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Influence of geometrical imperfections on stresses in cylindrical shells

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ABSTRACT:

Results of the numerical analysis of the shells of storage tanks of 50 000 m^3 capacity with geometrical imperfections are presented in the paper. Results were verified by tensometric tests performed on the real tank. It was recognized that real geometrical imperfections cause increase of stresses in the tank construction by 30%.

INTRODUCTION

The analysis results of the influence geometrical imperfections on the shells of steel tanks for liquids are presented in the paper. The analysis was applied in particular to storage tanks of vertical axis, floating roof, and nominal volume of 50 000 m^3, which are used for storage of kerosene products.

The imperfections in the tank shell result from the changes in the arrangement of external forces stream, and thus of stresses within the shell. These constitute a threat to safe operation and are potentially the cause of phenomena like:

- vulnerability of shell to shape distortion under compressive forces,
- local loss of stability in a fragment of the shell,
- local overload of the main supporting element in the structure of the tank, i.e. the shell.

Apart from the impact of geometrical imperfections on the load capacity and effort of the facilities in use, they also influence the operational conditions of the tanks themselves, in particular the tanks with floating roofs. Very often the nature and shape of geometrical irregularities are revealed during the operation by sudden reaction of some fragments of the shell when emptying or filling the tank. The reaction consists in total change in the nature of the imperfection, e.g. from negative to positive and the opposite. Such effects are particularly dangerous, having significant impact on the changes in material effort and the strength of welds.

Important during acceptance and delivery of a new tank for operation, the issue of evaluating the shell deformation also applies in other situations. During the operation, changes may occur in the shape of the shell, which are caused for example by non-uniform settlement of the object. Always in such a case a question arises: to what extent do identified geometrical imperfections impact the section state of effort? This question further gains in importance when applied to tanks after dozens of years in operation, where next to geometrical defects, corrosion is present, related to the loss of plate thickness, or to a significant degree of pitting.

STRUCTURE OF TANKS

The main element in the structure of the analysed tank type is the steel bottom and shell (Fig. 1). Two parts make up the bottom: the central part and the rim ring. The central part of the steel bottom is made from plates, 8 mm thick. The plates are placed directly on the sand foundation. That part of the tank is surrounded with the rim ring, made from plates, 16 mm thick. The internal part of the ring is placed on the sand foundation, the external one on a reinforced concrete foundation ring (Fig. 2). The bottom plates are joined crosswise with butt welds with the use of pads, the lengthwise contacts are overlapping and fillet welded. The central part of the tank bottom is joined with the rim ring through overlap and fillet welding. The tank bottom is executed from two steel grades: the central part from carbon steel marked S235, and the external – steel marked S355.

The tank shell is made from steel rings, for which the following steel grades are used:

- S355 – for four lower shell rings,
- S235 – for top shell rings.

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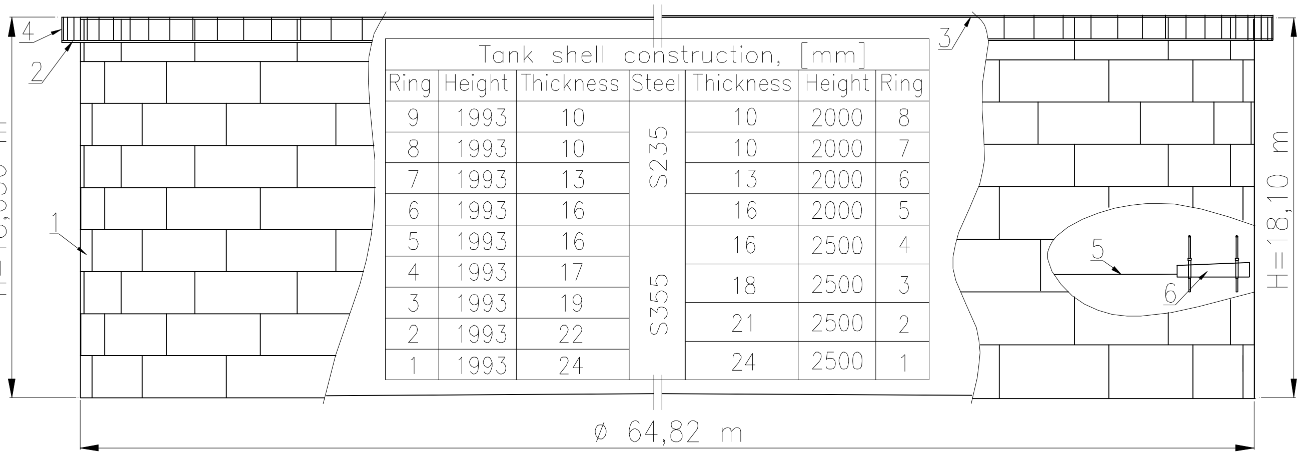

