Hana R. Qananah[1], Radovan Petrović[1], Andrzej Banaszek[2], Maja Anđelković[1], Radoje Cvejić[1], Nataša Đorđević[3], Nikola Milovanović[4]*

STRESS STATE OPTIMISATION OF VERTICAL ATMOSPHERIC LARGE-VOLUME TANKS

OPTIMIZACIJA NAPONSKOG STANJA VERTIKALNIH ATMOSFERSKIH REZERVOARA VELIKIH ZAPREMINA

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Adresa autora / Author's address:
[1)] University 'Union-Nikola Tesla,' Faculty of Information Technology and Engineering, Belgrade, Serbia
[*]email: radovan4700@yahoo.com
[2)] West Pomeranian University of Technology, Marine Research and Transport Faculty, Szczecin, Poland
[3)] Institute for Technology of Nuclear and Other Mineral Raw Materials, Belgrade, Serbia
[4)] University of Belgrade, Innovation Centre of the Faculty of Mechanical Engineering, Belgrade, Serbia

Keywords
- tank
- optimisation
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Abstract

The strength calculation is very important in the design of the tank. Significant efforts have been made to solve this task and have led to standardized procedures, recommendations and standards for tank design. Within the existing standards, the designers are able to define mainly the geometry of the tank and technical conditions of the structure. When it is necessary to check the stability of the shell or the complete tank, they resort to analytical methods with the use of classical patterns from general theory of shells. As is well known, the application of general shell theory, even in the simplest of cases, leads to very complex calculations. When using membrane theory in the calculation, it is shown that satisfactory results are obtained only for parts of the shell far enough from ends, but it cannot satisfy all the conditions on the contour and the area of supports.

Ključne reči
- rezervoar
- optimizacija
- naponsko stanje
- metoda konačnih elemenata (MKE)

Izvod

U projektovanju rezervoara proračun čvrstoće je veoma značajan. Značajniji napori uloženi u cilju rešavanja ovog zadatka doveli su do standardizovanih postupaka i do preporuka i standarda u oblasti projektovanja rezervoara. U okvirima postojećih standarda projektanti su u mogućnosti da definišu uglavnom geometriju rezervoara i tehničke uslove izrade. Kada je potrebno proveriti stabilnost omotača ili kompletnog rezervoara, pribegavali su analitičkim metodama uz korišćenje klasičnih obrazaca iz opšte teorije ljuski. Kako je poznato, primena opšte teorije ljuski, čak i u najjednostavnijim slučajevima, dovodi do vrlo složenih računa. Primena membranske teorije u proračunu pokazuje da se dobijaju zadovoljavajući rezultati samo za delove ljuske dovoljno udaljene od krajeva, ali ona ne može zadovoljiti sve uslove na konturi i u području oslonaca.

INTRODUCTION

To reach practical solutions in tank design, simplifications of the theory are needed. Such simplifications are not able to provide a precise picture of the stress and displacement field at a number of locations on the tank. Having no other methods (primarily numerical), resorting to empirical formulas, the designers are forced to anticipate experiments in every case, in order to determine the stress and strain fields /1, 2/. New methods in the analysis of structures, such as the finite element method (FEM), with the help of computers, provide far greater opportunities compared to classical, /3-7/.

ANALYTICAL METHODS

Analytical methods can be used to observe the membrane state of stress and only partially to analyse the disturbance of the membrane state of stress at the place of clamping the shell and the bottom. When solving analytically, special difficulties arise when calculating tanks with stepped wall thickness /8, 9/. Every place with a jump in wall thickness causes a disturbance of the membrane state of tension. Having in mind that wall thickness is constant within each member, this equation applies to each component, where constants C_1 to C_4 of each member are determined from boundary and transition conditions, /10/:
- to have equal deflections w,
- to have equal slopes of elastic line dw/dx,
- their transverse forces P_x match,
- their bending moments M_x match.

Therefore, if there are r articles, $4r$ conditions must be met, and we have the same number of constants that need to be determined.

