# Experimental Research on the State of Stress and Deformations of Cylindrical Structures Subjected to Internal Pressure

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***Abstract:*** *The paper presents the experimental results obtained from the tests carried out on a cylindrical body with variable geometry, subjected to an internal pressure in three steps. The present work discusses the case of a transition without fillet from a thickness of the wall to a smaller one of the cylindrical body, in which case the values of the normal strains and the corresponding stress are determined experimentally. In the present case, strain gauge method was used.*

***Keywords:*** *Normal strains, stress, tensometry*

## 1. Introduction

Pressured equipment is widely used in all industrial activities, as chemical plants, power plants, gas, fuel and utilities pipelines, etc. The intensive development of the economy requires intensive construction of new, and modernization of main pipelines, vertical and horizontal tanks, pressure vessels and apparatus, etc. Long time exploitation of pipelines and other cylindrical structures leads to their failure that can be accelerated by the internal and external conditions such as corrosion or erosion. The substances flowing or stored inside generally have chemical or erosive aggressiveness that is difficult to control, in association with high temperature and pressure parameters. This puts a challenge to engineers: to evaluate the progress of mechanical damage [1,2].

Damage processes may be initialized due to the accumulation of stress concentrators that may cause initiation and growth of surface cracks and finally may lead to failures. Structural failure in pipes occurs due to a diversity of causes. One of the causes is the formation of stress concentration zones in the pipe wall. These include surface defects [3-8] located inside or outside constructions, geometric discontinuities in static equipment: assemblies with flanges [9-21], jackets for heating/cooling [22-25], horizontal supports and/or vertical [24-30], dynamic - centrifugal equipment [33, 34] etc., but also shape deviations [35 - 37].

Industrial equipment for thermal and/or chemical processes are made with a particularly complex constructive configuration, characteristic for each practical case. Even if a single metal material or associations of different materials are used, it is often necessary to resort to a variable geometry of the walls (different thicknesses). The respective passages can be without, or with fillet, or progressively variable passage from one thickness to another. As a result, in the respective areas and in the neighboring portions, it is necessary to carefully analyze the stress state, to detect the maximum values and compare them with the minimum allowable strength, for the certification of the construction.

This article considers the determination of the stress manifested on the outer cylindrical surface of some areas with different geometries, using the strain gauge method.

Strain gauge method is an effective method for the practical verification of the state of mechanical stress in the situation of a technical system, which is difficult to analyze through analytical procedures, because it allows the measurement of normal strains in several directions and the application of analytical formulas corresponding to the theory of elasticity [38 - 40].

Strain gauge method is used in various fields, such as equipment engineering, the aerospace industry, the automotive industry and in materials research. This technique can be used to measure mechanical stress in materials such as metal, rubber, polymers, or composite materials.

## 2. Materials and methods

### 2.1. Description of the materials and methods used

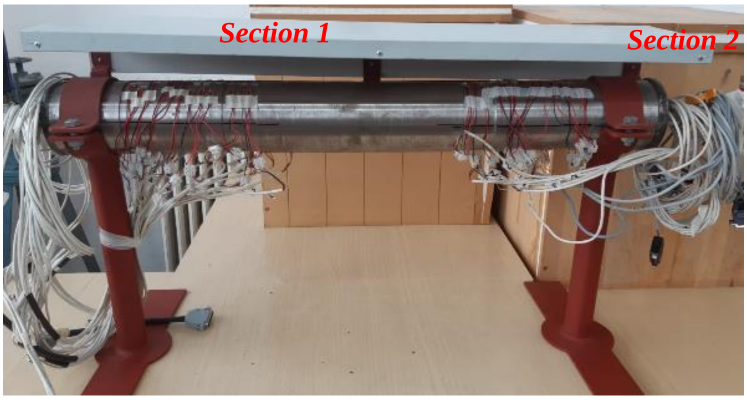
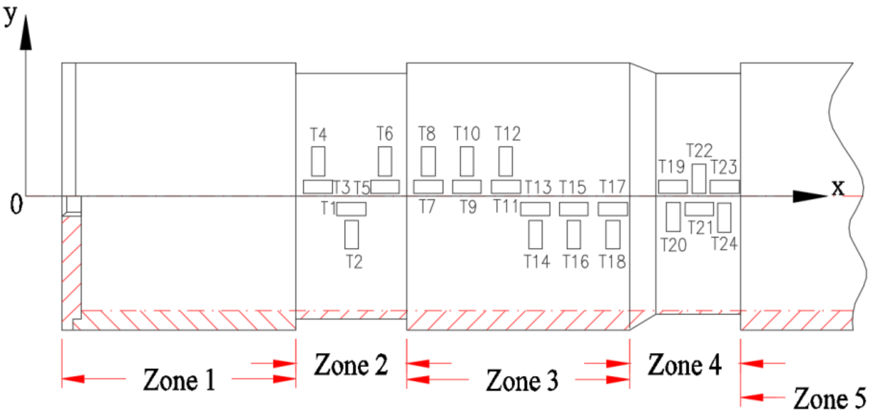



