sciendo

DOI: 10.2478/rjti-2018-0007

ROMANIAN JOURNAL
OF TRANSPORT INFRASTRUCTURE

COMPARATIVE STUDY ON THE APPLICABILITY OF ANALYTICAL AND EXPERIMENTAL METHODS IN THE ANALYSIS OF THE SAFE USE OF RAIL TANKERS CARRYING PETROLEUM PRODUCTS UNDER PRESSURE

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Abstract

The safety of railways has been and remains a critical topic. Whether it is infrastructure or rolling stock, the issue of safety is a permanent concern of the utmost importance, being reflected in the efficiency of any transport system.

This paper focuses on the safety in operation of pressure vessels that equip railway tanks. There are many articles and works on this subject, and it is well-known that there are both national and international regulations regarding their design, execution, operation and maintenance. Also, there are quite a few reports on the BLEVE (Boiling Liquid Expanding Vapour Explosion) phenomenon resulting in material damage and significant casualties. The BLEVE-type explosion is not considered a chemical explosion derived from a gas-air explosive environment (also present in non-flammable gases), but rather a mechanical explosion through over-pressurization.

Thus, we propose a comparative study between the results obtained using theoretical methods and those obtained as a result of tensoresistive measurements on such a tanker.

Keywords: Rail tank, safety in operation, finite element method, tensometric measurements

1. OBJECTIVES, DEFINITIONS

The proposed objective is to determine the state of stress and the deformations occurring at the container of a railway tanker. The approach of this subject can be either an analytical one (analytical calculation, numerical methods) or by using experimental methods.

It is well known that the theoretical calculation of the stress and strain condition requires the acceptance of simplifying the assumptions with reference to the shape and structure of the item, the mechanical characteristics of the material from which the item is made, or even its loading and abutment procedures. Moreover, in our research, the material of the item on which the calculations are made is considered ideal: continuous, homogeneous, isotropic and perfectly elastic. In reality, these conditions are not fully met and, consequently, the results do not match real-life procedures.

Under these conditions, a mandatory requirement is the use of experimental methods for determining the stress and strain condition of the required bodies. In most cases, experimental methods are used in parallel with analytical methods. In fact, experimental methods are based on theoretical knowledge and on the resulting conclusions.

Both approaches have advantages and disadvantages. Used together, the two methods lead to very good results. Experimental results may confirm or invalidate analytical results.

Today, several experimental methods are known to determine the stress and deformation state of the required items. They can be applied to models or real structures under static or operating conditions, focusing on the influence of all the factors that affect their behavior.

2. OUTLINE OF PROPOSED METHODS

The investigation and expertise of the equipment in operation is made so that its proper functionality is not jeopardized. For example, pressurized fluid transport tanks are periodically checked and subjected to pressure tests. These tests consist of checking whether the tank casing being subjected to overpressure (about 1.25 maximum authorized operating pressure) remains in the elastic range, i.e. there are no residual deformations.

Arguably, by using this method the equipment is periodically subjected to overloading while, given its gauge, it is impossible to notice residual deformations of small values.

The problem becomes more complex when an estimate of their lifetime according to the legislation in force is required.

This paper proposes a comparative study of the analytical results and of those obtained from measurements on the behavior of such pressure tanks until a dangerous voltage (flow limit) has been reached.

The subject of the study is a rail tanker used for the transport of oil products under pressure. The tank was manufactured by the Chisinau Chemical Equipment Company in accordance with the national and RID regulations in force in 1977.

The main technical parameters of its design are the following:

Max working pressure	16 bar
Hydraulic test pressure	20 bar
Minimum working temperature	-250°C
Maximum working temperature	500°C
Volume	90 m^3
Inner diameter	2968 mm
Tank weight	16920 kg
Tank mass during hydraulic test	108000 kg

According to its manufacturing documentation, the material from which it was made was a structural steel whose minimum mechanical properties for one of the shells that make up the mantle are:

Breaking tensile strength at 200°C	480 MPa
Flow limit at the calculation temperature	600 MPa

2.1 Analytical method

2.1.1 Stress risk calculation

The design calculation of such equipment complies with reference standards and normative standards (SR EN 13445 in the present case)

Accordingly, the admissible voltage setting is defined as the minimum value between the Rc^{20} / cs1 and R / cs2 ratios where:

Rc^{20} = tensile strength at 20°C in MPa
R = flow limit at the calculation temperature
cs1 = safety factor (= 2.4)
cs2 = safety factor (= 1.5)

Following the dimensioning calculation, the resulting value is used to determine the minimum wall thickness of the tank, to which add-ons will be added for the operating conditions. For this case, the calculated thickness is 14 mm.

