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SIMPLIFIED MODELING OF STRESS AND DEFLECTION LIMIT STATES OF UNDERGROUND TANKS

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ABSTRACT: Fuel tanks are designed with regard to standard actions and operating conditions. The work analyses the impact of corrosion and other means to variation of stresses and deformation of a horizontal underground tank shell. The computations are preliminary. Due to the long computational time of the entire tank the analysis is restricted to its part only. The full analysis is bound to assess structural reliability, further allowing for its optimization.

Keywords: underground fuel tanks, shell corrosion, non-standard actions

1. INTRODUCTION

Pressure tanks belong to the most responsible structures in the present design. Possible failure affects a huge financial loss due to the loss of stored or processed material, technological breaks and tank refurbish, it also affects human health and life. The consequences of failure may be as well environmental due to the medium exposition into the surrounding environment, possibly bringing environmental degradation like ground water pollution, etc.
The present EU regulations bring the so-called pressure directive PED with a requirement to satisfy basic safety conditions in Appendix I to the directive 2014/68/UE. To assure the accordance of pressure tank design with the PED directive the designer may apply a set of standards harmonized with the code, e.g. EN 13445, or other standards to assure fulfilling the directive requirements e.g. The Conditions of Technical Supervision Agency (WUDT) or ASME Boiler and Pressure Vessel Code and other. All the enlisted standards emphasize the operational safety and durability of tanks. The prior assumptions state that relevant ultimate and serviceability limit states and appropriate structural solutions assure a proper safety level and durability. None of the sources distinguishes the way the safety level is quantified.
The answer may be partial or an entire application of Eurocodes, say, EN 1990 - Fundamentals of structural design and EN 1993-4-2, Eurocode 3 - Design of steel structures, the standards of the Eurocode series.

The EN 1990 code regards structural safety in terms of its reliability, introducing the reliability index beta. The index is affected by the so-called consequence class: CC1 (the lowest), CC2, and CC3 (the highest). The standard allows for introducing partial safety factors, moreover, it allows estimating the index beta and comparing it with the limit value included in Table 2 of EN 1990.
The FE models of fuel tanks should exceed the deterministic analytical standards for perfect structures, to consider the issues like material and geometric imperfections and post-welding stresses [Rasiulis et al. 2006]. The problem of determining the limit values of the parameters of imperfections and their impact on the stress/strain state of a shell structure is the subject of many papers, e.g. [Rotter, 2011, Górski et al. 2015, Górski et al. 2020].
It is important that the pressure tanks (pressure devices covered by the directive PED) are assumed the CC3 class. Thus we are able to state that taking a 50 year reference period the reliability index of pressure tanks is estimated 4.3, corresponding to failure probability lower than 0.00001. Hence it is reasonable to assess the structural reliability of the tanks designed by the non-Eurocode standards [Gwóźdź & Michałowski 2012, Kamiński & Świta 2015]. Reliability assessment is incorporated to address the impact of corrosion-based degradation [Geary & Hobbs, 2013].
The work presents a preliminary analysis of a simplified model of an underground fuel tank. Some parameters are selected, e.g. softening (thickness reduction) of sheets because of corrosion [Melchers 2010] and the number of stiffeners, and a check is completed of their impact on critical states due to negative pressure.

2. THE UNDERGROUND FUEL TANK MODEL

The analysis concerns a standard underground storage horizontal tank. The tank length is 72599 mm, outer diameter 5600 mm (Fig. 1). Spherical end caps are assumed for the analysis. The base material used for tank manufacture is steel P355NL2, 28 mm thick for cylindrical shell and 26 mm thick for the caps. The cylindrical shell is stiffened with 13 T-shaped rings. The tank features five manholes in the upper tank region.
The commercial engineering software allows to perform LBA (Linear Bifurcation Analysis) and GMNA (Geometrically and Materially Non-linear Analysis) [Hotała et al. 2014]. While the tanks are often loaded by negative pressure, it is crucial to consider imperfections during analysis i.e. GNIA (geometrically non-linear analysis of imperfect structures) or GMNIA (geometrically and physically non-linear analysis of imperfect structures). This sort of sensitivity and reliability assessment is complex and time-consuming.
The work presents preliminary analysis of a half shell. It is aimed at sensitivity assessment of the structure to cross-sectional variations, e.g. in the case of corrosion, including the non-uniform case.