**Fig. 1.** Experimental model

For research purposes addressed in the present case, a model was created for carrying out the experiments. The design, manufacture, and assembly of the experimental model (fig. 1) were carried out in the laboratory of the Faculty of Mechanical and Mechatronic Engineering, Department of Industrial Process Equipment, within Politehnica University of Bucharest.
The construction material of the experimental model is P265GH, having the symbolization 1.4025, according to EN 10216 (yield stress $R_{0,2} = 388\ \mathrm{N/mm^2}$; ultimate tensile strength, $R_m = 542\ \mathrm{N/mm^2}$; elongation at break $A = 32\%$).
The other components and characteristics of the experimental model are as follows: pipe Ø 114.3 mm x 8 mm x 931 mm; cover Ø 114.3x10mm, 2 pcs.; pipe supports, 2 pcs.; equipment protection made of sheet metal with a thickness of 1mm; 2 connections 21/2"; supply valve 21/2"; Afriso manometer, $p_{max}$ = 4 MPa.


a)



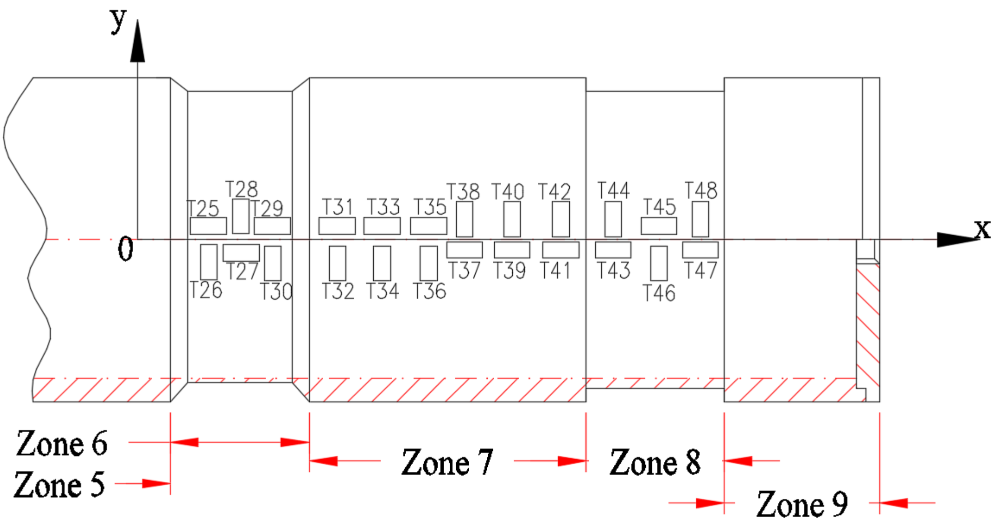

b)

**Fig. 2.** Experimental model - Section 1
a) Section 1; b) Sketch 1 – location of transducers 1, 2, 3 ... 24.

Transducers were placed on the experimental model according to figures 2 and 3. The model was divided into two sections: section 1 (left side – with pressure gauge) and section 2 (right side – with the power connection). The model was divided into 9 zones. Zones 1, 5 and 9 were zones of constant thickness, which no transducers were attached, and which, in the present work, were not considered for research. Zones 2, 3, 4, 6, 7 and 8 are zones of different thicknesses and different diameter variations, where transducers have been placed as follows:

- zone 2, with transducers $T_1 \dots T_6$, on the length $L_1 = 50\ mm$, the outer diameter of the pipe $\phi 109\ mm$;
- zone 3, with transducers $T_7 \dots T_{18}$, on the length $L_2 = 100\ mm$, the outer diameter of the pipe $\phi 113.5\ mm$;
- zone 4, with transducers $T_{19} \dots T_{24}$, on the length $L_3 = 50\ mm$, the outer diameter of the pipe $\phi 109.5 mm$;
- zone 6, with transducers $T_{25} \dots T_{30}$, on the length $L_4 = 50\ mm$, the outer diameter of the pipe $\phi 108.5 mm$;
- zone 7, with transducers $T_{31} \dots T_{42}$, on the length $L_5 = 100\ mm$, the outer diameter of the pipe $\phi 113.5\ mm$;
- zone 8, with transducers $T_{43} \dots T_{48}$, on the length $L_6 = 50\ mm$, the outer diameter of the pipe $\phi 108.5\ mm$.


