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Evaluation Of The Structural Behavior Of Vertical Metallic Tanks Through A Geometric Perspective

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Abstract:
The tanks are an integral part of the supply system and the water distribution network, compensating for fluctuations in consumption throughout the day because of the supply, emergency reserve, pressure balance in the network, and the pump operation's regularization. The steel tanks could have internal physical divisions (vertical cells) whose upper cell has the bottom of the suspended at a height that would guarantee the necessary manometric pressure to meet the said norm. This work aims to evaluate, through numerical analysis, through the Finite Element Method, the structural behavior of three types of vertical water tanks, type bowl, tubular and spherical, with the same volume of reserve composed of an elevated cell, submitted to the hydrostatic and wind actions, dimensioned within the recommendations of the AWWA D100-05 standard through a comparative study of the typologies used in the construction of these tanks through a geometric perspective. Within the typology of the three tanks analyzed, the most economical tank was the goblet one.

Key Word: *Vertical steel tank, AWWA D100 standard, Tank typology.*

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I. Introduction

The tanks are an integral part of the adduction system and the water distribution network, compensating for fluctuations in consumption throughout the day, given the adduction, emergency reserve, pressure balance in the network, and regularization of the repression operation [1].

They are considered heavy boiler equipment due to no small amount of material used in their manufacture, and they usually operate at atmospheric pressure or slightly above. These tanks build in different types, shapes, sizes, and materials depending on the application type [2].

The storage tanks are built with calendered steel sheets (curves), commonly known as courses, with dimensions dependent on the local steel industry and weld to form the cylinder. Due to their geometric slenderness, tanks are prone to fail by buckling, and often this failure starts in an elastic buckling form [3].

Elevated water tanks are subject to various loading types, such as dead loads, hydrostatic pressure, wind loads, imposed loads, and earthquake loads[4].

In the last decade, driven by government incentives through the housing program of the Ministry of the City, called Minha Casa Minha Vida Program, it caused the implementation of new subdivisions and horizontal condominiums, causing a great demand for drinking water storage tanks, most aerial, cylindrical and with variable diameter and height, called water castle [5].

The standards for design and sizing of metal tanks regularly used by designers in Brazil are NBR 7821 [6], API 650 [7], and AWWA D100 [8], comding with [9]. Within these standards, The NBR 7821/1983 - Welded Tanks for Storage of Oil and Derivatives, of the Brazilian Technical Standards Association (ABNT) and the American regulatory standard API 650 - 2013 - Welded Steel Tanks for Oil Storage - of the American Petroleum Institute (API), are specific to the oil and oil products reserve. [9] further states that for water storage, the AWWA D100-05 - Welded Carbon Steel Tanks for Water Storage, from American Water Works Associations, aims to provide minimum requirements for the design, construction, inspection, and testing of new welded carbon steel tanks. For tubular metallic tanks with no upper cells, the use of API 650, AWWA D100, and NBR 2871 standards present practically the same results of circumferential stresses and thicknesses when the standard minimum thicknesses are used [10].

Due to the lack of specific Brazilian technical standards for water storage in a metallic reservoir, the AWWA D100 standard has been used as a sizing parameter for tanks with vertical water storage cells. Integrally or partially, depending on the axial forces on the sides (ferrules) to check the allowable stresses to buckling (FL). They also state that within the design requirements, the AWWA D100 presents three methods for determining the allowable buckling stress (*FL*) for cylindrical sections, verifying the maximum compression stress due to the axial load to the loading of the applied to the courses [11].

This paper aims to evaluate the structural behavior of vertical water tanks, with the same reservoir volume composed of an elevated cell, submitted to hydrostatic and wind actions, dimensioned according to the recommendations of the AWWA D100-05 standard through a comparative study of three types used in the construction of these tanks through a geometric perspective depending on the characteristics of each tank.

II. Material and Methods

The tanks analyzed in this paper are metallic reservoirs for reserving water, composed of a suspended cell, with a capacity of 95.00 m³ and elevation of de the suspended boto of 12.0 m with three types of cells (Figure 1).