The problem is to see if, after a number of years of operation (when the thickness of the wall determined by ultrasound measurements is no longer the same as that from the date of manufacture), the tank can also be used in safety conditions.

For the tank under study, the minimum measured value was 12.4 mm.

2.1.2. Finite Element Method (FEM) analysis

The Finite Element Method (FEM) is one of the most powerful numerical methods used today in engineering. The tool becomes all the more powerful as this method has been used in design programs, thus enabling the simulation of static and dynamic behavior of the equipment in operation.

As far as the modeling itself is concerned, the Solidworks Simulation 2014 application has been used, which allows for several approaches, the main criterion being the use of "part" or "assembly" elements (a multiple-part structure);

However, it is also worth noting that the modeling criterion on the basis of which simplification results from using symmetry (which in this case is circular), in the modeling or discretization of the element to be studied.

Thus, by using a unique element (a part - without the use of symmetry) in the study, one arrives at the model in Figure 1, which only took into account its own mass.

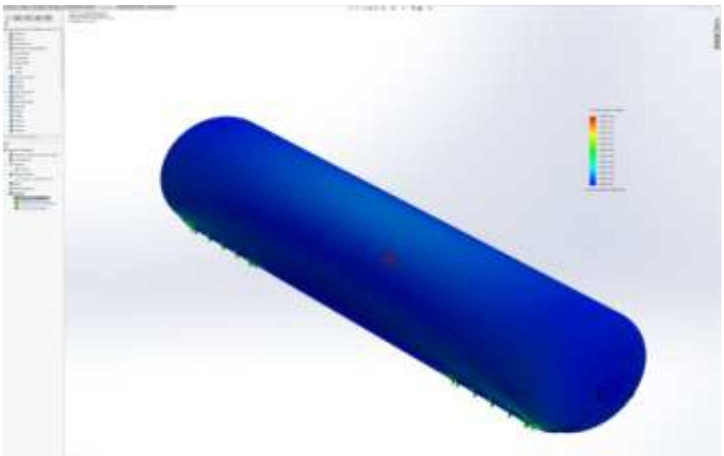

Figure 1. Model resulting from its own mass

Note that the model is made at a 1: 1 scale, considering that the thickness of the entire wall of the sheath is the minimum determined, i.e. 12.4 mm. At the same time, the values for the flow limit and the breaking strength are considered to be the same for all the tank components, being equal to the minimum values recorded in the manufacturing documentation (Figure 2).

The state of equivalent stresses (von Mises) for this situation is shown in Figure 2.

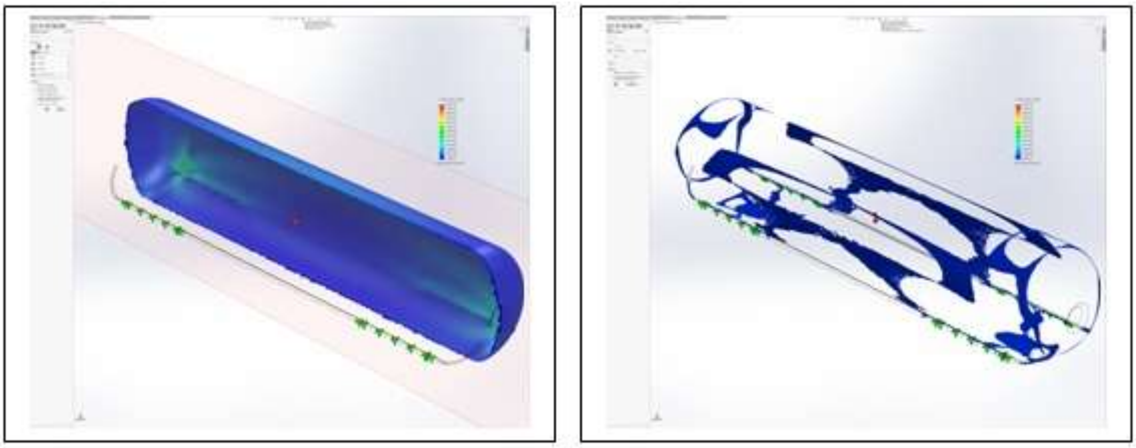

Figure 2. Equivalent stress state (von Mises)
a) section, b) distribution of values

Figure 2b is of ISO clipping type, used for viewing the value of interest in the coil / coat, allowing the assessment of the obtained value, depending on the simulation case under focus;

Studies have been carried out regarding water loading for pressure tests, as well as on the pressurizing condition at 20 bar (test pressure according to the technical documentation) and at a pressure of 50 bar.
The results are presented in Figures 3 and 4.

