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# STRESS-STRAIN ANALYSIS OF THE PRESSURE VESSELS WITH THE APPLICATION OF LAWS OF SIMILARITY IN MECHANCS

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## ABSTRACT
*The topic of this paper is the possibility of application of the laws of similarity in mechanics and experimental measuring conducted on the model of stationary multi-chamber cylindrical tank, during stress and strain condition analysis on actual tank (pressure vessel). The paper will present the results of the experimental strain measuring and stress estimation at critical points of the model of the vertical multi-chamber cylindrical tank with partitions, by experimental testing using cold water pressure, reduced 20 times in comparison to the actual tank. By using law of similarity in mechanics we will be able to, based on measured micro-strains, transfer calculated stress results from the model to the original, i.e. to the actual tank with estimated size of Ø 24.384[mm] x 11.010[mm], and 5.000[m$^3$]volume capacity.*

**Keywords:** pressure, micro-strain, stress, welding, tank, model, original, similarity in mechanics.

## 1. INTRODUCTION

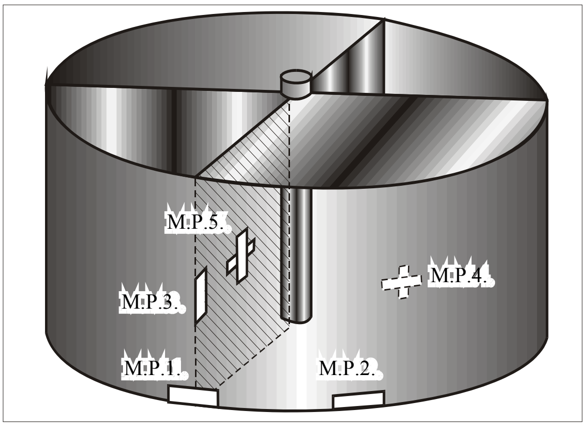
Examination of the selected welding technology was tested on the defined multi-chamber tank model [1]. A model of the overhead tank with 4 chambers with 20 times decreased dimensions (1:20) was constructed. The construction of the model was conducted according to the standards stipulated for the manufacturing of the overhead cylindrical tanks. For butt, angle and T weld joints we used E welding procedure (former mark REL) that has, through the analysis of the experimental results obtained by testing of standard and complex samples, given the best results. The model was constructed of the same material as the 5.000[m$^3$] volume tanks, i.e. steel plates of S.0361 quality. The model of the overhead tank is given in Picture 1.


*Picture 1. Model of the vertical cylindrical tank with partitions*

As the plate thickness cannot be decreased 20 times, due to chosen welding technology, it was decided that coat and partitions thickness of the model would be 2 mm. As a result of its particular nature in the part related to partitions and node points, and as the numerical analysis has predicted and indicated, multi-chamber tank belongs to the category of pressure vessels, what should be confirmed by appropriate examinations. Having in mind the working fluid as the optimally selected welding technology, during the cold water pressure testing (hydro testing), changes in stress and strain condition of the model tank were monitored in the zones that have been defined as the critical by the numerical analysis. Testing was conducted on the outer side by using tenzometric method (measuring tapes). The purpose of this testing is to, besides testing tank tightness, conduct the testing of the welded joints and base material by pressure that is 30-50% higher than the working (atmospheric) pressure.

## 2. STRAIN AND STRESS DETERMINATION USING MEASURING TAPES

In order to determine strain, as well as stress condition on one chamber of the overhead cylindrical tank model, on M.P.1 chain of measuring tapes 4/120 KY 11 was used (ten individual measuring tapes oriented across the range of overhead cylindrical tank), on M.P.2 chain of measuring tapes 4/120 KY 41 was used (five individual measuring tapes oriented across the height of the overhead cylindrical tank and five individual measuring tapes oriented across the range of the overhead cylindrical tank), on M.P.3 half of the measuring tape chain 4/120 KY 21 was used (five individual measuring tapes oriented across the range of the overhead cylindrical tank), while measuring rosettes 10/120 XY 91 were used on M.P.4 and M.P.5. Measuring tapes were attached according to the scheme given in Picture 2, and measuring was conducted in the unfavorable conditions, when one chamber is full, whereas two neighboring chambers are empty.




*Picture 2. Scheme of the attaching of the measuring tapes on the model tank*

Based on measured micro-strains on chains of measuring tapes, that is, on measuring tapes of the rosette, we calculate main stress using the following equations:

$$\sigma_{max} = \frac{E}{1-\nu^2}\cdot(\varepsilon_1 + \nu\varepsilon_2) = \sigma_1 \quad ; \quad \sigma_{min} = \frac{E}{1-\nu^2}\cdot(\varepsilon_2 + \nu\varepsilon_1) = \sigma_2 \qquad (1)$$

Effective nominal normal stress is: $\sigma_{ef} = \sqrt{\sigma_1^2 - \sigma_1\sigma_2 + \sigma_2^2}$ (2)

## 3. MEASUREMENT RESULTS

Strain measurement on the model was conducted gradually during the cold water pressure testing. Obtained measuring results and calculated stress values are given in the Table 1 for M.P.1, Table 2 for M.P.3, and measuring rosette for M.P.5. in Table 3.