Ring	Height	Thickness	Steel	Thickness	Height	Ring
9	1993	10	S235	10	2000	8
8	1993	10	S235	10	2000	7
7	1993	13	S235	13	2000	6
6	1993	16	S235	16	2000	5
5	1993	16	S355	16	2500	4
4	1993	17	S355	18	2500	3
3	1993	19	S355			
2	1993	22	S355	21	2500	2
1	1993	24	S355	24	2500	1

Figure 1. Structure of the analysed tanks:
1 - tank shell , 2 - lateral bracing (flying bridge), 3 - crowning angle,
4 - protective railing on the lateral bracing, 5 - membrane, 6 - pontoon,

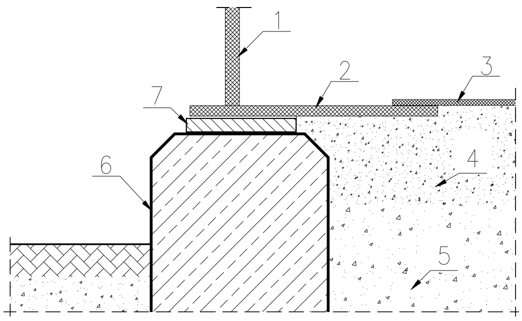

Figure 2. Foundation structure:
1 - tank shell, 2 - bottom ring, 3 - internal part of steel bottom,
4 - oil-moist sand pad, 5 - sand foundation, 6 - reinforced concrete ring, 7 - flexible pacer

The shell consists of eight or nine rings (depending on the tank construction time) from plates whose thickness changes stepwise, adapted for linear distribution of load. The number of rings depends on the adopted width of the plate sheets used, which is limited by: technological capacities of steel industry, design requirements, along with technical and organizational limitations during assembly. The thickness of plate sheets in individual rings has been presented in the enclosed Figure 1. The shell plates are joined by butt welds both in vertical and horizontal contact. The joint between the shell and the bottom is executed by means of double-side fillet weld. The tank shell is topped in its upper part by an angle 100×10 mm, in order to add stiffness to the loose edge. An important element of the discussed type of tank is the lateral bracing. Its role is particularly important when the floating roof is in its lowest possible position, i.e. when the tank is empty.

GEOMETRICAL IMPERFECTIONS IN TANK SHELLS

Geometrical imperfections in shell layers of the analysed tank group have been defined based on geodesic measurements of tanks delivered for operation. 40 plumb-line measurements were taken, uniformly distributed around the tank's perimeter. Every plumb-line measurement was taken at half the height of each ring, and at the level of welded contacts between individual rings. The measurements were taken in three phases, corresponding to the following stages in the geometrical quality inspection of the tank shells:

- directly after the conclusion of assembly works,
- during hydraulic test, of a tank filled with water up to the level of operation,
- after hydraulic test, i.e. after one complete filling of the tank.

The measurements results of twelve new tanks and one tank that had been used for more than 20 years were applied into numerical analysis. Figure 3 shows the diagrams of the envelope of the geometrical imperfections in the tank shells. The envelope values have been listed as deviations from the ideal geometry assumed in the design. The presented values have been grouped according to minor differences in the construction time (A, B), and to the measurement period (C). The quantitative distribution of geometrical imperfections values can be found in works (Kowalski, 1999, 2001a, 2001b).