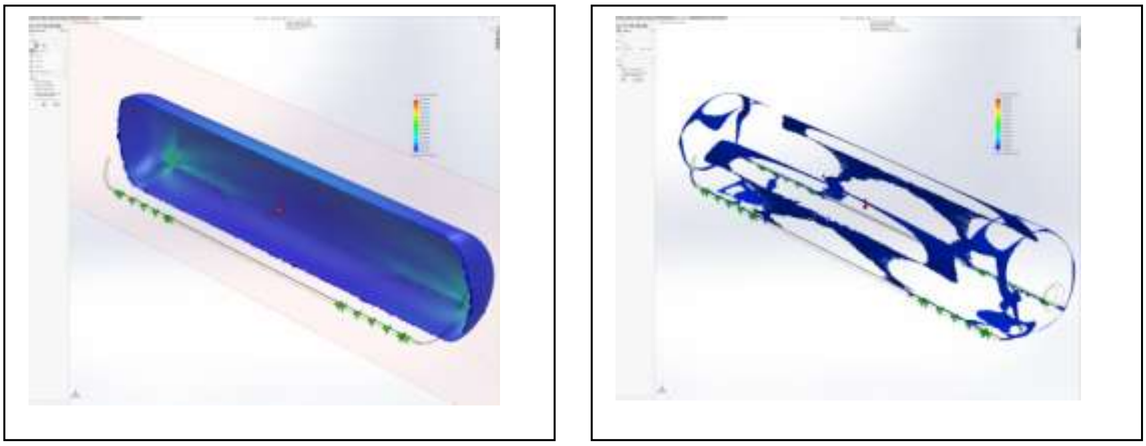

Figure 3. Equivalent stress state (von Mises) - pressure = 20 bar

It must be emphasized that, at a 20 bar pressure, the values close to the allowable voltage calculated according to EN 13445 can be achieved, i.e. 250 MPa. For the 50 bar pressure, both the flow and break limit are reached.

The objective of this study was also to highlight the most demanding areas, critical for the location of the tensometric marks for experimental determinations.

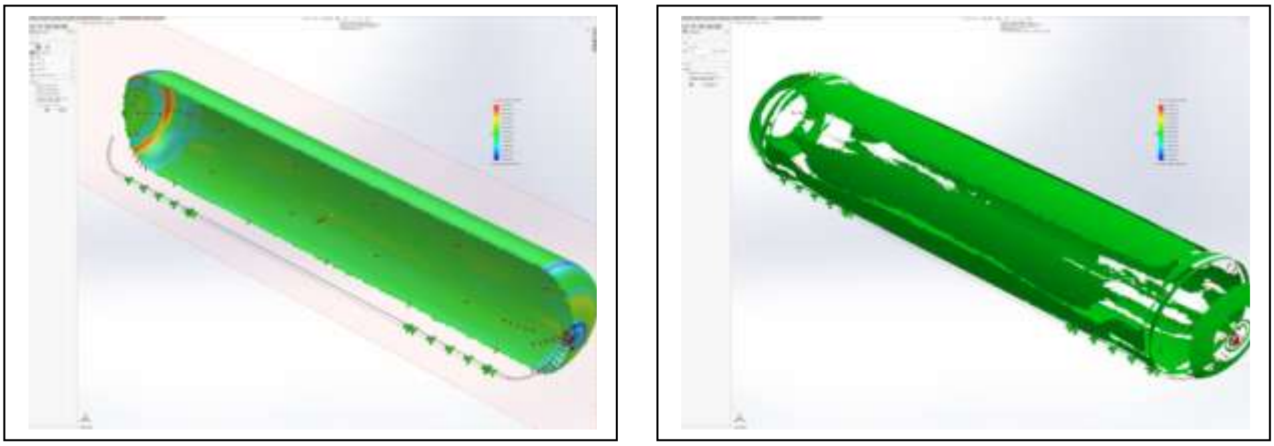

Figure 4. Equivalent stress state (von Mises) - pressure = 50 bar

2.2 Experimental method. Stress measurements under loading loads (resistive strain gauges)

The method of electro-resistive tensometric measurements is one of the most used experimental techniques and it takes into account the actual behavior of the material of the mechanical structure to be investigated. The option of applying this method is based on the fact that research can often be carried out on the structure under actual operating conditions.

