# DEFORMATIONS OF THE STEEL SHELL OF A VERTICAL CYLINDRICAL TANK CAUSED BY UNDERPRESSURE

Розрідження в резервуарі з фіксованим покриттям може виникнути на завершальній стадії будівництва, а також у процесі його експлуатації. Після завершення будівництва, коли резервуар порожній і всі люки та клапани, через які повітря може потрапити в резервуар, щільно закриті, вакуумeтричний тиск може виникнути у разі різкої зміни погоди – тиску і температури повітря, що особливо небезпечно навесні або влітку.

У процесі експлуатації резервуара розрідження може виникнути, якщо дихальні клапани перекриті, наприклад, покриті снігом під час відкачування продукту, що зберігається в резервуарі .

Вакууметричний тиск може викликати значні деформації оболонки або покриття резервуара. Однак, оболонка піддається деформації частіше, оскільки покриття має жорстку опорну конструкцію.

У статті представлено стадії деформації оболонки резервуара і їх розвиток, починаючи від появи першої деформації до усунення причин розрідження або виникнення тріщин сталевої оболонки і, таким чином, автоматичного вирівнювання тиску всередині резервуара з атмосферним тиском.

Underpressure in a tank with a fixed roof may arise in the final stage of its construction as well as during its exploitation. After completion of the construction, when the tank is empty and all manholes and valves, through which air could get into the tank, are closed tightly, underpressure may arise in case of sudden change in weather – air pressure and temperature, which is particularly dangerous in spring or summer.

In the process of tank exploitation underpressure may arise if breathing valves are obstructed, for example covered by snow during pumping out a product stored in the tank.

Underpressure may cause extensive deformations of the shell or the roof of the tank. However, the shell undergoes deformation more frequently, since the roof has a stiff support structure.

The article presents stages of deformations of the tank shell and their development from the occurrence of the first deformation to either removal of causes of underpressure or crack of the steel shell and thus automatic equalization of pressure inside the tank with atmospheric pressure.

**Keywords:** cylindrical tank, steel, shell, underpressure, deformations

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## 1. Introduction

Authors of this article have already published a number of papers on the subject of underpressure in steel vertical tanks [1]–[6]. Papers [1] and [2] present original methods of repairing the deformed tank shells, while paper [3] describes causes of underpressure (Fig. 1). Apart from obstruction of breathing valves during pumping out liquids stored in the tank, underpressure may be caused by changes in weather conditions even if there is a constant level of stored liquid.

Analysis of the tank with a capacity of 10000 m$^3$ (shell diameter $d$ = 29,0 m) revealed that the first deformations of the shell in the hermetically sealed tank shall occur in case of temperature drop of 10 °C and pressure difference of 32 hPa.

Paper [4] shows that the value of underpressure causing the first shell deformation depends not only on the thickness of sheets, which the upper part of the shell is made of (Fig. 2), but also on the level of liquid in the tank. The more liquid, the more underpressure is needed to cause deformations, which however shall be of a narrower extent due to the amount of liquid (Fig. 3 and 4). Paper [5] deals with theoretical issues and model research on local loss of stability of cylindrical shells caused by underpressure.

This article is a summary of above publications concerning underpressure in steel vertical cylindrical tanks. It analyses the behaviour of the tank shell after its first deformation caused by underpressure. These deformations, however, do not mean a serviceability limited state of the tank as the shell is still sealed. Along with changes in underpressure, there will be a change in location and shape of deformations as well as in deflection value.