*Table 1: Measured micro-strains and calculated stress for measuring point 1(M.P.1.)*

| Pressure bar | M/T 1 μm/m | Stress $\sigma_1$ MPa | M/T 2 μm/m | Stress $\sigma_1$ MPa | M/T 3 μm/m | Stress $\sigma_1$ MPa | M/T 4 μm/m | Stress $\sigma_1$ MPa | M/T 5 μm/m | Stress $\sigma_1$ MPa |
|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0.0 | -1 | -0.2 | 1 | 0.2 | 0 | 0.0 | 1 | 0.2 |
| 0,4 | 8 | 1.6 | 9 | 1.8 | 23 | 4.7 | 25 | 5.1 | 27 | 5.5 |
| 0,8 | 15 | 3.0 | 18 | 3.7 | 46 | 9.3 | 49 | 9.9 | 54 | 11.0 |
| 1,2 | 23 | 4.7 | 27 | 5.5 | 68 | 13.8 | 72 | 14.6 | 80 | 16.2 |
| 1,5 | 28 | 5.7 | 34 | 6.9 | 85 | 17.3 | 90 | 18.3 | 99 | 20.1 |
| 1,0 | 20 | 4.1 | 22 | 4.5 | 58 | 11.8 | 58 | 11.8 | 65 | 13.2 |
| 0,5 | 9 | 1.8 | 11 | 2.2 | 28 | 5.7 | 31 | 6.3 | 34 | 6.9 |
| 0 | 1 | 0.2 | -2 | -0.4 | 1 | 0.2 | -1 | -0.2 | -1 | -0.2 |

*Table 1: Continued*

| Pressure bar | M/T6 μm/m | Stress $\sigma_1$ MPa | M/T 7 μm/m | Stress $\sigma_1$ MPa | M/T 8 μm/m | Stress $\sigma_1$ MPa | M/T 9 μm/m | Stress $\sigma_1$ MPa | M/T10 μm/m | Stress $\sigma_1$ MPa |
|---|---|---|---|---|---|---|---|---|---|---|
| 0 | -1 | -0.2 | 0 | 0.0 | 1 | 0.2 | 1 | 0.2 | 1 | 0.2 |
| 0,4 | 29 | 5.9 | 31 | 6.3 | 33 | 6.7 | 32 | 6.5 | 34 | 6.9 |
| 0,8 | 58 | 11.8 | 61 | 12.4 | 65 | 13.2 | 63 | 12.8 | 67 | 13.6 |
| 1,2 | 86 | 17.5 | 91 | 18.5 | 97 | 19.7 | 94 | 19.1 | 99 | 20.1 |
| 1,5 | 106 | 21.5 | 113 | 22.9 | 120 | 24.4 | 117 | 23.8 | 123 | 25.0 |
| 1,0 | 75 | 15.2 | 79 | 16.0 | 83 | 16.8 | 81 | 16.4 | 86 | 17.5 |
| 0,5 | 37 | 7.5 | 38 | 7.7 | 40 | 8.1 | 38 | 7.7 | 41 | 8.3 |
| 0 | 2 | 0.4 | 2 | 0.4 | 1 | 0.2 | 3 | 0.6 | 2 | 0.4 |

*Table 2: Measured micro-strains and calculated stress for measuring point 3 (M.P.3.)*

| Pressure bar | M/T 1 μm/m | Stress $\sigma_1$ MPa | M/T 2 μm/m | Stress $\sigma_1$ MPa | M/T 3 μm/m | Stress $\sigma_1$ MPa | M/T 4 μm/m | Stress $\sigma_1$ MPa | M/T5 μm/m | Stress $\sigma_1$ MPa |
|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 1 | 0.2 | -1 | -0.2 | 1 | 0.2 | 0 | 0 |
| 0,4 | 32 | 6.5 | 36 | 7.3 | 38 | 7.7 | 34 | 6.9 | 29 | 5.9 |
| 0,8 | 62 | 12.6 | 69 | 14 | 73 | 14.8 | 65 | 13.2 | 61 | 12.4 |
| 1,2 | 94 | 19.1 | 107 | 21.7 | 110 | 22.3 | 98 | 19.9 | 90 | 18.3 |
| 1,5 | 116 | 23.5 | 131 | 26.6 | 136 | 27.6 | 124 | 25.2 | 113 | 22.9 |
| 1,0 | 79 | 16 | 84 | 17.1 | 88 | 17.9 | 84 | 17.1 | 77 | 15.6 |
| 0,5 | 38 | 7.7 | 45 | 9.1 | 48 | 9.7 | 43 | 8.7 | 35 | 7.1 |
| 0 | -3 | -0.6 | -3 | -0.6 | -2 | -0.4 | 2 | 0.4 | 2 | 0.4 |