a)




b)

**Fig. 3.** Experimental model - section 2
a) Section 2; b) Sketch 2 – location of transducers 25, 26, 27...48.

During the testing, the following cases were considered:
1. In case 1, an internal pressure was used in the equipment up to the value $p_1$ = 1 [MPa], after which it was discharged to the value 0 MPa.
2. In case 2, an internal pressure was used in the equipment up to the value $p_2$ = 2 [MPa], after which it was discharged to the value 0 MPa.
3. In case 3, an internal pressure in the equipment was raised to the value $p_3$ = 3 [MPa], after which it was discharged to the value 0 MPa.

With the help of the MGC plus tensometric bridges, specific linear deformations in the radial direction and in the circumferential direction, at the above-mentioned up/down pressures, were obtained.
The calculation of the stress on each area of the experimental model, depending on the internal pressure, was carried out with the formulas from [36 - 38]:

$$\sigma_{1j} = \frac{p \cdot R_{mj}}{2 \cdot \delta_j}, \quad \sigma_{2j} = \frac{p \cdot R_{mj}}{\delta_j}, \tag{1}$$

where $p$ is the internal pressure;

$$R_{mj} = \frac{R_{ej} + R_i}{2}, \tag{2}$$

where $R_{mj}$ - the average radius of the considered cylindrical part,
$R_{ej}$ - the outer radius of the section "$j$",
$R_i$ - the inner radius of the section "$j$".

and:

$$\delta_j = R_{ei} - R_i, \tag{3}$$

where $\delta_j$, the thickness of the zone where the strain gauges were placed.
According to the experimentally processed data, the specific linear deformations $\varepsilon_{1j}$ (μm/m) and $\varepsilon_{2j}$ (μm/m), respectively the values of the stress $\sigma_{1j}$ and $\sigma_{2j}$, using the relations [36 - 38] :

$$\sigma_{1j} = \frac{E}{1-\mu^2} \cdot \left(\varepsilon_{1j} + \mu \cdot \varepsilon_{2j}\right) \left[N / mm^2\right], \tag{4}$$

$$\sigma_{2j} = \frac{E}{1-\mu^2} \cdot \left(\varepsilon_{2j} + \mu \cdot \varepsilon_{1j}\right) \left[N / mm^2\right], \tag{5}$$

where E - the modulus of longitudinal elasticity (Young's modulus), in N/mm$^2$, $\mu$ - the transverse contraction coefficient (Poisson's ratio), $\varepsilon_{1j}$ , $\varepsilon_{2j}$ - the normal specific linear strains in the radial and circumferential directions, determined on the length of the cylindrical section " $j$ ", in µm/m.
The equivalent von Mises stress, in each zone, were calculated with the formula [36 - 38]:

$$\sigma_{ech\,j}^{IV} = \sqrt{\sigma_{1j}^{\ 2} + \sigma_{2j}^{\ 2} - \sigma_{1j} \cdot \sigma_{2j}} \,. \tag{6}$$

### 2. 2. Equipment used

The following equipment was used for the experiments:

1. Test stand (fig. 4);

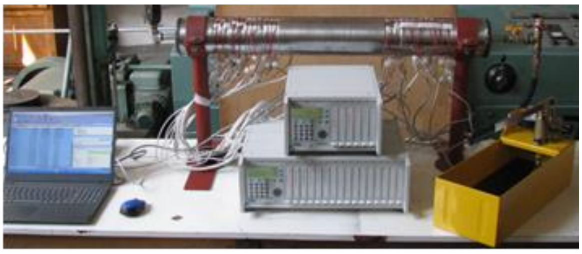


**Fig. 4**. Test stand

2. Pump with pressure gauge (fig.5);

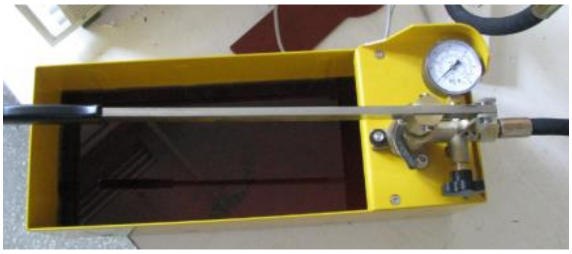


**Fig. 5.** Pump

3. MGCplus 1 and MGCplus 2 equipments (fig.6), necessary for data acquisition (MGCplus 1 acquired 40 measurement points, and MGCplus 2 acquired 8 measurement points).
4. Lenovo laptop (fig. 7) with Catman Easy software, necessary for the acquisition of experimental data.