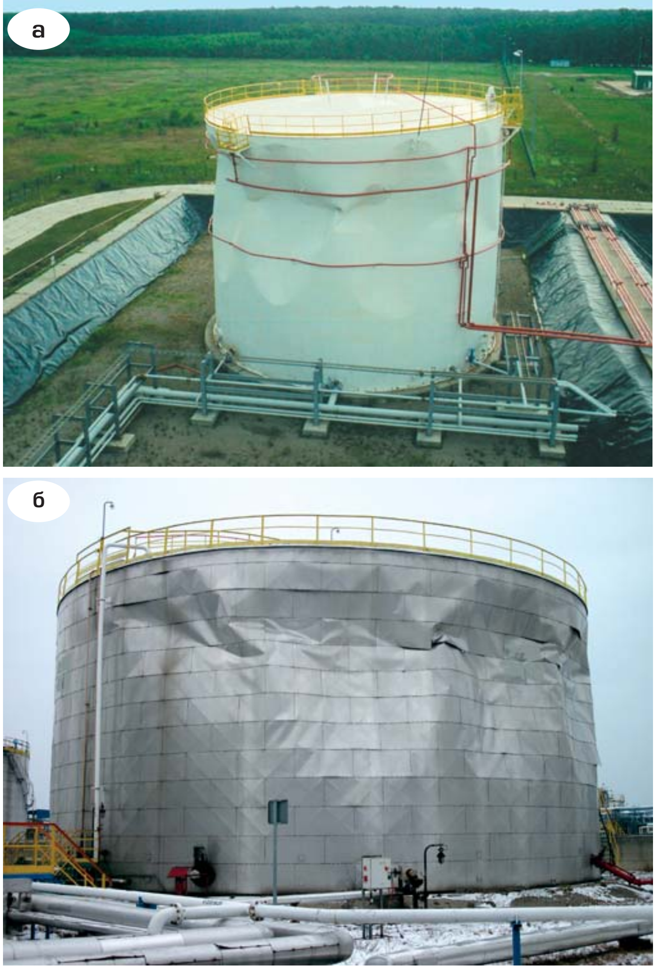

Fig. 1. Tanks injured by underpressure:

**a)** developed during the productivity test of the sucking pump on the product pipeline

**b)** developed due the freeze up of the breathing valves

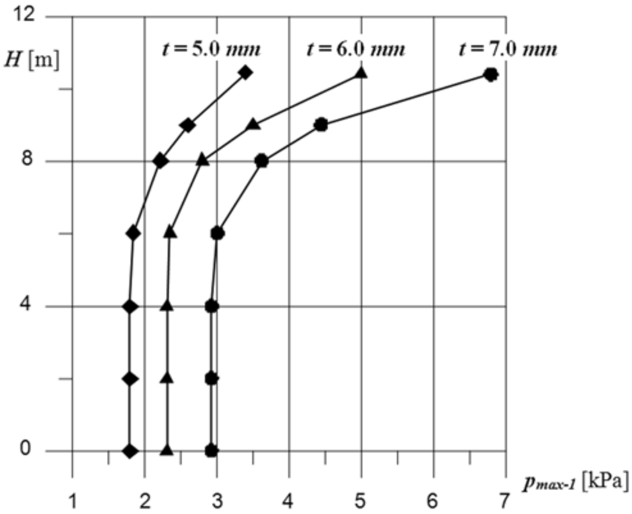

Fig. 2. Influence of the amount of H(m) liquid in the tank on critical underpressure value $p_{\max\text{-}1}$ [kPa] [4]

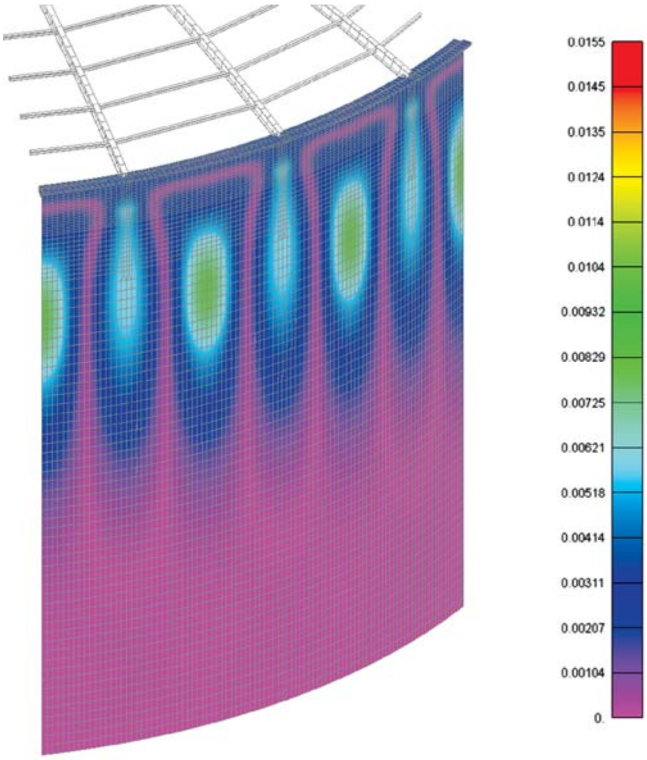

Fig. 3. State of tank shell deformation [*m*] - empty tank [4]