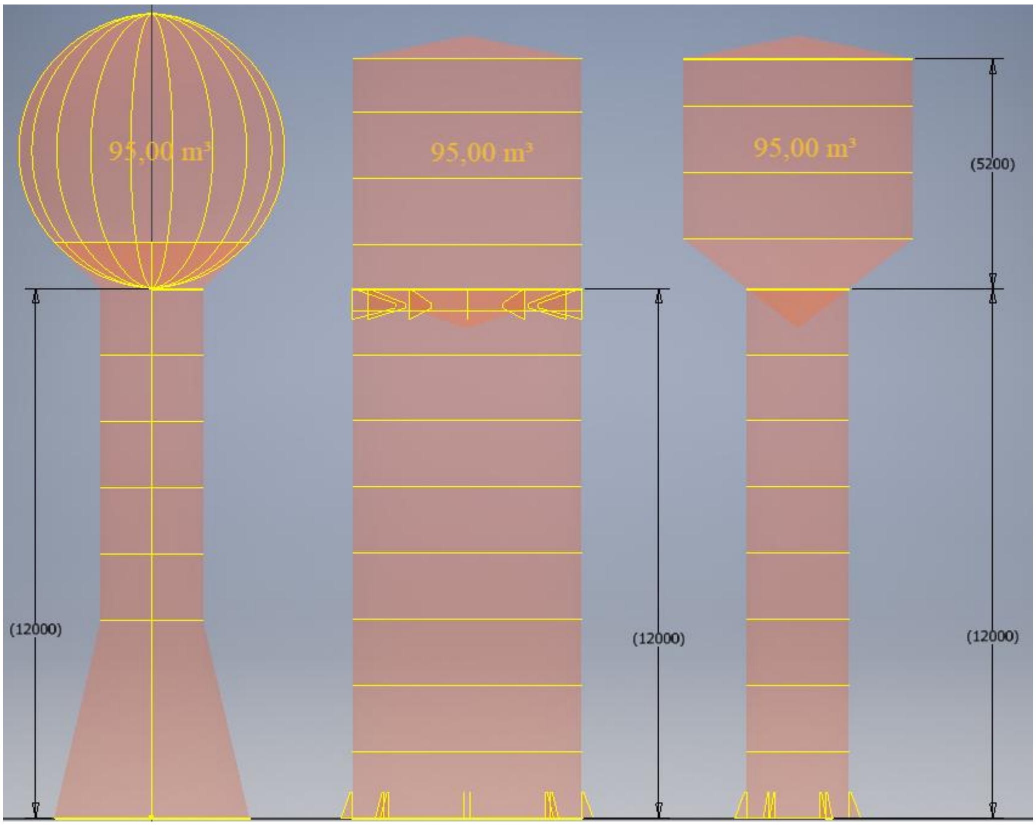


Fig1. The pattern of three steel tanks: Spherical cell, Tubular cell, and cup cell

2.1. NUMERICAL MODELING AND ANALYSIS

Numerical modeling and analysis have performed using Autocad Simulation Mechanical 2018 structural design and analysis software. Each tank ferrule has modeled as a shell element with constant thickness, isotropic properties, and a central plane. The dimensions of the finite elements were at 0.20 x 0.20 m (mesh). For each type of tank, according to the typology, a 3D finite element model was created. Figure 2 shows the meshing of the analyzed tanks.

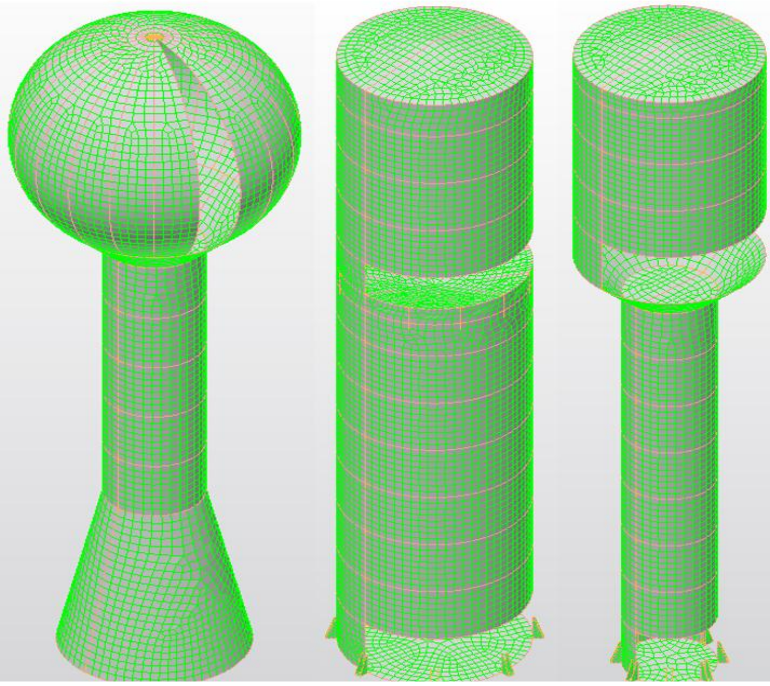


Fig2. The meshing of the pattern steel tanks

Tubular-type and goblet-type are the most used tanks in Brazil, and the spherical cell-type tank with a simple pedestal is used in the United States of America, as shown by the [12], in Figure 2.

Fig3. Spherical cell storage tank

2.2. LOADS AND ACTIONS

For the Finite Element Method analysis using the Autodesk Simulation Mechanical software, the following actions/loads are considered: wind, stored water (hydrostatic action), live loads on the ceiling, and the structure's dead load (Figure 3A and 3B).