For a vertical atmospheric tank, in addition to variable wall thickness, we have the effect of wind, concentrated loads, and a given inaccuracy that analytical methods cannot cover at the same time.

By the finite element method, it is possible to analyse all influences separately, as well as their total influence on the behaviour of the structure.

FINITE ELEMENT METHOD

The application of finite element method (FEM) enables a detailed view of displacement and stress fields for different loading conditions. In Fig. 1, a vertical atmospheric tank of volume $V = 3000\ m^3$ is given. Measures, discretization on finite elements, and the loading sketch are indicated.

In the example in Fig. 1 (dimensions in figures refer to A4 format) a change in the membrane stress state caused by concentrated forces, wind action, stepped wall thickness, stiffening at the top of the tank, and clamping at the bottom of the shell, are shown, /11/.

A tank with variable wall thickness reinforced in the upper part with a DB ring is observed. Regarding the load, the following is taken into account: concentrated load from the roof structure of the tank $F = 1200$ daN, wind pressure $p_v = 0.009$ bar, and liquid pressure $GH = 0.0014$ bar. Due to the reinforcement with DB ring, the conditions are taken such that there are no radial displacements on that circle /6/.

Figure 1 shows deformed shapes of the CD and AB derivatives, as well as the distribution of radial stress σ_y, along AB, and circular σ_x, on the circular line EF, /7/.

From Fig. 1c it can be seen that the greatest disturbance of the membrane stress state occurs at the sheath-bottom joint where the sign of the radial stress σ_y changes. In this particular case, the magnitude is $\sigma_y = -2500$ daN/cm^2 and represents the highest value. When designing, special attention must be paid to the sizing of the first two shell members, as well as to the sizing of the tank bottom. Here, a solid base is assumed to support the bottom of the tank, i.e. limited displacement of the bottom nodes in the z-axis direction. If the substrate is not absolutely rigid, it is possible, in addition to knowing the characteristics of the soil, to include these influences in a computer program, /12/.

Observing the diagram of radial stress σ_x along the derivative AB, another extreme value of the stress in the middle of the tank (1965.08 daN/cm^2) is noticed at the location of maximal radial displacement. Bearing in mind that the influence of clamping at the bottom-shell place decreases towards the middle of the tank, and also the influence of the upper stiffening ring DB decreases, this value is the closest to the membrane stress state at that location. Of course, we must keep in mind that there is an antisymmetric wind load (p_v) in the middle of the tank, as well as that we have the influence of concentrated loads (F). This approximation to the membrane stress state in the middle of the tank implies the liquid pressure as the main load.

The value of radial stress decreases towards the top of the tank, whereby the displacements in the x and y axes are limited on the DB ring.

Regarding circular stress σ_x (Fig. 1d), its maximal value was observed on elements of the fourth member with a thickness of 0.7 cm - the EF line. The explanation lies in the abrupt change in thickness from 0.9 to 0.7 cm. The magnitude of the maximal stress of 2016.47 daN/cm^2 occurs in the element closest to the DB exponent, as a consequence, in addition to the mentioned influences, of the influence of wind pressure which creates suction forces on that side.

The deformations of the derivatives AB and CD (Fig. 1b) are approximately symmetric with respect to the z axis. The bottom and the shell are the smallest at the points of connection, and the largest are in the middle of the tank. Their sizes are of the order 0.299 cm at the bottom to 5.529 cm in the middle of the tank. In the middle of the AB and CD derivatives, a difference in displacements is observed, which originates from the action of the wind, the influence of which is reflected in the bending of the tank towards the CD derivative.