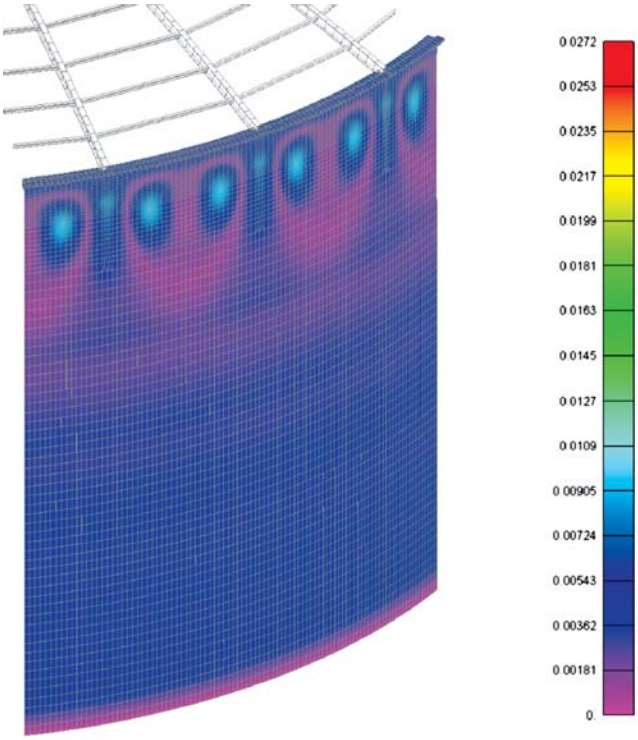

Fig. 4. State of tank shell deformation [*m*] – tank filled with a product to a maximum level [4]

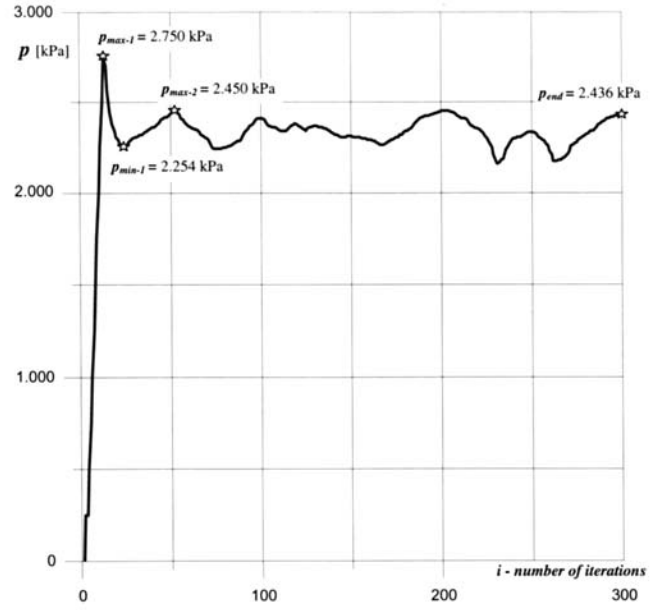

Fig. 5. Value of underpressure *p* [kPa] during a nonlinear static FEM analysis

## 2. Behaviour of the steel shell of a vertical cylindrical tank after occurrence of the first deformation caused by underpressure

Underpressure in a steel vertical cylindrical tank with a fixed roof arises when the tank is hermetically sealed (all manholes and valves are closed tightly) and the product stored is being pumped out of the tank or there is an adverse change in temperature and air pressure. When underpressure reaches the limit value ($p_{\text{max-1}}$ – Fig. 5) resulting in loss of stability of the cylindrical shell in the upper part of the shell made of the thinnest sheets, the first deformations, deflections of tank, occur. In case of an ideally shaped tank, these deformations would be evenly spread around the tank perimeter. However, in reality, they will be located in places with some imperfections, for example angle crossings of sheets at vertical edges of welded sheets constituting a ring of the shell. Local deflections of side surface of the tank cause a reduction of steam and air area in the tank (area limited by a fixed roof from the top and a surface of liquid stored from the bottom). Such a reduction of the steam and air area will also cause a decrease in underpressure inside the tank (Fig. 5 – part of a line graph from $p_{\text{max-1}}$ to $p_{\text{min-1}}$) and a temporary stopping of new deformations or expansion of the existing ones. If the cause of underpressure increase is not removed, for example, if pumping out a product stored continues, deformation of the shell will begin again (Fig. 5 – part of a line graph from $p_{\text{min-1}}$ to $p_{\text{max-2}}$) and the number of deformations will grow or they will join together and change their location. This cycle of temporary stability of the deformed shell and redeformation of the shell will persist until occurrence of a crack at the crossings of sheets. The crack shall result in equalization of underpressure in the tank with atmospheric pressure and thus no further deformations shall occur. This state of the tank will mean a serviceability limited state. The tank will no longer be sealed and the hydrocarbon vapours (in case of tanks for liquid fuel) will be emitted to atmosphere, which is unacceptable (environment protection regulations).