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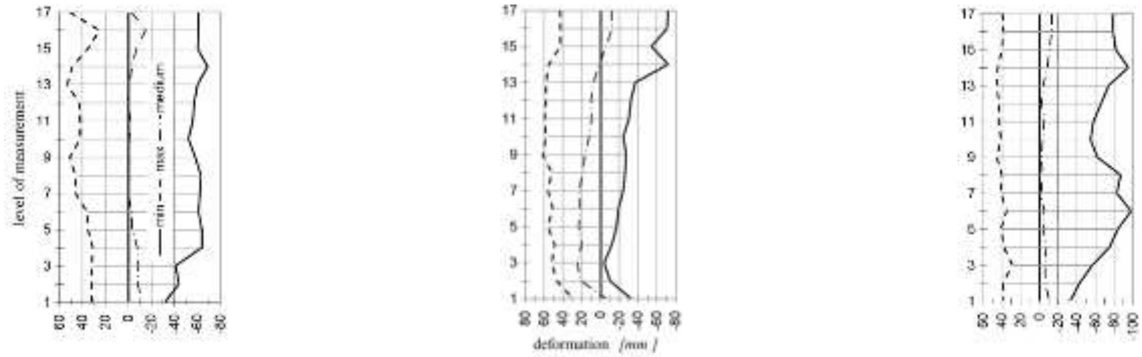
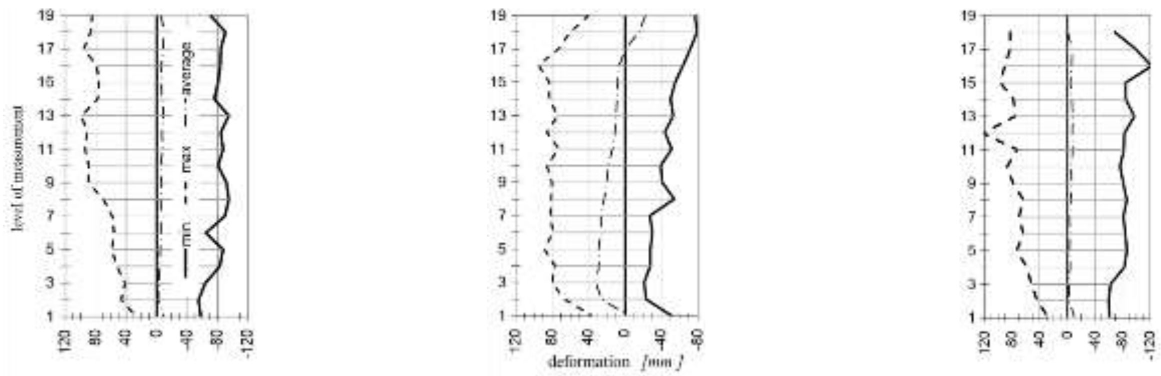
Tank group of the "A"



Tank of the group "B"



a) after assembly b) during test c) after test

Tank of the group "C"

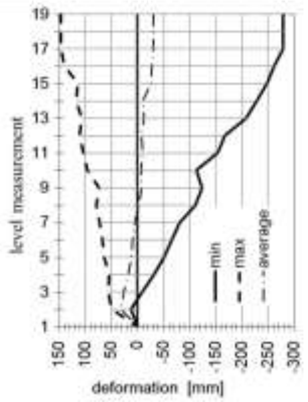


Figure 3. Envelopes of geometrical imperfections in the tank shells

NUMERICAL CALCULATIONS FOR TANKS WITH IMPERFECTIONS

Distorted tank shells have been numerically analysed by means of MSC NASTRAN calculating package. Based on the geodetic measurements results and on specially designed copyright protected computer software, complex numerical models of real objects were generated. These provided for the specific conditions of geometrical imperfections in shells and for the supporting foundation whose rigidity changes stepwise. The computer tank model consisted of two hundred generating lines, distributed uniformly on the perimeter. The coordinates for the missing intermediate joints were defined based on interpolations between the values obtained from geodetic measurements. When modelling structures, panel-type isoperimetric four-joint elements were used, in which the formulas describe the features of the flexural and disk state (QUAD4). The analysed models were subjected to hydrostatic pressure by a liquid on the internal surfaces of the shell and on the tank bottom. The modelled liquid level in the tanks was 17 m and corresponded to the level of the liquid during the operation. The strength analyses were made for typical load values. The changing distribution of internal forces and the resulting changes in the distribution of stresses were analysed separately for each tank. The geometrical imperfections of the

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tank and their impact on the analysed states were treated globally in order to define the envelope of the searched static and strength values. It is very difficult to individually analyse the impact of each single imperfection or else each plumb line or level line on the condition of the tank, due to the differences in surrounding environments of each geometrical defect. To illustrate this, representative sets of stress distribution (Fig. 4) in a randomly selected tank have been presented. The vertical element division band of the tank shell was selected randomly. In order to capture the details of variability in the analysed distributions, some quantities were presented in two diagrams. One of them illustrated the whole variability range of a given quantity. Such comparison provided illustration for the variability of the analysed quantities against their total range or else its selected parts, whose representation on the diagram covering the whole variability range of the quantity is rather poor. The state of deformation in the shell corresponding to the geometrical conditions on the vertical edges of a selected vertical element band was presented as the first diagram. Continuous curve of the diagram represents the primary conditions, the dotted one – the final geometrical edge conditions in the element division grid of a selected band.