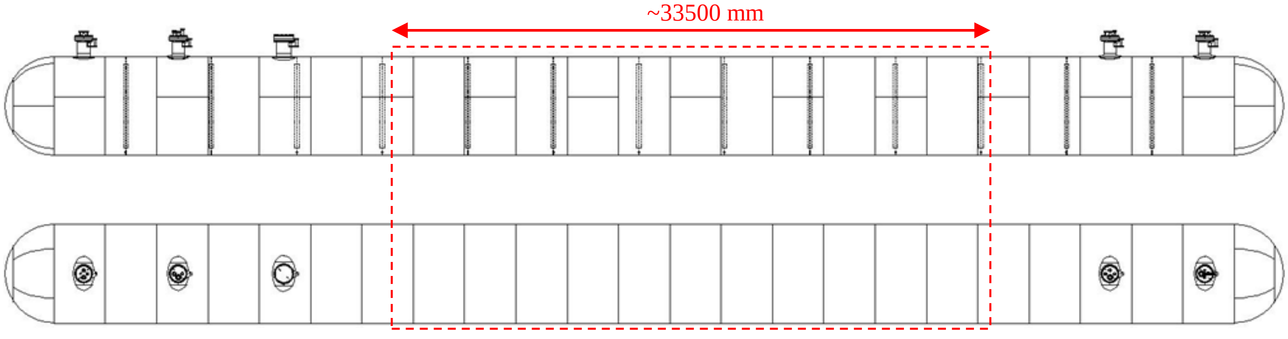
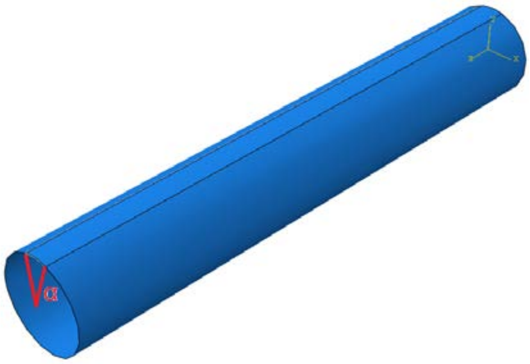


Fig. 1. Example - the analysed underground fuel storage tank

3. THE TANK FEM MODEL

The preliminary analysis was completed of the simplified tank models (Fig. 2). The computations are performed for the cylindrical shell with the following parameters: length L=33500 mm (half of the real tank length) and diameter d_c=5600 mm (Fig. 1). The computations are conducted using the ABAQUS software [Smith 2009]. The model incorporates 37632 shell elements. Simplified boundary conditions are modelled by restraining the translations at both edges. This modelling pattern of boundary conditions is possible because of specific loading, i.e. negative pressure. The edges of a simplified tank model are stiffened (Fig. 1), and it is possible to represent them by restraint upon all modes. Negative pressure was assumed of an initial value of $p = -1.0$ MPa. The negative pressure multiplier p was investigated to yield global or local stability loss [Burkacki et al. 2013]. The computations are directed to the corrosion check by means of sheet thickness reduction in the case of overall or partial tank analysis. The influence of stiffener spacing was also analyzed.



a)

b)

Fig. 2. Simplified models of an underground fuel tank (ABAQUS) without ribs (a) and including stiffening ribs (b).

The following variants of tank loading are assumed (Fig. 3):

a) internal radial pressure p_n,

b) compressive load in the longitudinal direction, the derivative of internal pressure p_x,

c) the combination of internal radial pressure p_n and compressive load in longitudinal direction p_x.

The longitudinal load p_x is a function of radial load p_n:

$$\pi R^2 p_n = 2\pi R p_x \quad \rightarrow \quad p_x = 1400\, p_n$$

where R is the tank radius.

