi przesyłowe dalekosiężne służące do transportu ropy naftowej i produktów naftowych i ich usytuowanie (Dz.U. nr 243, poz. 2063).

[3] Sokólski W. 2015. Aspekty korozyjne stosowanych metod zabezpieczenia gruntu i wód podskórnych przed wyciekami paliw płynnych z nadziemnych i podziemnych zbiorników stalowych. Doroczna IX konferencja naukowo-techniczna Współczesne technologie przeciwkorozyjne.

[4] PN-EN 12285-1:2018-11 Zbiorniki stalowe wytwarzane fabrycznie – Część 1: Poziome cylindryczne zbiorniki jednopłaszczowe i dwupłaszczowe do podziemnego magazynowania cieczy palnych i niepalnych zanieczyszczających wodę, innych niż służące do ogrzewania i chłodzenia budynków.

[5] Masek R. Belzona 1212 – nowy kompozyt naprawczy na trudne warunki aplikacji. Ochrona przed korozją. Zeszyt 6. 2016.

[6] Lietard V. 1998. Study of the separate and coupled effects of a hydrothermal environment and mechanical loading on the long-term deformability and toughness of glass/resin composites. University of Lille.

[7] Aksielrud GA, Altszuler MA. Ruch masy w ciałach porowatych. Wydawnictwo Naukowo--Techniczne, Warszawa. 1987.

[8] PN-EN ISO 62:2008 Tworzywa sztuczne – Oznaczanie absorpcji wody.

[9] PN-EN 60695-2-11:2015 Badanie zagrożenia ogniowego – Część 2-11: Metody badań oparte na stosowaniu rozżarzonego/gorącego drutu – Metoda badania rozżarzonym drutem palności wyrobów gotowych.

[10] PN-EN 60695-11-5:2017 Badanie zagrożenia ogniowego – Część 11-5: Płomienie probiercze – Metoda badania płomieniem igłowym – Urządzenie, układ do próby sprawdzającej i wytyczne.

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