Recurring increase in deformation of the tank shell cannot be usually observed since the user of the tank, after the occurrence of the first deformation, tries to remove causes of that deformation as soon as possible and to deliver it for repair for restoring the proper shape of the shell and to enable its exploitation. Due to lack of possibility to observe the behaviour of the shell after its first deformation caused by underpressure, a computer simulation of the situation was carried out. For this purpose MSC/Nastran for Windows v. 2002 [6], which is the application of finite element method, was used. The static analysis of a model tank with the following types of elements was conducted:

- ***shell elements*** – a shell, a perimeter ring supporting a load-bearing structure of the roof and wind ties;
- ***beam elements*** – elements of roof supporting structure.

The following data was adopted for the purpose of calculations:

- $E = 210$ GPa – Young's Modulus of Elasticity;
- $\nu = 0{,}3$ – Poisson's ratio for steel;
- $\rho = 78{,}5$ kN/m$^3$ – steel weight;
- $R_e = 235$ MPa – yield strength of steel used.
- The analysis was carried out:
- for characteristic loads;
- for an adopted model of elastic-perfectly plastic body (nonlinear material analysis);
- with regard to the influence of deformation on the internal force distribution (nonlinear geometric analysis).

The behaviour of the shell of a completely empty tank was analysed. Results of the simulation are shown in Figures 6 to 9.