**Fig. 6.** MGCplus 1 and MGCplus 2 equipment

**Fig. 7.** Lenovo laptop

### 3. Experimental results

The resulting theoretical equivalent stress, $\sigma_{ech\,t}$, calculated with formula (6), respectively relations (1), along the length of Section 1 (zones 2, 3 and 4) and along the length of Section 2 (zones 6, 7 and 8), are presented in Table 1:

**Table 1:** Equivalent stress calculated in the 6 zones

| Pressure [MPa] | Zone 2 | Zone 3 | Zone 4 | Zone 6 | Zone 7 | Zone 8 |
|---|---|---|---|---|---|---|
| | $\sigma_{ech\,t}$ [MPa] | | | | | |
| $p_1 = 1$ | 8.39 | 6.03 | 8.03 | 8.78 | 8.99 | 5.89 |
| $p_2 = 2$ | 16.78 | 12.07 | 16.07 | 17.56 | 17.98 | 11.78 |
| $p_3 = 3$ | 25.17 | 18.10 | 24.10 | 26.34 | 26.97 | 17.67 |

The theoretical equivalent stresses, calculated along the length of each section, without concentrations influenced by discontinuities, are used for comparison with the values of the experimental equivalent stresses in the different sections shown in Figures 8-13.
Figures 8-13 show only the calculations corresponding to each section, where the strain gauges have been glued.
Figures 8-13 show the experimental equivalent stress variations, calculated with formula (6), along the length of Section 1 (zones 2, 3 and 4) and along the length of Section 2 (zones 6, 7 and 8) – in sections with strain gauges.