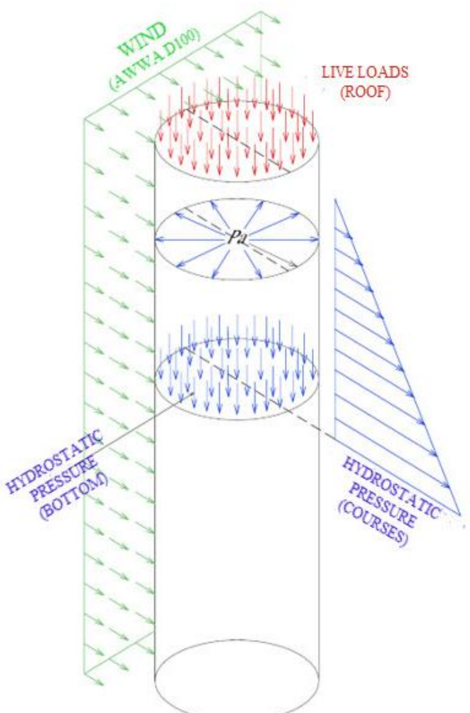


Fig3A. Loads

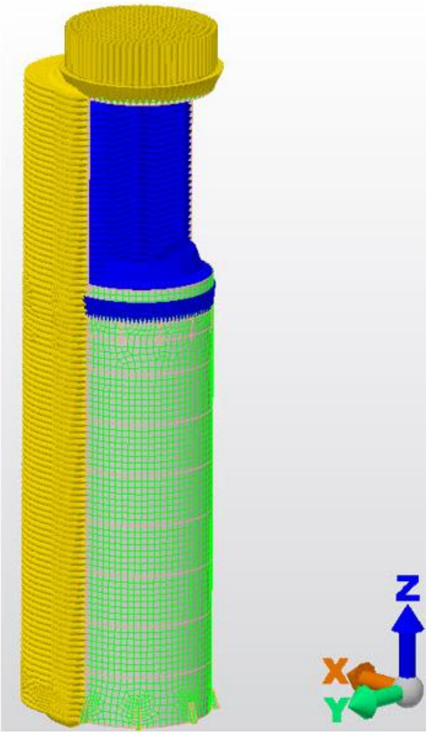


Fig3B. Loads by Simulation Mechanical

2.2.1. Wind Action

The wind action in a circular reservoir has calculated according to ABNT NBR 6123: 1987 - Forces decided by the wind in buildings, and it has assumed that the wind can act in any horizontal direction [13]. Since the tank structure is symmetrical about the Z-axis, perpendicular to the wind direction, the wind can strike perpendicularly to any generatrix in the tank. The tanks are considered empty and subject to uniform wind pressure q acting along the Z-axis, as shown in figures 3A and 3B [14].

The static component of wind pressure, DP, acts perpendicularly over an area element, is given by Expression 1:

$$\Delta \boldsymbol{P} = C_{pe} \cdot q \cdot dA$$

(1)

Since $\boldsymbol{C_{pe}}$, the external pressure coefficient is expressed for the structure's body type, assuming AWWA D100-05 that $\boldsymbol{C_{pe}}$, = $\boldsymbol{Cf}$ (Table 1). Furthermore, q is the wind pressure at a point where air stagnation occurs, obtained from Expression 2:

$$\boldsymbol{q} = 0{,}613 \cdot V_K^2 \quad , \quad \boldsymbol{V_K} = S_1 \cdot S_2 \cdot S_3 \cdot V_0$$

(2)

$\boldsymbol{V_K}$ in [m/s] and $\boldsymbol{q}$ in [N/m²]

The NBR 6123: 1987 denominates $\boldsymbol{V_0}$ of basic speed, corresponding to a burst of 3 seconds, exceeded average once every 50 years, measured at 10,0 m above the ground, in a flat and open location. For this work, V0 = 40.0 m / s was adopted.

The topographic factor S_1 is used to evaluate variations in terrain relief and adopted equal to 1.0 for this work.

The factor S_2 considers the combined effect of the terrain's roughness, the wind speed variation with the height above the terrain, and the building's dimensions.

$$S_2 = b \cdot F_r \cdot (Z/10)^P$$

(3)

b = meteorological parameter, p = exponent of variation of Z / 10, Fr = wind gust factor. For the tank height of 17,20 m, roughness II, class A, then S_2 = 1,05.

The S_3 factor assesses the degree of safety and the useful life of the structure, considering reservoirs with a low human occupation factor, and for this work, the value of 0.95 was adopted.

According to the structure's shape, the AWWA D100-05 recommends using the drag coefficient (*Cf*), as shown in Table 1. For a tubular tank with a cylindrical shape, the adopted *Cf* is 0,6.

Table 1. Force coeficiente C_f

Type of Surface	Cf
Flat	1.00
Cylindrical or conical with apex angle < 15°	0.60
Double curved or conical apex angle ≥ 15°	0.50

Considering the values already determined for V_0, S_1, S_2, and S_3, the value of DP is:

$$V_k = 40 \cdot 1.0 \cdot 1.05 \cdot 0.95 = 39.90 \text{ m/s}$$

$$q = 0{,}613 \cdot 39.90^2 = 975.90 \text{ N/m}^2 \text{ ou } 99.51 \text{ kgf/m}^2$$

$$\Delta_p = 0.6 \cdot 975.90 = 585.54 \text{ N/m}^2 \text{ ou } 58.71 \text{ kgf/m}^2$$

The wind pressure at the tank sides (DP) was 585.54 N / m².