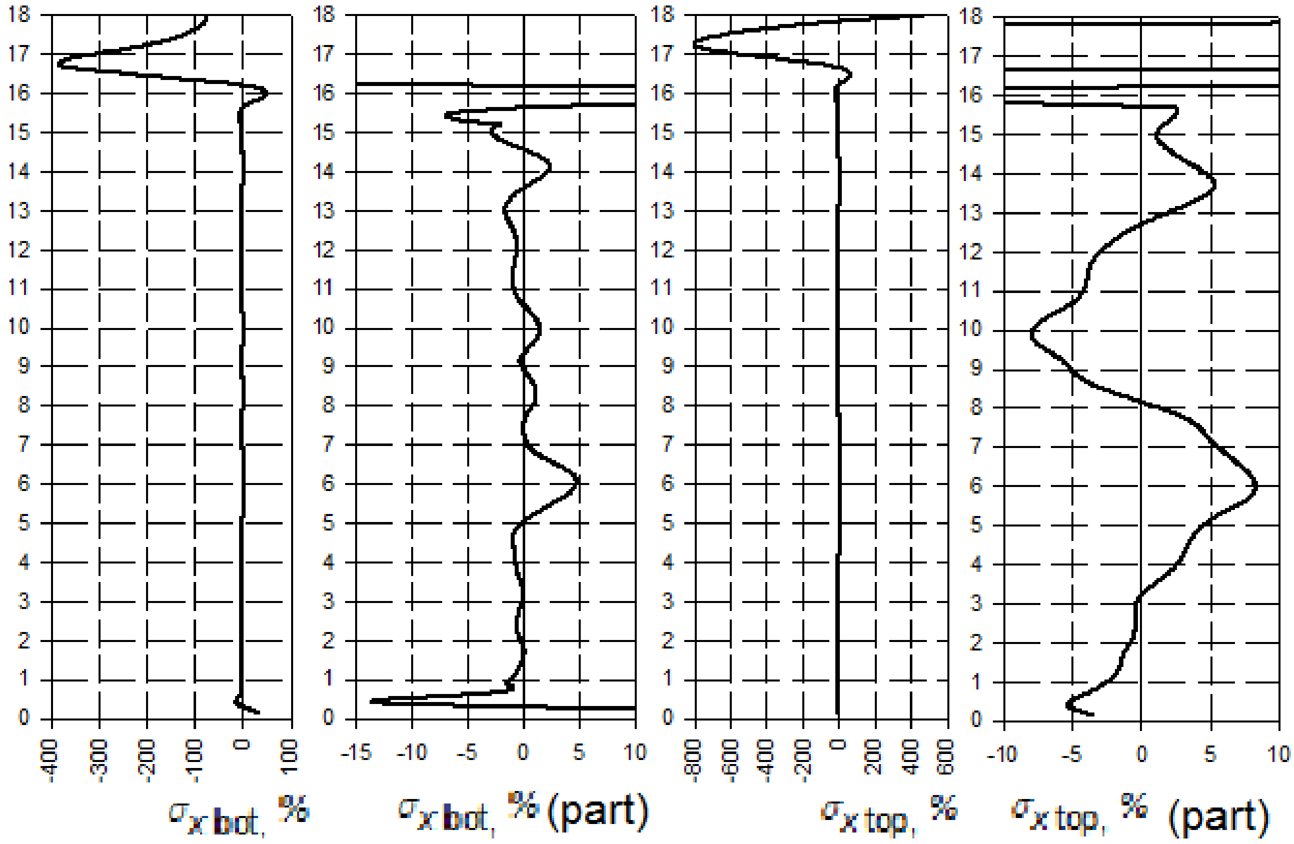

Figure. 4. Comparison of stress distributions (bot – external surface, top – internal surface)