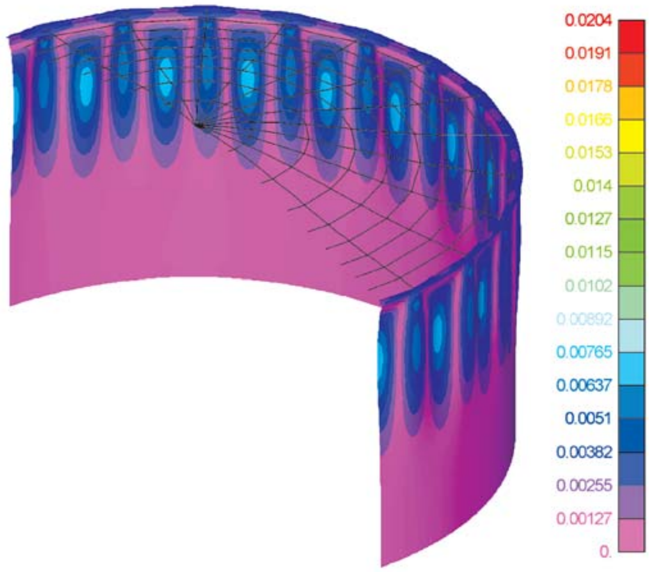

**Fig. 6.** Deformation of the tank shell corresponding to the limited value of underpressure $p_{max-1}$ = 2,750 kPa

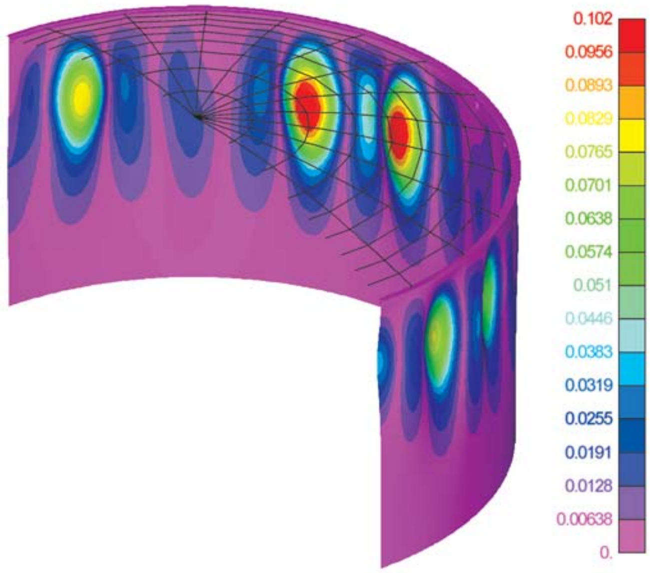

**Fig. 8.** Deformation of the tank shell corresponding to the value of underpressure $p_{max-2}$ = 2,450 kPa

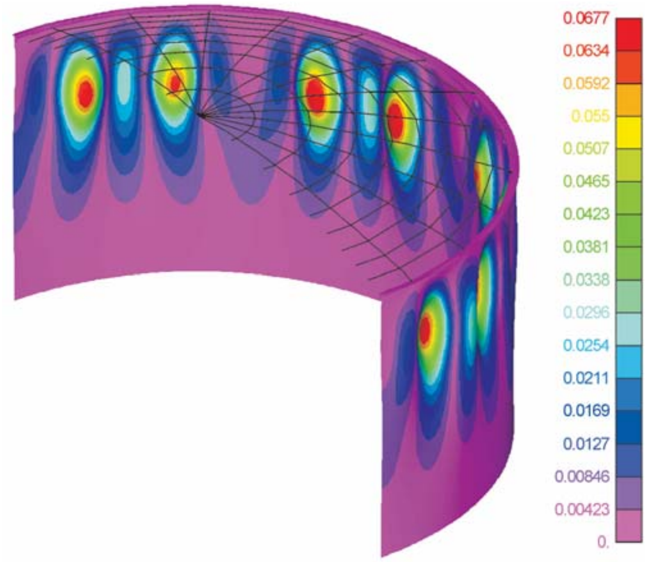

**Fig. 7.** Deformation of the tank shell corresponding to the value of underpressure $p_{min-1}$ = 2,254 kPa

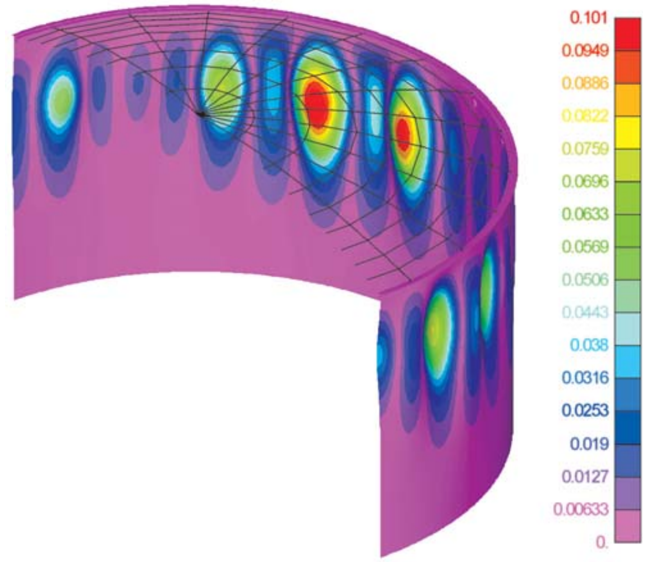

**Fig. 9.** Deformations of the tank shell corresponding to the value of underpressure $p_{end}$ = 2,436 kPa

Figure 6 presents the first deformations of the shell of the tank with $V$ = 10000 m$^3$ caused by underpressure. Since the model tank has an ideal shape, deformations are evenly spread around the perimeter. They are vertical. Spacing between deflections corresponds to spacing between radial ribs of a supporting structure of a fixed dome roof. The ribs are attached to the inner perimeter ring located at the upper edge of sheets of the tank shell (roof ribs are marked by a thin line).

Figure 7 shows the state of the shell deformation after its stabilization and after completion of the first cycle of deformation (point $p_{min-1}$ in Fig. 5). There may be observed the occurrence of densely arranged, local elliptic deformations.

Figure 8 presents deformations after completion of the second cycle of the underpressure increase in the tank (point $p_{max-2}$). There are fewer elliptic deformations. Neighbouring deformations joined together and their extent is wider than earlier.

Figure 9 demonstrates deformations of the shell after 300 iterations (adopted end of numerical analysis). Deformations are still irregular, they take different form and value.