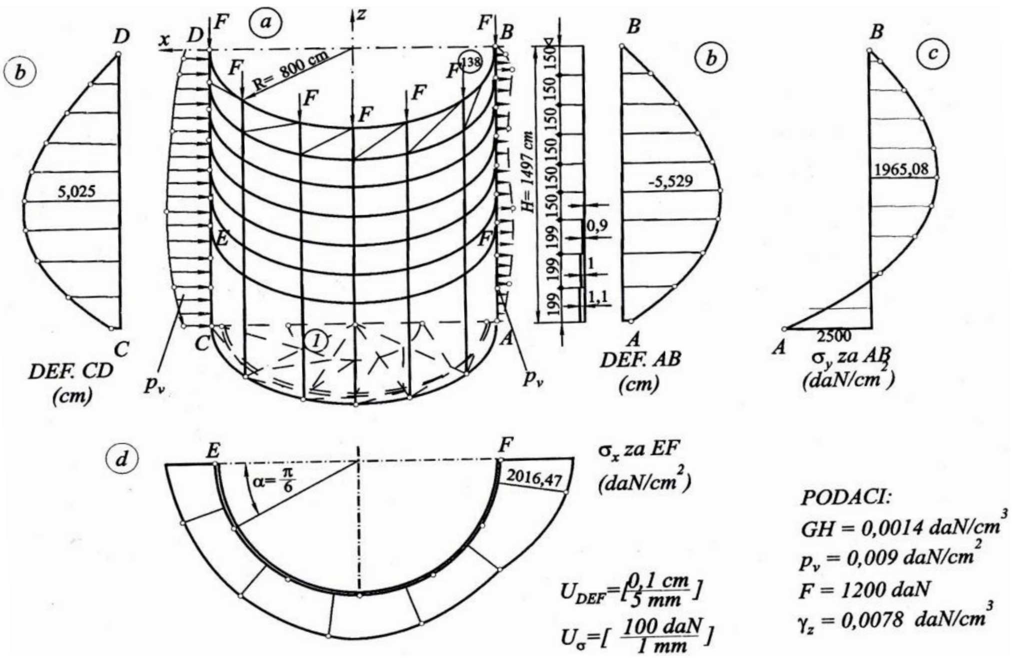

Figure 1. Vertical atmospheric tank of volume $V = 3000\ m^3$ (change in membrane stress).

In Fig. 3, the influence of structural inaccuracies in the shell on displacement and stress fields is observed. The inaccuracy of making NETC = 40 mm is given. The diagram of deformations and stresses is given by dashed lines in Fig. 3(b, c, and d). It can be noticed that with the given inaccuracy, we have somewhat smaller deformations of the derivatives, as well as the magnitude of radial and circular stresses. The explanation lies in the change in shape of the tank that takes the shape of a ball. It is known that ball-shaped tanks, supported by tangents to the middle surface, have a membrane stress state completely free of bending stress /13, 14/.

In this particular case, we have a partial release of stress from bending, which results in a reduction in total stress.

By bulging the shell, a significant reduction of forces in the circular direction N_θ can be produced, because in that case forces are transmitted in the direction of meridian forces N_φ . In this case, the sheath at the upper end must be held in place by a horizontal DB ring to which it can transmit its edge forces N_φ (Fig. 2).

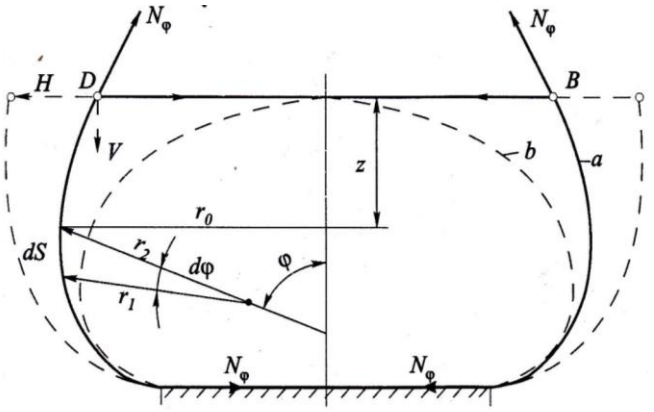

Figure 2. Shell of equal resistance.

Horizontal components (H) of N_φ are taken over by the DB ring and the vertical components (V) are taken over by vertical supports that must be provided at points D and B.

The obtained results at a given inaccuracy are confirmed by the analysis of tanks of equal resistance given in the literature. With such results, in order to make the best use of the material, the shell is convex shaped, and continuously passes into the ground, as a shell of equal resistance, so that the relationship applies in every place:

$$N_\theta = N_\phi = \sigma\delta ,$$

where: σ stress and δ shell thickness are allowed.