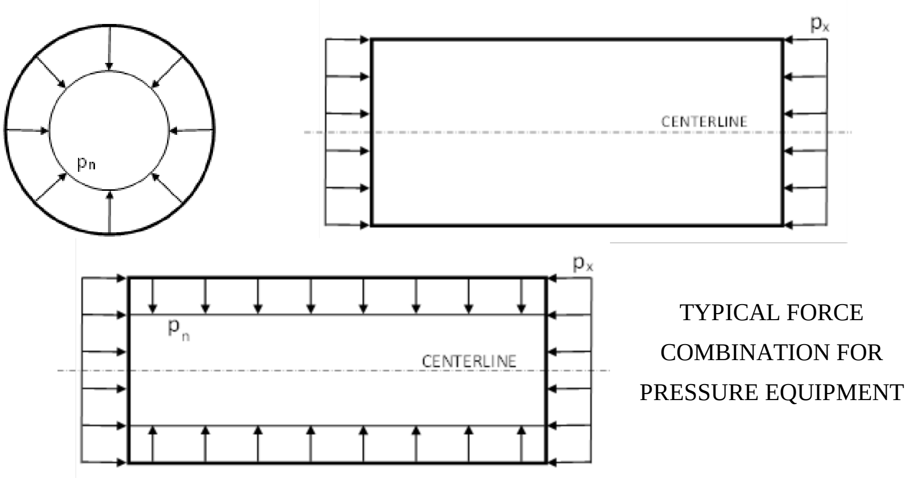


Fig. 3. Three loading variants of a tank (details in the text)

4. THE RESULTS OF SENSITIVITY ANALYSIS

The following computational variants were conducted:

1) unstiffened cylindrical shell with uniform thickness, the impact of the overall tank thickness variation to buckling,

2) unstiffened cylindrical shell with a constant basic thickness equal 28 mm, reduced thickness along the generating line, the reduced strip is denoted by the angle α = 30, 90, 180 [deg].

3) stiffened cylindrical shell with a variable number of stiffeners (1, 2, 3, 6) impact analysis of the number of stiffeners to buckling.

Figures 4 and 5 compare the critical pressure results with regard to variable sheet thickness *t* and two different loading schemes. The variation of sheet thickness *t* reflects the corrosion processes which may happen in a long-term tank operation. It was assumed that the reduction of sheet thickness is uniform throughout the entire shell.

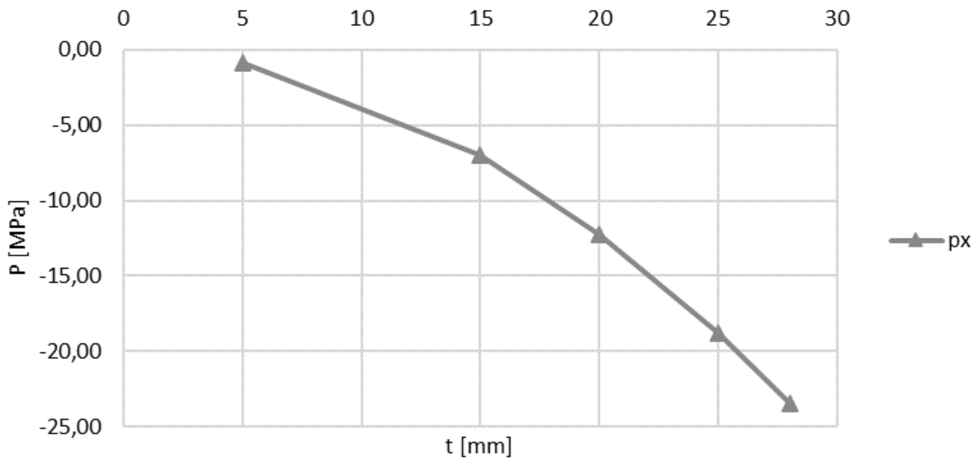


Fig. 4. Unstiffened cylindrical shell with uniform thickness: the impact of sheet thickness *t* on critical pressure p_x

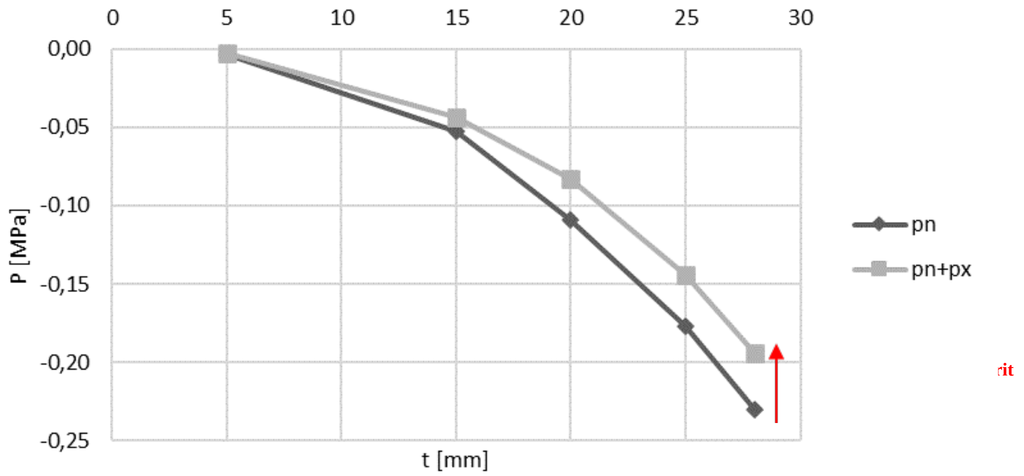


Fig. 5. Unstiffened cylindrical shell with uniform thickness: the impact of sheet thickness *t* and two different loading patterns on critical pressure p_n and p_x