2.2.2 Hydrostatic Action

The hydrostatic action causes effects that act in the radial and vertical directions and result in lateral pressure on the side and vertical pressure at the bottom of the tank [13]:

Lateral hydrostatic pressure $p = \gamma \cdot z$ (4)

Bottom hydrostatic pressure $qf = \gamma \cdot H$ (5)

γ is the liquid's specific weight, z the side pressure application rate, and H is the bottom's liquid rate.

2.2.3. Live Load

According to item 3.1.3.2 of the AWWA D100-05 standard, the minimum roof design live load applied to the tank' roof shall be 750 N / m² (15 lb / ft²).

2.2.4. Dead load structures

The dead load structure is automatically released by the Autodesk Simulation Mechanical 2018 software, considering the steels' specific weight in the tank design.

2.3. Application of the AWWA D100-05 Standard

2.3.1. Materials

The AWWA D100-05 classifies the structural materials to be used in the tanks into three classes for determining the allowable design stress based on their published minimum yield strength, *Fy*, as shown in Table 2 - Material classes.

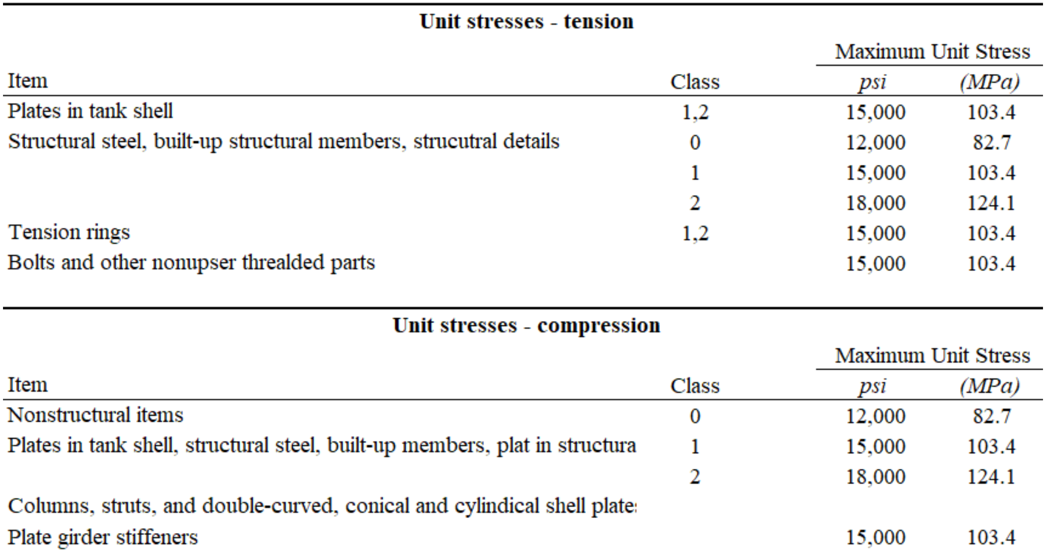
Table 2. Material classes

	F_y^*	
Class	*psi*	(*MPa*)
0	$F_y < 27{,}000$	$(F_y < 186.2)$
1	$27{,}000 \le F_y \le 34{,}000$	$(186.2 \le F_y \le 234.4)$
2	$F_y > 34{,}000$	$(F_y > 234.4)$

In this paper, the material used in the cylindrical shells (course), bottoms, and the roof is ASTM A36, with elasticity modulus (E): 205,000 MPa, Poisson's ratio (μ): 0.30, density (γ): 77,000 N / mm³, yield stress fy = 250.00 MPpa and last tension fu = 400.00 MPa. Its material is a Class 2 material.

The principal allowable stresses prescribed by AWWA D100-05 (Table 3), depending on the class of materials and applications in the metallic tanks.

Table 3. Maximum stresses allowed per class of material



Unit stresses - tension

Item	Class	Maximum Unit Stress *psi*	Maximum Unit Stress *(MPa)*
Plates in tank shell	1,2	15,000	103.4
Structural steel, built-up structural members, strucutral details	0	12,000	82.7
	1	15,000	103.4
	2	18,000	124.1
Tension rings	1,2	15,000	103.4
Bolts and other nonupser threalded parts		15,000	103.4