The shape of the meridian curve of line - a (Fig. 2) is defined by the differential equation:

$$\frac{d(r_0 \sin\phi)}{r_0 dr_0} = \frac{\gamma}{\sigma\delta} z ,$$

performed by observing elementary surface dS loaded with fluid pressure. The solution of this equation can be obtained graphically or by numerical integration. A shell of equal resistance can also have a closed shape that resembles a ‘rain drop’: ‘A drop-shaped tank’ will have a pure membrane state only in the case of uniform internal pressure.

In Fig. 4, the effect of wind on the tank shell without the upper DB stiffening ring is observed. Displacement and stress diagrams (Fig. 4 -b and c) show that the sheath behaves as a console. The largest displacements occur at the upper end of the tank, and for point D it is –0.446 cm, and at point B –0.228 cm. Point D has a larger displacement because the wind pressure on elements near CD derivative is greater than on elements along the AB derivative.

The radial stress σ_y diagram shows that the maximal stress is in the clamp (bottom-shell connection) where displacement is zero. The shape of the circular stress diagram is similar to the wind load diagram on the tank shell. The maximal value of this stress occurs at the place of the highest wind pressure and is 10.86 bar.

The effect of wind is especially important when assembling tank rings and their partial welding in several layers. The length of the partially welded places must be such as to ensure safety during installation, having in mind the amount of stress in individual layers.

The influence of wind in the case that the upper end of the tank is stiffened by the DB ring is shown in Fig. 5. Stiffening at the upper end of the tank, where displacements in the x and y axes are limited, significantly affects the distribution of stresses and displacements along AB and CD terminals. Due to mentioned limitations, we also have a change in sign of radial stress σ_y on derivative AB (Fig. 5c). Elements near the AB derivative in the first two joints are exposed to pressure, and further towards the top - to tensile stress.

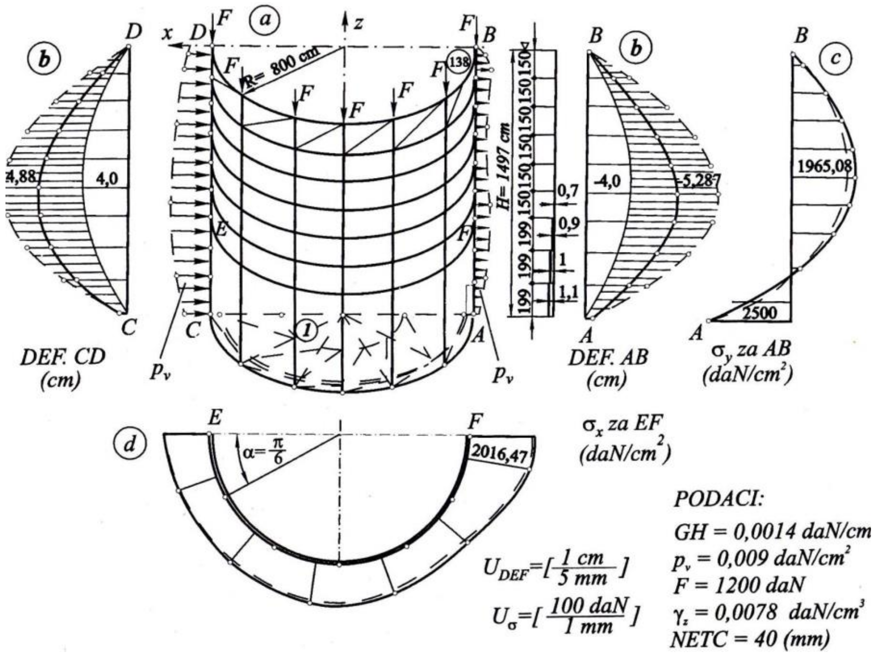

Figure 3. Vertical atmospheric tank of volume $V = 3000$ m^3 - influence of inaccuracies in the structure on displacement and stress.