The preliminary computations concerned a perfect tank, free of geometric imperfections. A high impact was observed of longitudinal load p_x (Fig. 4), radial load p_n and the combination of both p_n and p_x (Fig. 5). A 20% critical pressure drop is observed in the combination case of p_n and p_x. The computations proved the necessity to consider these loads in the analysis of pressure tanks. The examples of type the computations are included in Fig. 6.

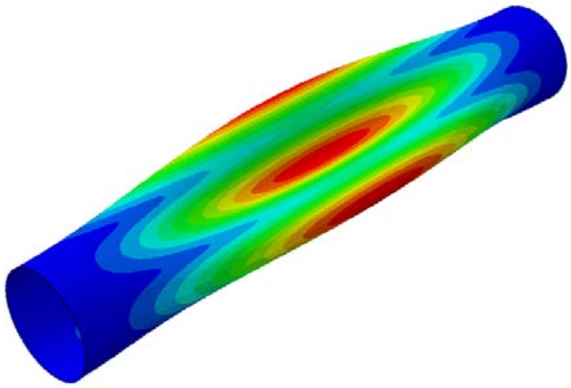


Fig. 6. Buckling modes of a tank subjected to uniform corrosion (ABAQUS).

The second analysed model consider corrosion on the part of a tank shell only. The computations define the weakened part by the angle α (Fig. 7).

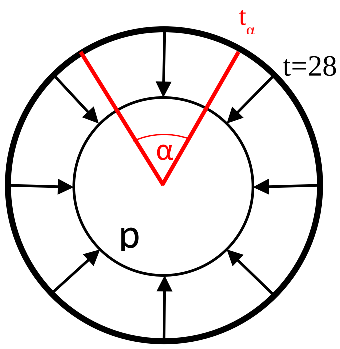


Fig. 7. Illustration of the assumed shell part of reduced sheet thickness (the impact of corrosion process)

Figure 8 presents the diagrams of breaking load change with regard to tank shell thickness.
In this case the critical state involves a local buckling mode. This mode ($\alpha = 30^{o}$) is presented in Fig. 9.

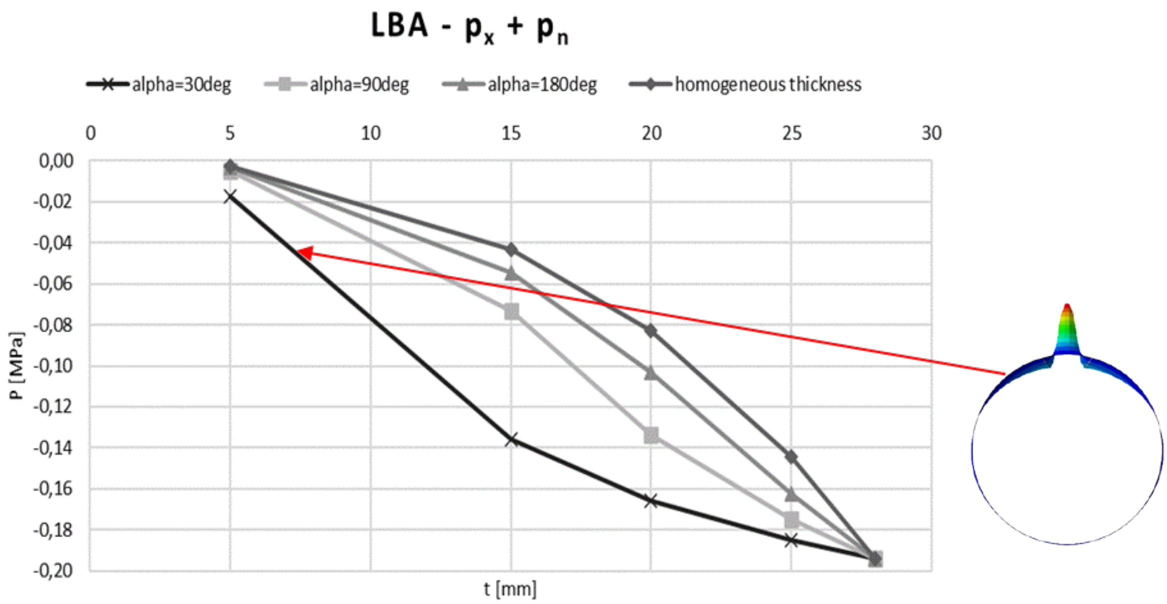


Fig. 8. Unstiffened cylindrical shell with partially reduced thickness: the impact of range and thickness reduction on the critical load