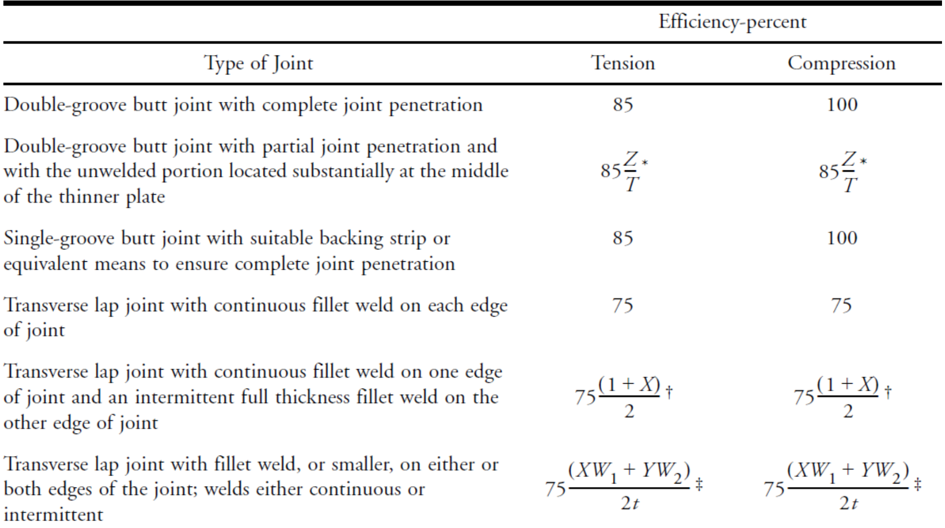
Unit stresses - compression

Item	Class	Maximum Unit Stress *psi*	Maximum Unit Stress *(MPa)*
Nonstructural items	0	12,000	82.7
Plates in tank shell, structural steel, built-up members, plat in structura	1	15,000	103.4
	2	18,000	124.1
Columns, struts, and double-curved, conical and cylindical shell plate:			
Plate girder stiffeners		15,000	103.4

2.3.2. Welding Efficiency

The welding efficiency values prescribed by the AWWA D100-05 standard are partially presented in Table 4, based on Table 15 - Weld design values - tank plate joints. In this paper, a double-groove butt joint with complete joint penetration was adopted. For plate welding subjected to tensile stress, the adopted efficiency was 85% (0.85).

Table 4. Weld design values - tank plate joints



Type of Joint	Efficiency-percent Tension	Efficiency-percent Compression
Double-groove butt joint with complete joint penetration	85	100
Double-groove butt joint with partial joint penetration and with the unwelded portion located substantially at the middle of the thinner plate	$85\frac{Z}{T}*$	$85\frac{Z}{T}*$
Single-groove butt joint with suitable backing strip or equivalent means to ensure complete joint penetration	85	100
Transverse lap joint with continuous fillet weld on each edge of joint	75	75
Transverse lap joint with continuous fillet weld on one edge of joint and an intermittent full thickness fillet weld on the other edge of joint	$75\frac{(1+X)}{2}\dagger$	$75\frac{(1+X)}{2}\dagger$
Transverse lap joint with fillet weld, or smaller, on either or both edges of the joint; welds either continuous or intermittent	$75\frac{(XW_1+YW_2)}{2t}\ddagger$	$75\frac{(XW_1+YW_2)}{2t}\ddagger$

2.3.3. Thickness of the Courses

The thickness of the courses on the side under circumferential pressure due to the tank's hydraulic pressure of tanks was calculated based on the following Expression (6), according to equation 3-40 of Sec. 3.7 of AWWA D100-05 [1] - Cylindrical Shell Plates:

$$t = \frac{4.9 \cdot h_p \cdot D \cdot G}{s \cdot E}$$

equation (6)

Where:

t = the required design shell-plate thickness, in mm

h_p = the height of liquid from the design nivel to the bottom of the sehll course being design, in m

D = the nominal tank diamenter, in m

G = product specific gravity (1.0 for water)

s = allowable design stress, in MPa (Table 3)

E = Joint efficiency (Table 4)

2.3.4. Buckling Analysis

AWWA D100-05 prescribes three analysis methods to check the tank's stability according to the side's buckling. In this work, Method 1, a simplified procedure based on membrane analysis techniques, was used. For Class 2 materials, the thickness/radius ratio of the reservoir where the buckling changes from elastic to inelastic regime, the value of (t / R)c is 0.0025372. The following formulas give the allowable buckling stress for Class 2 material:

- If 0 ≤ t / R ≤ (t / R) c means that buckling occurs in the elastic regime and the allowable buckling stress (F_L) is given by Expression 7:

$$F_L = 12.066 \cdot \left(\frac{t}{R}\right) \cdot \left[1 + 50.000 \cdot \left(\frac{t^2}{R}\right)\right]$$

(7)

- If (t / R) c ≤ t / R ≤ 0.0125, it means that buckling occurs in the inelastic regime, and the allowable buckling stress (F_L) is given by Expression 8:

$$F_L = 47.75 + 6109 \cdot \left(\frac{t}{R}\right)$$

(8)

- If t / R> 0.0125, it means that the buckling takes place in a plastic regime and the allowable buckling stress (F_L) is constant and is worth:

$$F_L = 124{,}10\ MPa\ (18.000\ psi)$$

III. Results

For dimensioning the side thickness, the thickness was verified due to circumferential pressure, using Expression (6), the thickness due to buckling, with the determination of the allowable tension (FL), using Expressions (7) and (8), and with the axial stresses exerted on the sides determined by the Simulation Mechanical software and the minimum thicknesses determined by Sec. 3.23 of the AWWA D100 - 05. Each course's required and adopted thickness was the most significant thickness determined within the three design criteria. Of course, with no contact with water (without hydrostatic pressure), thicknesses due to buckling and minimum thicknesses were verified.