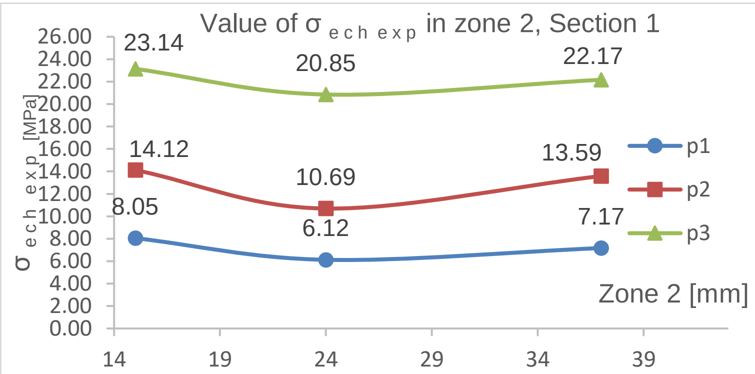



**Fig. 8.** The values of the experimental equivalent stress in zone 2, Section 1

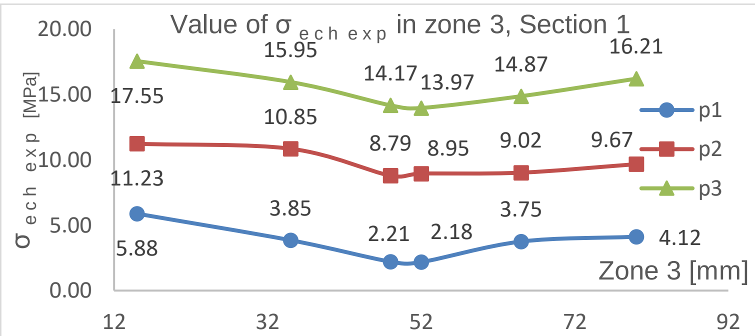



**Fig. 9.** The values of the experimental equivalent stress in zone 3, Section 1

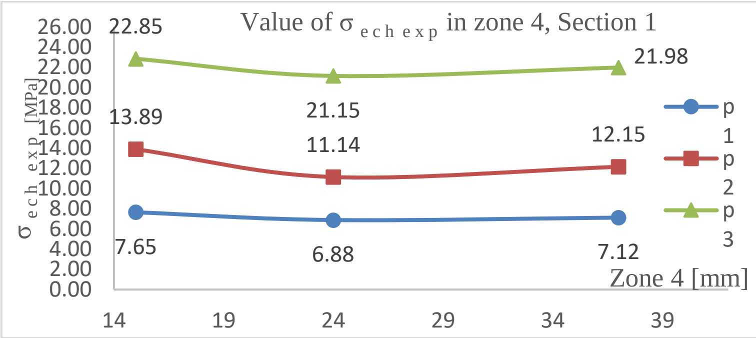



**Fig. 10.** The values of the experimental equivalent stress in zone 4, Section 1

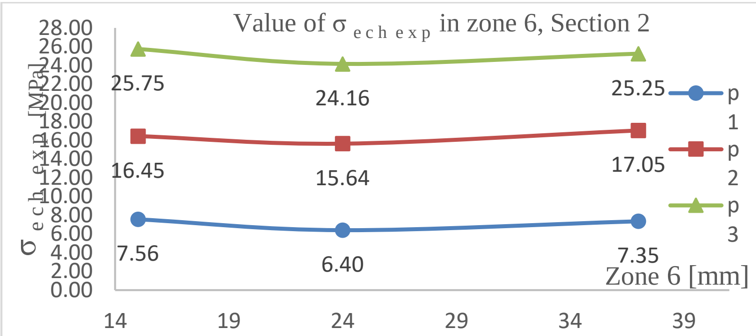



**Fig. 11.** The values of the experimental equivalent stress in zone 6, Section 2

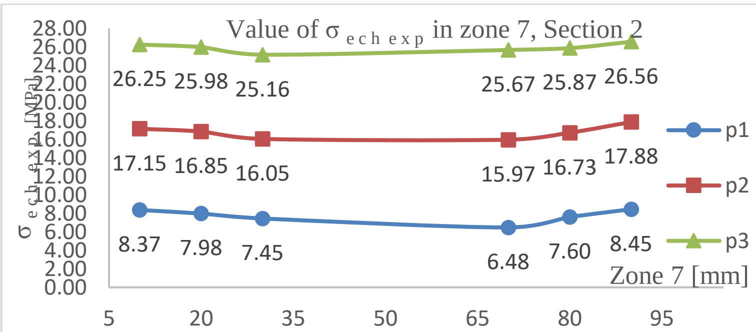



**Fig. 12.** The values of the experimental equivalent stress in zone 7, Section 2

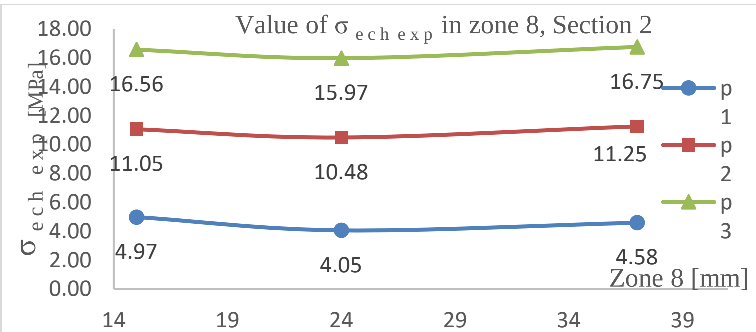



**Fig. 13.** The values of the experimental equivalent stress in zone 8, Section 2

The experimental results obtained in this work, showed that when the internal pressure increases, there is a gradual increase in the values of specific linear strains, meridional (axial) stress and annular (circumferential) stress; respectively the equivalent stress, established based on the fourth strength theory.

Finally, the maximum value of the equivalent stress, for given conditions, working pressure and temperature, can be compared with the resistance/allowable stress, characteristic of the material from which the cylindrical body is made.
It is observed that for all analyzed areas, the values of the measured equivalent stress are lower than the values of the theoretical equivalent stress. For example, in zone 7, for the pressure $p_2 = 2\,MPa$, the value $\sigma_{ech\,mas} = 15.97\,MPa \quad < \quad \sigma_{ech\,t} = 17.98\,MPa$.
The experiment was carried out under normal working conditions and at ambient temperature.

## 4. Conclusions

From the interpretation of the obtained results, it can be observed that with an increase in the internal pressure, the value of the stress in the radial and annular direction also increases.
The normal strains in the two directions, radial and annular, were automatically recorded with the help of MGC plus strain gauges. Based on the recorded values, the axial and annular stress, respectively the equivalent stress, were calculated. *It is noted that the experimental values of equivalent stress are lower, than the membrane equivalent stress.* The differences are insignificant, within the present experiment.
Considering the results obtained, the development of research in the field is encouraged, by further evaluating a methodology for the analytical study of specific linear strains and stress, considering progressive thickness transitions or appropriate fillets. In this sense, the method of finite elements can be used, respectively the method of short structural elements. The results obtained by means of the mentioned study variants can be compared in value, to establish the maximum safety in the operation of a cylindrical body-type pressurized equipment, during design or during operation. In this way, the actual duration of operation is evaluated, in each case.

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