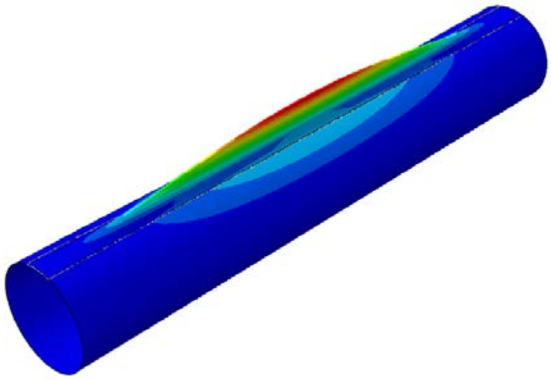


Fig. 9. Unstiffened cylindrical shell with partially reduced thickness: buckling mode of a tank subjected to corrosion covering part of the tank α = 30 deg

The third computational series is intended to check the necessary number of stiffeners preventing the tank from reaching its critical states. Assuming an optimal spacing between the stiffeners is essential to assess the mechanical response of the structure to negative pressure. Figure 10 shows the impact of the number of stiffeners on the critical pressure calculated by LBA.

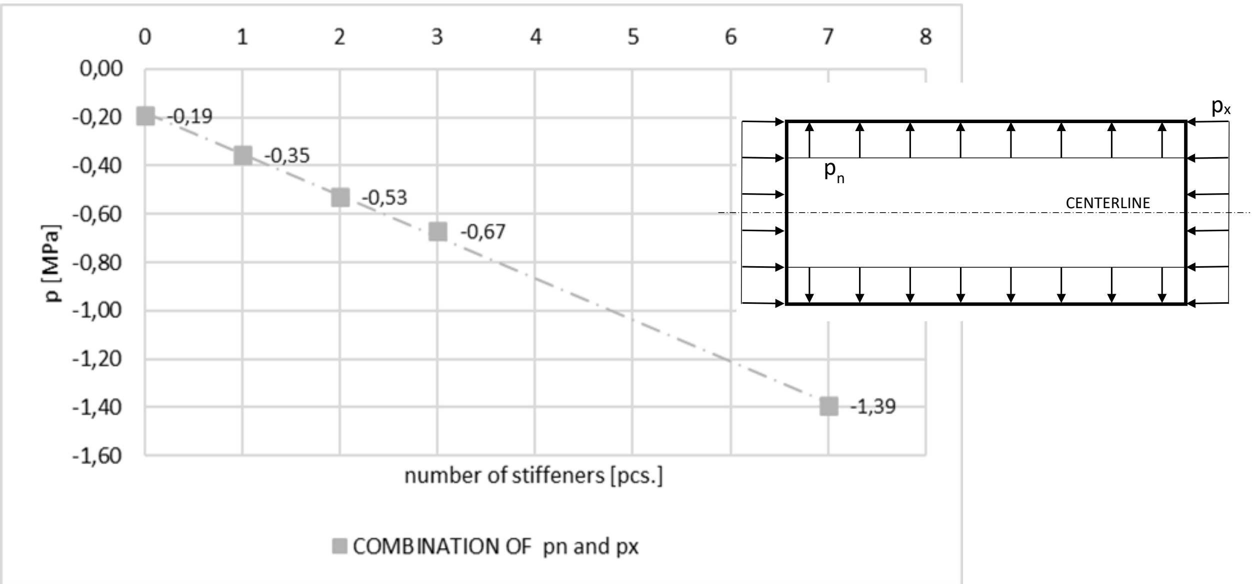


Fig. 10. Unstiffened cylindrical shell with uniform thickness: the impact of the number of stiffeners on the critical pressure (ABAQUS).