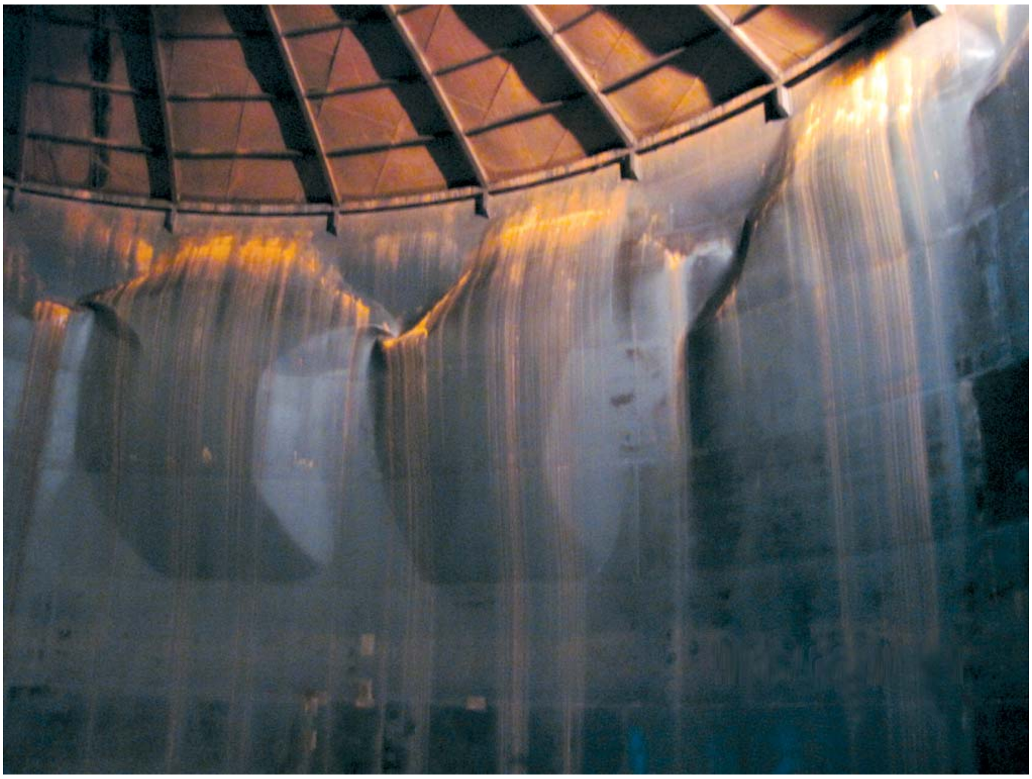

Fig. 10. Deformations of the upper part of the tank shell caused by underpressure

Figure 10 is a photograph of deformation of the upper part of the tank shell, where underpressure was generated. These deformations are permanent – they remain unchanged after opening of manholes and equalization of pressure inside the tank with atmospheric pressure.

## 3. Summary

Deformations of the shell of a steel vertical cylindrical tank with a fixed roof occur when underpressure inside the tank reaches a limit value after the cycle of underpressure decrease and increase. During the cycle, the deformations change their location and type (local deformations or deformations covering a larger area of the shell). The cycle continues until the user of the tank removes the cause of underpressure, or the shell cracks, which will result in the equalization of pressure inside the tank with atmospheric pressure.

[1] Ziólko J.: Die Instandsetzung durch Unterdruck beschädigter zylindrischer Stahlbehälter. Der Stahlbau, 49(1980), No. 11, pp. 347–348.

[2] Ziólko J.: Reparatur von Dächern und Mänteln durch Unterdruck verformter Stahltanks. Stahlbau, 70 (2001), No. 5, pp. 357–361.

[3] Supernak E., Ziólko J.: Podcisnienie w zbiornikach. Wnioski ze zdarzen w ostatnich latach. (Vacuum in tanks. Conclusions from the events in recent years) XXVI Scientific-technical Conference «Structural Failures» Szczecin – Miedzyzdroje, Poland, 21–24 May 2013, pp. 589–598.

[4] Ziólko J., Mikulski T., Supernak E.: Stability of the steel shell of a vertical cylindrical tank under vacuum. Scientific-Technical Conference «Metal Structures», 2–4 July 2014, Kielce – Suchedniów, Poland, Kielce University of Technology. Short papers pp. 85–88.

[5] Ziólko J., Schneider W., Bialek T., Heizig T., Gettel M.: Längenabhängigkeit des Beulwiderstandes umfangsdruckbeanspruchter stählener Kreiszylinderschalen. Stahlbau, 78 (2009), No. 12, pp. 947–951.

[6] MSC Nastran for Windows, Los Angeles: MSC Software Corporation, 2002.

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