It is well-known that, in the case of elastic stresses, for most materials, there is a linear relationship between specific deformations and strains. Above this stress limit, plastic deformations occur, and the relationship between specific deformations and stresses is no longer linear. In this area, the relationships that express the link between specific deformations and strains become very complicated.

As a result of the strain, elements are deformed, giving the rise of normal and tangential stresses (σ, τ). Direct experimental determination of voltages is impossible. Therefore, in order to reach strains through experimental means, we must first calculate the deformations produced by the strain, and then the strain value is calculated on the basis of the known theoretical relations between the specific deformations and strains.

The experimental study of the required elements generally consists of determining their deformations. The study can be performed on real equipment. In fact, deformation is a directly measurable and physically accessible phenomenon, while strain is an abstract measurement unit that cannot be measured directly.

The main disadvantage of the method is that it does not indicate the areas of the equipment which are mostly affected by the strain, a situation that has been overcome with the help of the previous study.

Starting from the geometrical and structural tank characteristics, and in order to determine the von Mises stress states, the chosen method has been to use three-directional markings (rings) for each measuring point (see Figure 5).

Figure 5. Tank with mounted markings

The equivalent normal tension (uniform equivalent unit effort) is established with the relation:

$$\sigma^{vonMises} = \sqrt{\sigma_1^2 + \sigma_2^2 - \sigma_1\sigma_2};$$

in which σ_1, σ_2 are the main normal unitary stresses for a thin-walled cylindrical container;

In this case, we have:

$$\sigma_1 = \sigma_{\theta\theta} = \frac{pr}{t};$$

$$\sigma_2 = \sigma_{xx} = \frac{pr}{2t},$$

where the pressure is rendered by p, while r is the radius of the container wall, and t is its thickness.

The placement of the markings is shown in Figure 6.

One of these (MTV2) is located on the skirt whose specified mechanical properties are also used in the analytical calculation, at an equal distance from the perimeter welding cords.

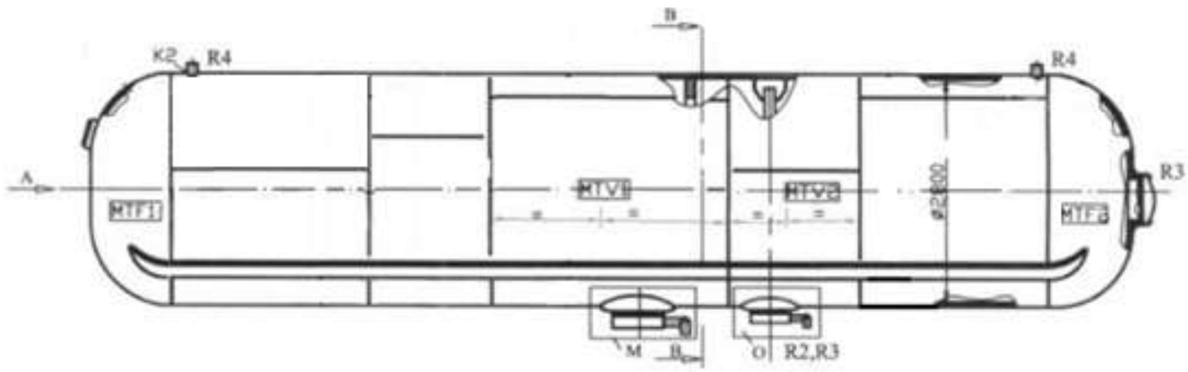

Figure 6. Location of measure points MTV 1,2 ; MTF 1,2

Figure 7 shows the variation of the displacements with pressure, for the four measuring points: two on the skirts and one for each ellipsoidal bottom.

Table 1 shows the maximum values set / measured for the same point determined by all three methods: the standard method, obtained analytically by applying the finite element method, or tensometrically measured.

Table 1. Comparative von Mises pressure values

POINT	Pressure (bar)	Values vonMises [MPa]		
		EN13445	MEF	Experimental
MTV1	20	240	195 - 235	210

	50	540	450 - 580	482
MTV2	20	240	195 - 235	268
	50	540	450 - 580	518
MTF1	20	240	195 - 235	197
	50	540	450 - 580	419
MTF2	20	240	195 - 235	156
	50	540	450 - 580	339