Table 5 shows the summary of the Von Mises, circumferential and axial stresses, in each course of the three tanks, and the final thicknesses determined by the criterion described above for the different geometric types of tanks

Table 5. Courses stress and adopted thickness for the different geometric types of tanks

		Tubular tank					**Goblet tank**					**Spherical tank**				
	Course	Thickness	F_L	Stress (Mpa) with wind			Thickness	FL	Stress (Mpa)			Thickness	FL	Strees (Mpa)		
		(mm)	(Mpa)	Von Mises	Circunf.	Axial	(mm)	(Mpa)	Von Mises	Circunf.	Axial	(mm)	(Mpa)	Von Mises	Circunf.	Axial
Reservoir	12	4,75	27,1	3,6	3,37	0,54	4,75	25,4	2,8	2,6	0,4	4,75	0,0	2,8	0,4	0,0
	11	4,75	27,1	11,9	11,8	0,6	4,75	25,4	11,1	10,8	0,6	4,75	0,0	13,8	9,2	0,0
	10	4,75	27,1	19,7	19,8	2,6	4,75	25,4	19,8	20,6	8,2	4,75	21,6	33,5	27,4	4,2
	9	4,75	27,1	25,1	25,9	9,0	8,00	53,8	22,2	13,7	12,5	8,00	43,9	16,7	0,7	22,9
Column	8	6,35	40,5	14,8	8,9	15,0	6,35	78,3	21,7	0,0	21,8	4,75	73,9	29,4	0,1	30,0
	7	4,75	27,1	14,1	0,1	14,2	4,75	70,6	28,3	0,0	28,3	4,75	73,9	29,3	0,3	26,7
	6	4,75	27,1	14,0	0,1	13,9	4,75	70,6	27,8	0,0	27,8	4,75	73,9	29,3	0,3	29,3
	5	4,75	27,1	13,9	0,2	19,9	4,75	70,6	27,3	0,0	27,3	4,75	73,9	29,2	0,1	28,9
	4	4,75	27,0	14,0	0,4	14,0	4,75	70,6	26,8	0,2	26,9	4,75	73,9	33,0	0,0	30,0
	3	4,75	27,1	14,2	0,7	14,3	4,75	70,6	26,4	0,0	26,4	6,35	82,7	17,3	0,7	17,5
	2	4,75	27,1	14,9	4,4	15,0	4,75	70,6	26,5	3,4	26,5	6,35	71,5	16,5	1,3	15,0
	1	4,75	27,1	18,6	3,5	16,6	6,35	78,3	20,6	0,7	21,4	6,35	51,2	12,4	0,8	12,3

Figure 4 shows the tanks with the required thickness for each course of the thanks side, according to Table 5.