The analysis results of variability in the analysed quantities of individual tanks are another evaluation stage of changes resulting from imperfections. The exemplary diagrams presented in figure 5 were elaborated on the basis of differences in maximum and minimum values from the envelopes of individual quantities, against the model values compliant with the following formula:

$$[(X_{\max} - X_{\min}) / X_{model}] \cdot 100\% \tag{1}$$

where: X_{min} , X_{max} – respectively, minimum and maximum value of the analysed static quantity defined at individual calculation levels, X_{model} – model quantity at individual calculation levels referring to the tank that is free from geometrical imperfections. The percentage variability ranges of internal stresses and forces presented in Tables 1 and 2 indicate the general tendency to increase their values as the height of the tank rises. This corresponds to the increasing variability ranges of geometrical deviations in the shell that rise together with its height. It is also noticeable that there is a significant increase in the analysed values in the part adjacent to the tank bottom and the lateral ring. In these locations the impact of imperfections on the state of edge disturbances results from additional rigidity of the elements in question. Ignoring these fragments of disturbances one can say that as regards the performance of the shell as a shelling structure the variability of individual analysed quantities of stress ranges between the limits presented in Table 2. In particular, high percentage values of some of the presented quantities result from low model value (often close to zero), which serves the standardisation of the analysed quantity. Due to the operational safety of the facility and the load capacity reserves of the structure, importance must be attached to the size of the rise in the value of the analysed internal forces and stresses $\Delta_{max}X$ above the values of forces and stresses defined based on the designing standards (Figs. 5).

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Table 1. Internal force variability

Static forces	Range of variability [%] for groups of tanks	
	„A"	„B+C"
F_x	3 ÷ 25	3 ÷ 30
F_y	-200 ÷ - 5000	-1500 ÷ -10000
M_y	-60 ÷ 100	-80 ÷ 800
Q_y	-70 ÷ 250	-80 ÷ 600

Table 2. Ranges stresses variability

Stresses	The percent variation for the tanks of the group	
	„A"	„B+C"
$\sigma_{x\,bot}$	5 ÷ 40	2 ÷ 55
$\sigma_{x\,top}$	5 ÷ 30	7 ÷ 45
$\sigma_{y\,bot}$	10 ÷ 550	30 ÷ 350
$\sigma_{y\,top}$	-50 ÷ 450	-30 ÷ 600
$\sigma_{HMH\,bot}$	7 ÷ 25	7 ÷ 35
$\sigma_{HMH\,top}$	4 ÷ 30	4 ÷ 45

$$\Delta_{\max} X = \left[\left(X_{\max} - X_{model}\right) / X_{model}\right] \cdot 100\% \tag{2}$$