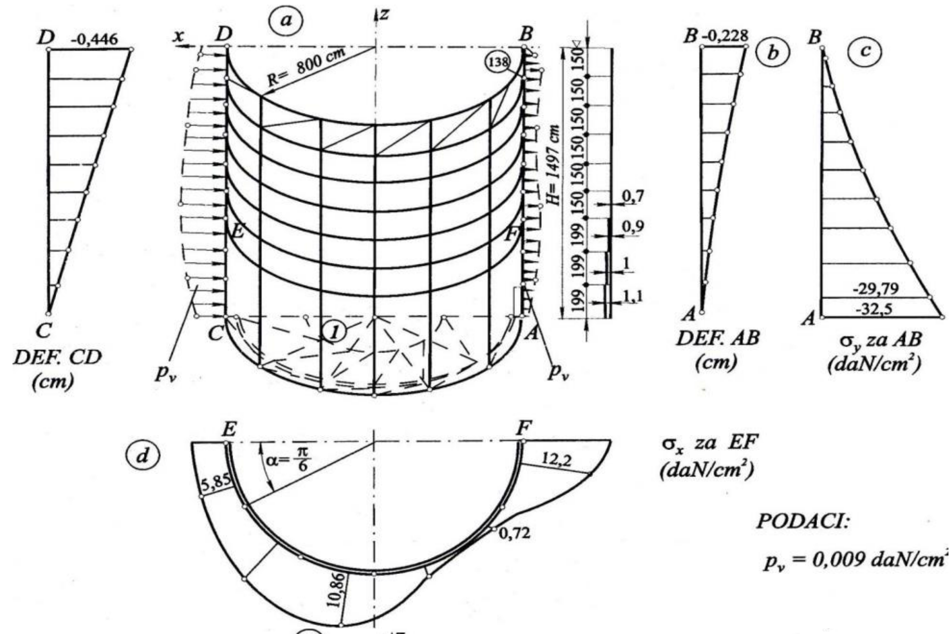

Figure 4. Vertical atmospheric tank of volume $V = 3000$ m^3 (influence of wind, without the upper stiffening ring DB).

Also interesting is the circular stress σ_x (Fig. 5d) in the circular line EF. The influence of mentioned restrictions on the top of the tank is manifested so that the elements near the CD outlet are exposed to compressive stresses, and further in elements near the EF line - to tensile stresses /15/. This is quite logical considering the load diagram of the mantle from wind pressure /16-18/.

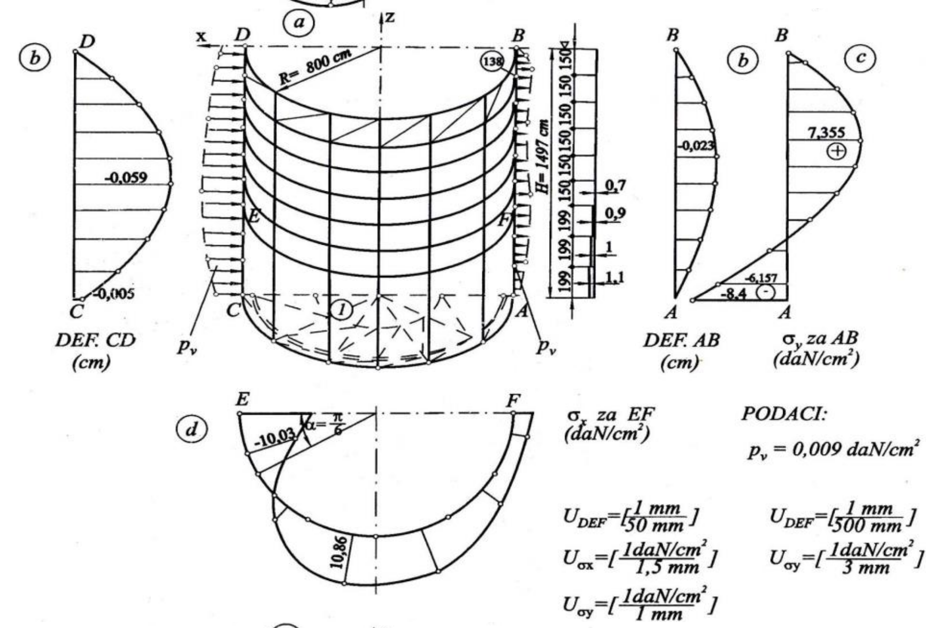

Figure 5 . Vertical atmospheric tank of volume $V = 3000$ m^3 (influence of wind, with upper stiffening ring DB).