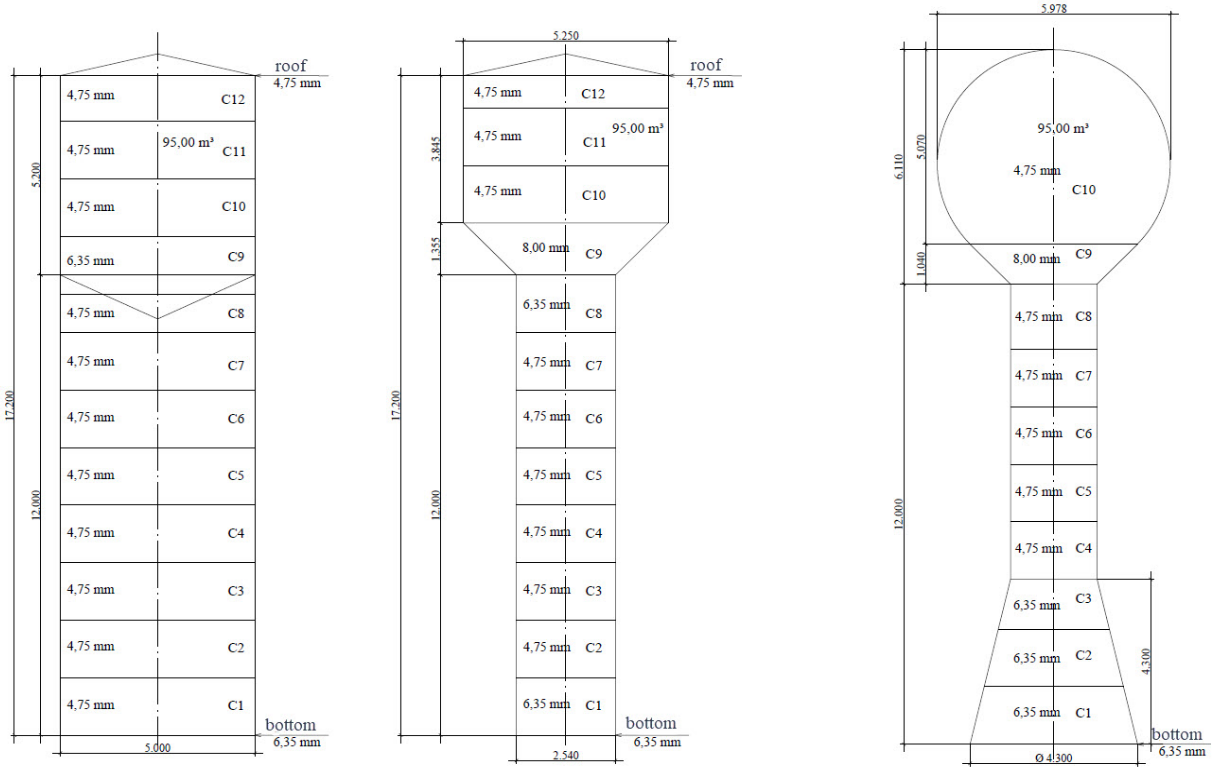


Fig4. Von Mises, circumferential and axial stresses [MPa] of the tubular tank

Figures 5, 6, and 7 show the Von Mises, circumferential and axial stresses acquired by the Autodesk Simulation Mechanical 2018 software on each side shell of the three tank types.

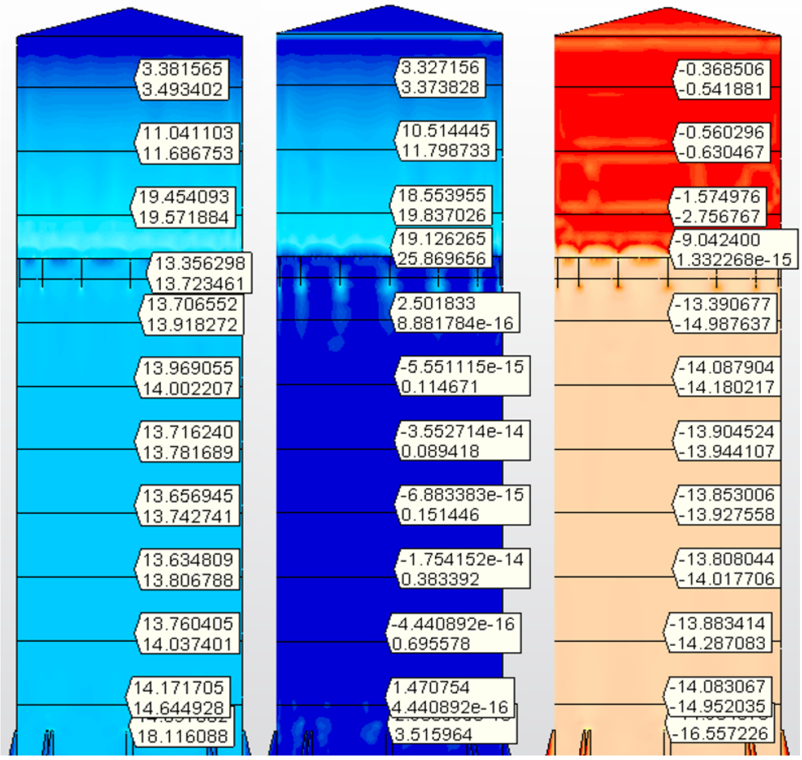


Fig5. Von Mises, circumferential and axial stresses [MPa] of the tubular tank

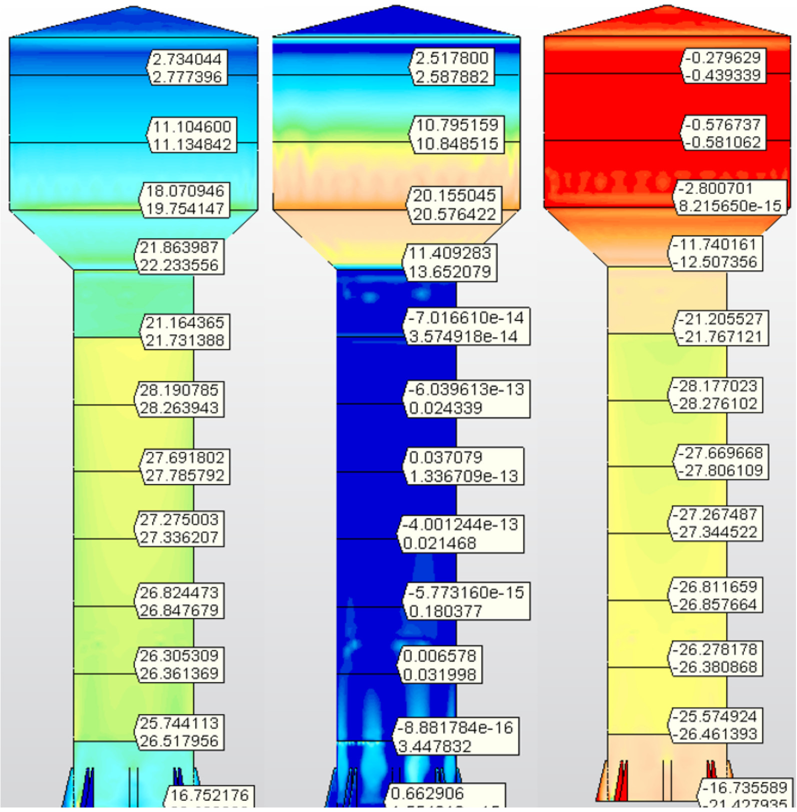


Fig6. Von Mises, circumferential and axial stresses [MPa] of the goblet tank.