The computational results presented in Fig. 10 allow to conclude the following:

– linear relation is achieved between the critical pressure and the number of stiffeners in each loading scheme,

– in the case of internal pressure of the models with a single stiffener and seven rings a 700% rise of critical pressure is observed,

– a 6% rise of critical pressure is denoted in the case of longitudinal compressive force for the models with one and seven stiffeners

The last stage of the preliminary analysis compares the design critical stresses of the stiffened cylindrical shell subjected to longitudinal compressive force and internal pressure. It is shown(Fig. 11) that the critical stresses due to the standard formula is higher than the corresponding numerical result.

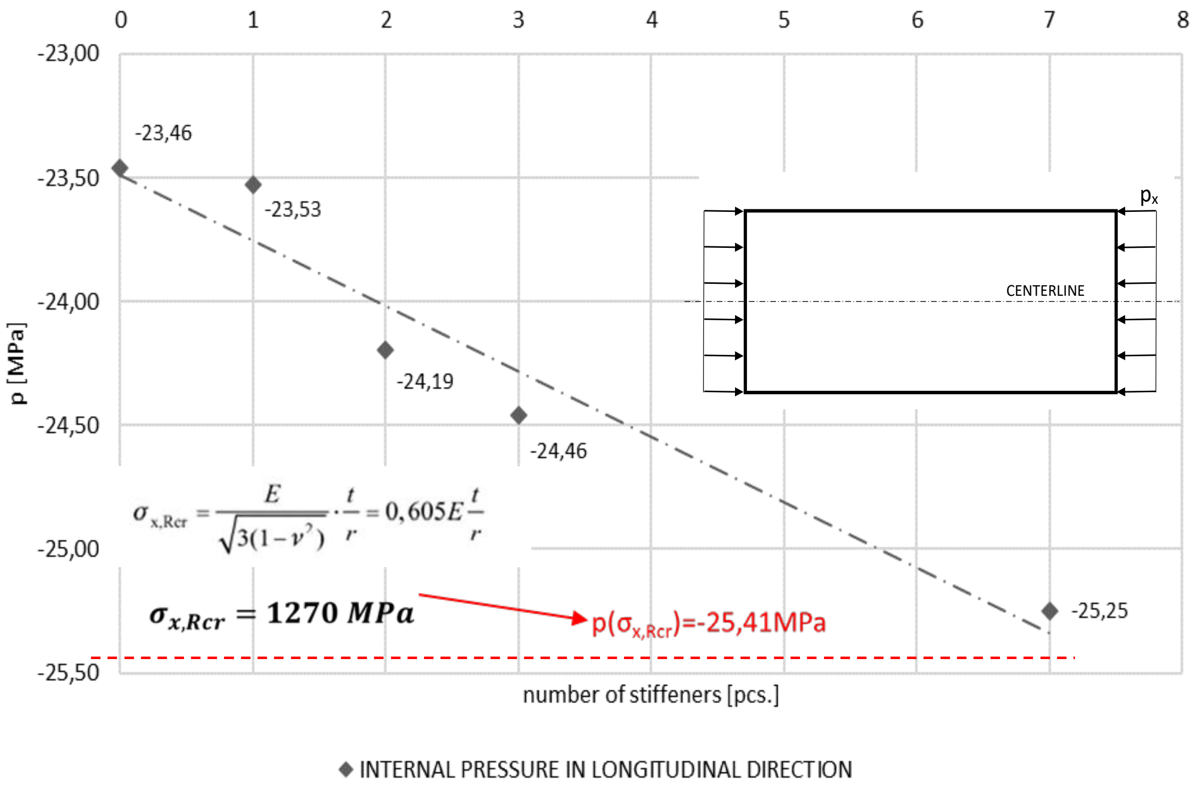


Fig. 11. Critical load of the stiffened cylindrical shell subjected to longitudinal compressive force and internal pressure in function of stiffeners number

5. CONCLUSIONS

Preliminary analysis of this tank proved the following:

– the variation in tank thickness decreases the negative pressure bringing stability loss,

– local reduction of shell thickness yields reduction of negative pressure causing stability loss,

– while the difference between the nominal shell thickness and its reduced value is substantial local stability loss occurs in the reduced thickness region,

– the use of reinforcing stiffeners of appropriately high stiffness increases the cylinder load-carrying capacity, and the required negative pressure to yield stability loss is higher than the one for the unstiffened shell.

The conducted computations and further conclusions are bound to accelerate the computations in the complex FEM model.

6. ACKNOWLEDGMENTS

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