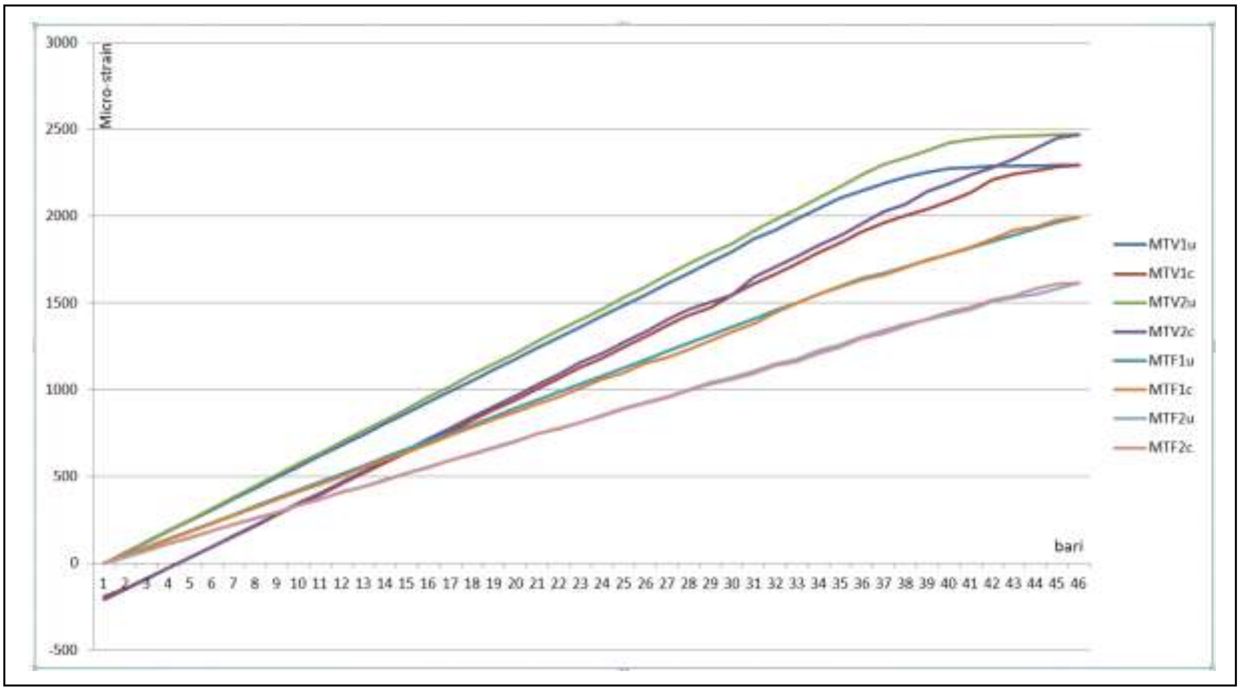

Figure 7. Variation of strain in relation to pressure

It can be noticed that the points located on the skirt results are not linear beyond a 34-35 bar pressure, which would correspond to reaching the limit of elasticity and transition into a plastic regime.

It can also be noted that, in the case of ellipsoidal supports, this limit is not reached, as they remain in the elastic range even at a pressure of 45 bar.

By studying the deformations which result during unloading, a hysteresis is also noticeable at the curve which has been previously mentioned, when the pressure rises and does not return to the starting point, which indicates the existence of important remanent deformations.

The results over 2 bar are considered to be extremely significant, as the water mass itself does not influence the results of the measurements made.

3. CONCLUSIONS

Increasing costs by applying such methods in expert programmes or even including them in maintenance programmes and in-service surveillance of installations might lead to a reluctance in their inclusion in current practice.

The authors of this study did not want to use statements such as "Safety in equipment operation and the lives of those who serve them have no price!". The aim we have been pursuing is to show the usefulness of applying such methods and how they can help to reasonably determine the lifetime of a piece of equipment, to establish the duration of periodic checks, the possibility of conducting a risk analysis, and last but not least, to determine specific sizes or properties of the materials used.

At the same time, we wanted to show the level of confidence that we can give to the results obtained by using such methods.

Thus, it is important to note that the values obtained by using the two methods are quite close. This does not lead to the idea that one method excludes the other.

It is worth mentioning that the modeling of the tank was made by considering that the entire thickness of its shell has the minimum measured value and the mechanical properties of the material are the lowest recorded.

A first conclusion is that the simultaneous application of the two methods leads to a highly reliable result, each method being an element of control over the other.

Under these conditions, we can have a real perspective on the tank's behavior during check-up, after a number of years of operation.

This is all the more useful as, unfortunately, there are examples of equipment on the market which no longer have the manufacturing manual, and are operated only according to a declaration of conformity, which in some cases may not be sufficient according to EU directives.

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