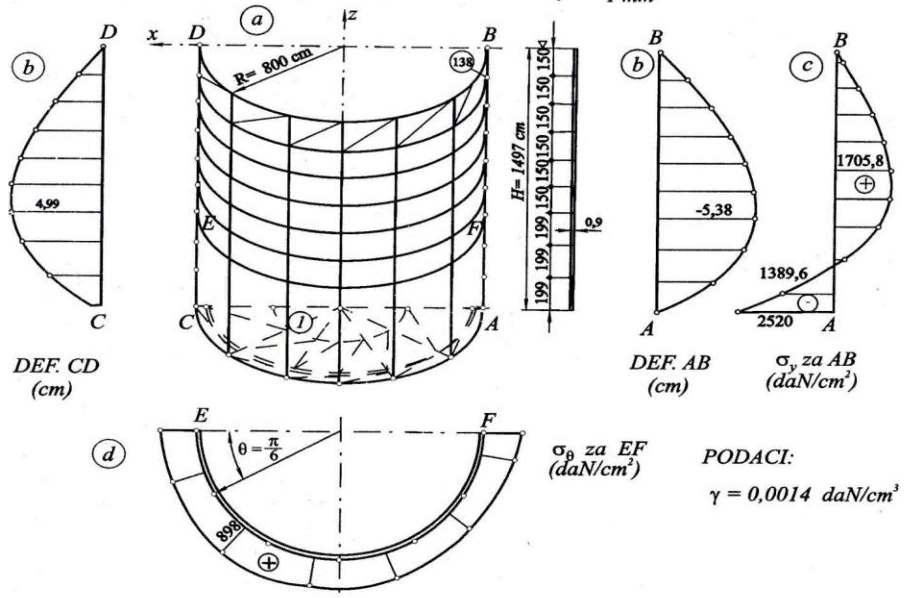

Figure 6. Vertical atmospheric tank of volume $V = 3000$ m^3 (magnitude of circular stresses for circular line EF).

Finally, the influence of hydrostatic pressure on the tank of constant thickness is observed (Fig. 6) in order to make a comparison with the analytical solution.

CONCLUSION

Comparing the obtained results by finite element method with the analytical solution, we see a great coincidence of the obtained radial stresses at clamping point:

FEM: –2520 daN/cm^2, analytical: –2447.911 daN/cm^2.

By comparing the magnitudes of circular stresses for the circular line EF, approximate values are observed:

FEM: 898 daN/cm^2, analytical: 1038.38 daN/cm^2.

When analysing this deviation, it should be kept in mind that when solving the finite element method, the stiffening of the upper end of the tank with a rigid DB ring is taken into account, which affects the mentioned deviations. Also, this restriction affects the sign of radial stress, which can be seen in Fig. 6c, where the change of sign is noticed at the end of the second member of the tank, unlike the analytical solution where this change is made in the first member under the influence of only clamps at the location of the shell-bottom joint. Otherwise, if we only have a constant flow tank shell without restrictions, with an upper stiffening ring and without a bottom, a membrane stress state under the action of hydrostatic pressure would be possible.

Therefore, membrane theory can be applied to such tanks at a sufficient distance from the top and bottom. The problem is more complex for locations where certain structural parts are welded and where, in addition to membrane stresses, there are others, primarily bending stresses, whose influence can be solved only by approximate methods, and effectively only by finite element methods.

It should be particularly emphasized that it is not possible to cover all the influences of loading and reliance on the disturbance of the membrane stress state by analytical methods, which is possible in the application of finite element method. The results obtained by FEM are very close to those obtained by experimental tests.

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