*Table 3: Measured micro-strains and calculated stress for measuring point 5(M.P.5.)*

| Pressure bar | Tape 1 μm/m | Tape 2 μm/m | $\sigma_1$ MPa | $\sigma_2$ MPa | $\sigma_{ef.}$ MPa |
|---|---|---|---|---|---|
| 0 | -1 | 1 | -0.2 | 0.2 | 0.3 |
| 0,4 | 39 | 33 | 10.9 | 10.0 | 10.5 |
| 0,8 | 75 | 66 | 21.1 | 19.7 | 20.5 |
| 1,2 | 115 | 97 | 32.1 | 29.3 | 30.8 |
| 1,5 | 145 | 118 | 40.2 | 36.0 | 38.3 |
| 1,0 | 97 | 85 | 27.3 | 25.5 | 26.4 |
| 0,5 | 47 | 41 | 13.2 | 12.3 | 12.8 |
| 0 | 2 | 1 | 0.5 | 0.4 | 0.5 |

Measured strain in the zone of the selected measuring points on the cylindrical tank model and calculated stress indicate that in all measuring points yield strength was not exceeded, that is, stress is in the linear-elastic range. Measuring results obtained indicate that at the selected welding technology in the zone of nodal measuring point 1 at test pressure of 1,5 bar we acquired stress in range from 5,7 MPa to 25 MPa. On measuring point 2 calculated stress across height is extremely low and range from 4,9 MPa to 7,3 MPa, and does not present threat for the construction integrity. However, hoop stress is significantly larger and range from 23,5 MPa to 26,6 MPa, but this stress also does not present threat for overhead cylindrical tank construction. In the measuring point 3 zone, measured were strain and calculated stress condition on the outer side of the T welded joint of the tank model partition and jacket. Measured micro-strain and calculated stress at the test pressure of 1,5 bar range from 22,9 MPa to 27,6 MPa.
The highest measured main stress is at the measuring point 5 (approximately 40,2 MPa), what was expected, considering that fact that measuring tape was set in the middle of the partition. Next in size is stress at measuring point 4 (approximately 38,5 MPa). It is the point in the middle of the tank jacket, where strain across range is the highest, and minimum across height.

## 4. CONCLUSION

Information obtained during the model testing can be useful during the design of the multi-chamber 5.000 $m^3$ volume tank. In order to apply the results acquired by testing overhead cylindrical tank model (M) for the design of the overhead multi-chamber cylindrical 5.000$m^3$ volume tank (O), similarity mechanics is used, in respect to all specificities that are present when defining dimensions, material thickness selection and applied model production technology. The basic dimensions of the model were in ratio 1:20 to the original. However, the thickness of the used plates was not in this ratio, due to the welding specificity and ratio 1:6 was used for tank critical zones, including the thickness of the plate used for partitions.
As the testing pressure for testing of the overhead cylindrical tank model (M) was 1,5 bar, which is also the testing pressure for testing the tightness of the original tank (O), by using similarity in mechanics, that is, similarity theory model [3], as well as Laplace's equation [2], we were able to get the ratio of the stress in the model to the stress in the original tank from the following equations:

$$\sigma^O = \frac{p^O d^O}{2 s_p^{\ O}} \text{ (original)} \qquad \sigma^M = \frac{p^M d^M}{2 s_p^{\ M}} \text{ (model)} \tag{3}$$

By solving these equations at pressure p, and equalizing the pressure, we have:

$$p^O = \frac{2 s_p^{\ O} \sigma^O}{d^O} = p^M = \frac{2 s_p^{\ M} \sigma^M}{d^M} \tag{4}$$

Further solving of equations at stress $\sigma^O$, and depending upon stress $\sigma^M$ , follows:

$$\sigma^O = \sigma^M \frac{s_p^{\ M}}{s_p^{\ O}} \frac{d^O}{d^M} = \sigma^M \frac{1}{6} \frac{20}{1}, \quad \text{i.e.} \quad \sigma^O = \sigma^M \frac{10}{3} = 3{,}33.\sigma^M \tag{5}$$

$$\sigma^O_{max} = 3{,}33.\sigma_{max}^{\ M}, \quad \text{tj.} \quad \sigma^O_{max} = 3{,}33 \cdot 40{,}2 = 133{,}9 \text{ MPa} < \sigma_{doz}, \ \sigma_{doz} = 165 \text{ MPa}$$

The results of these measuring should foremost be accepted as approximate and examined with other, more reliable, methods. The reasons lie in the fact that, due to the application of appropriate welding technology it was not possible to apply ratio 1:20 when selecting plate thickness for model partitions and jacket (thickness is 2 mm, therefore plate ratio is 1:6), as well as the fact that the model was not simulated for the partition reinforcements with I-profiles, with the purpose of increasing bending rigidity of the entire tank model construction.

## 5. REFERENCES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