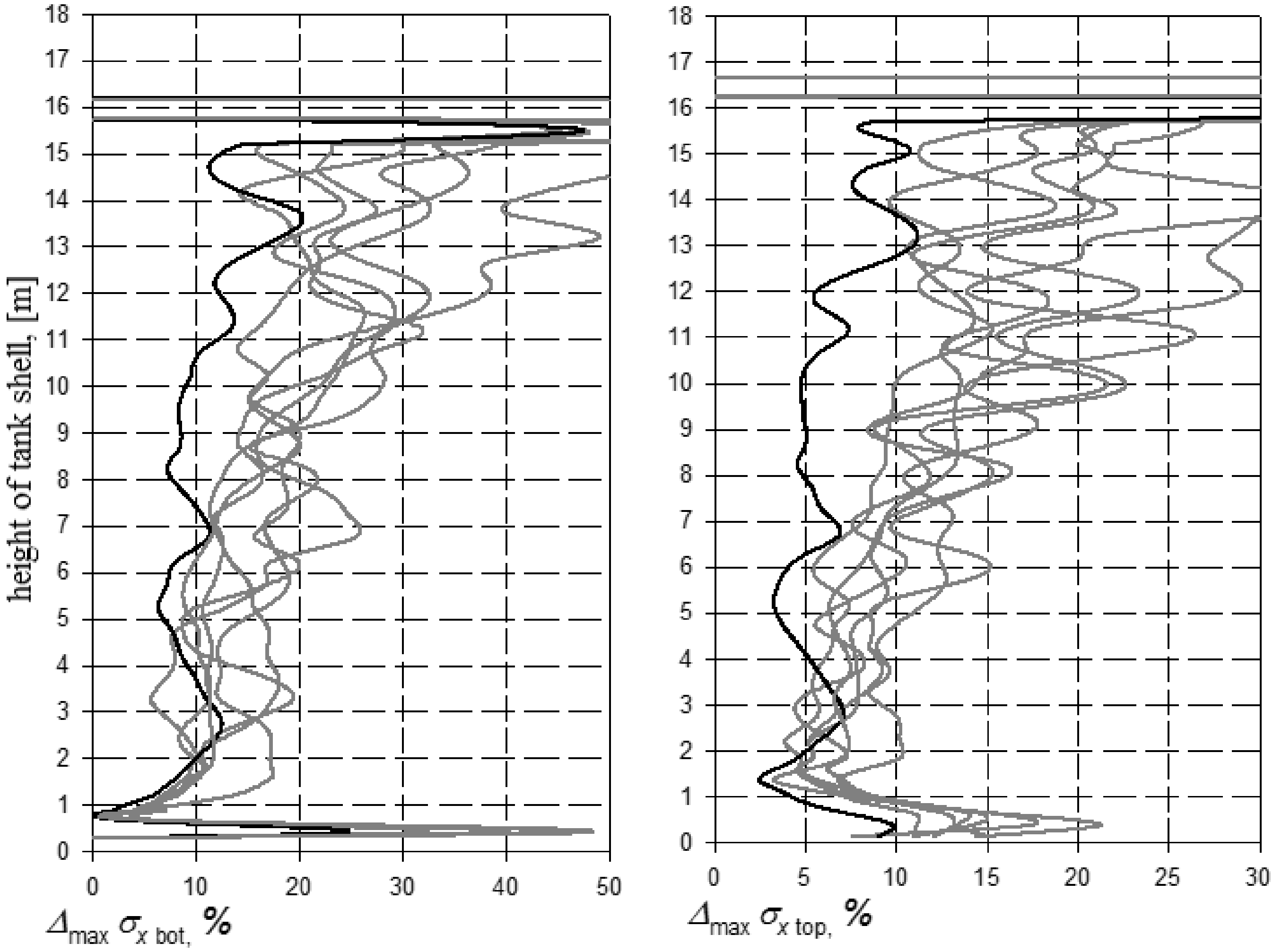

Figure. 5. Percentage rise in the values of stresses

The presented diagrams of percentage rise in the internal forces and stresses above those defined through calculations and providing for the values of characteristic load can be analysed through the values given in Table 3.

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Table 3. Maximum stress increase

Stresses	The percent variation for the tanks of the group	
	„A”	*„B+C”*
$\sigma_{x\,\mathrm{bot}}$	2 ÷ 25	0 ÷ 30
$\sigma_{x\,\mathrm{top}}$	3 ÷ 12	3 ÷ 22
$\sigma_{\mathrm{HMH\,bot}}$	4 ÷ 15	5 ÷ 20
$\sigma_{\mathrm{HMH\,top}}$	2 ÷ 15	5 ÷ 25

Thus we are able to claim that the growth of circumferential forces of maximum values 8-12% does not translate directly into identical increase in the circumferential and reduced stresses, which in the case of circumferential stresses ranges between 12 and 25% limits in the case of tanks group marked ‘A’. The other group of tanks, marked ‘B+C’ is characterised by greater rise in the reduced and circumferential stresses.

In order to execute a practical verification of the performed numerical analysis, field tensometer tests of a tank of V=12000 m³ volume were carried out. The tank was characterised by significant shape imperfections in its shell. The tests confirmed the variation in the shell stresses, which referred to individual measurement levels, and the correctness of the performed numerical analyses (Kowalski, 2004a, 2004b).

CONCLUSION

The performed numerical analyses confirmed that the rise in the geometrical imperfection values of the shell and their mutual variations results in dispersion of values of forces and stresses within the same compared levels of the tank height. The value envelopes of circumferential and reduced stresses in the analysed tanks of 50.000 m³ volume allow us to claim that there are no cases when the state of calculated strength of adequate steel grades are breeched. Thus, the operational safety of the facilities is preserved.

Hence, there are no reservations against the values of the admissible deviations during acceptance, referring to the geometry of the tank shell, specified in Polish standard regulations.
Also, the values of admissible geometrical imperfections quoted in the standard regulations have been correctly defined. It should be mentioned, however, that the Eurocode 3 draft that refers to steel shells quotes a very simplified form of the method to define the quality of shell execution as regards the shape regularity. The criteria it lists are much less demanding.

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