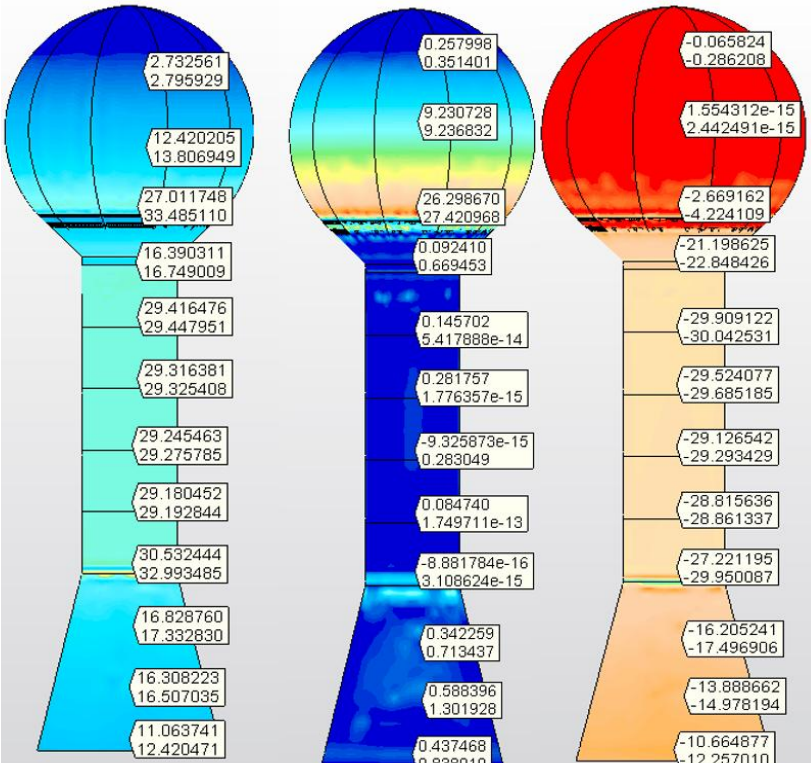


Fig7. Von Mises, circumferential and axial stresses [MPa] of the spherical tank

The tanks' weights were calculated without using cutouts or scraps and leftovers, but the plate surfaces. Table 6 shows the general summary of the weights of the three types of tanks proposed in this paper.

Table 6. Tanks' weights

TANK	
Type	Weight
Tubular	12,949.44
Goblet	9,858.34
Spherical	18,124.23

The weights of the tanks can be seen in the total weight x type of tanks, in Figure 8.

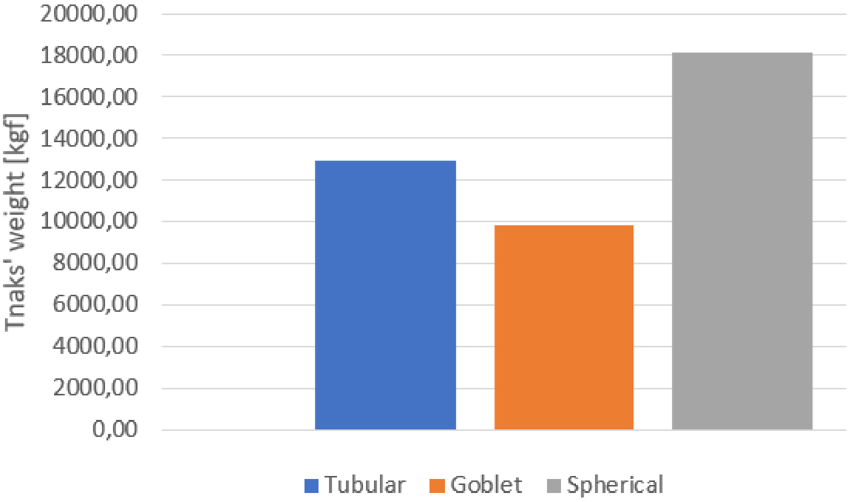


Fig8. Total weight x type of tanks

IV. Conclusion

From the results obtained in this paper, it can be concluded, within the studied volume and height, that the goblet-type tank is the most economically viable and is about 83.8% lighter than the spherical type tank, according to the rules of the AWWA D100- 05. The tubular tank is about 29.9% heavier than the goblet-type tank and can be considered an option. The bowl-type tank is the most economically viable within the three types studied, and the spherical type tank is anti-economic.

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