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Study and Design of a 500 m³ Fixed-Roof Diesel Storage Tank Using a Comparative Method Based on the Eurocode, API 650, and Codres Construction Codes

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Abstract

This work presents the study and design of a 500 m³ fixed-roof storage tank intended for diesel storage at the Limbe Oil Yard, using a comparative approach between the API 650, Eurocode, and CODRES standards. The project aims to ensure the refueling of ships and the supply of industrial equipment at the Cameroon Shipyard and Industrial Engineering Complex. The methodology adopts two approaches: a first analytical approach based on membrane theory for isotropic elastic materials, and a second numerical approach using the finite element method (FEM) implemented in *Autodesk Robot Structural Analysis* software. The comparison criteria include wind load analysis, structural components, ease of use, structural reliability, and construction cost. The results reveal a 1 mm thickness difference for the shell courses between Eurocode calculations and those obtained using the other codes. In addition, an estimated cost difference of approximately 3 million CFA francs is observed between the CODRES-based design and those developed according to API 650 or Eurocode.

Keywords

Design, Sizing, Reservoir, Dress, Methodology, Finite Elements

1. Introduction

Large-scale storage of liquids used in the petroleum, petrochemical, and chemical industries is primarily achieved through welded steel storage tanks, generally installed outdoors and either resting directly on the ground or supported by appropriate foundations [1]-[4]. The design and fabrication of such structures must comply with established engineering standards to ensure structural integrity, operational safety, and economic efficiency throughout their service life [1]-[4].

However, within the national context, the absence of specific regulatory guidance from the National Standards and Quality Agency (ANOR) regarding the design of steel structures, and particularly petroleum storage tanks, has led project owners to adopt various international design standards such as API 650, the Eurocodes, and the Tank Construction Code (CODRES) [1]-[7]. The use of different design standards may result in significant variations in structural dimensions, material requirements, construction costs, and overall reliability levels [1]-[7]. Consequently, selecting the most appropriate design standard becomes a critical engineering and economic challenge.

In light of these considerations, the central research question addressed in this study is as follows: Which construction standard is best suited to the technical, economic, and environmental conditions of our country for the design and fabrication of cylindrical petroleum storage tanks?

To answer this question, this work aims to design and perform the preliminary sizing of a fixed-roof diesel storage tank with a capacity of 500 m^3 using the provisions of API 650, the Eurocodes, and CODRES [1]-[7]. A comparative analysis of the results obtained from each standard is then conducted to identify the most appropriate approach for local implementation [8] [9].

The comparison is based on several key criteria, including wind load assessment procedures, design methodologies, ease of application, project construction costs, structural reliability, and the characteristics of the various tank components. Through this evaluation, the study seeks to provide a rational basis for selecting the most suitable design standard for petroleum storage tank projects in the national context.

2. Materials and Methods

Since tanks are generally intended to contain liquids, they must ensure complete leak-tightness [1]-[4]. In most cases, an adverse stress state is considered, and carbon steel S235JR is commonly used for construction, due to its high ductility and ability to deform without failure under high stress levels [1]-[4]. In addition, a specific internal coating is often applied to improve corrosion resistance.

The study focuses on a vertical cylindrical steel storage tank, also referred to as an atmospheric storage tank.

2.1. Tank Selection Criteria

2.1.1. Layout

The required storage capacity and the applicable regulatory safety distances, which depend on the selected nominal diameter, govern the choice of the installation site. The location of the tank and all associated auxiliary units is shown on layout drawing No. 1.

2.1.2. Construction Type

The tank is designed with a fixed roof supported by an internal steel structure. Assembly will be performed mainly by welding, with bolted connections used locally in the roof structural framing. A schematic view of the tank is provided in the figure below to illustrate the external configuration.

2.1.3. Design Assumptions

For the design and sizing of the diesel storage tank, the following assumptions are adopted:

H1: The study is restricted to the steel structure only.

H2: The live load on accessible areas is taken as 250 kg/m^2, as specified in the project specifications.

H3: Since the site wind speed is not known, a reference wind speed of 86.4 km/h is used, corresponding to the minimum value prescribed by wind design standards. The adoption of a reference wind speed of 86.4 km/h (24 m/s) for the Limbé site is based on the following considerations:

Lack of specific local data: The reference wind speed for Limbé is difficult to determine precisely from available historical local records. However, according to the EUROCODE, the basic wind $v_{b,0}$ speed is calculated from the 10-minute mean wind speed for the region. This value can be converted into the 10-minute reference wind speed at 10 m height using the following relation:

$$v_{b,0} = C_r C_s v_{ref} \tag{1}$$

$v_{b,0}$ is the basic wind speed (m/s);

C_r is the mean 10-minute wind speed (m/s);

C_s the roughness factor, accounting for terrain characteristics;

v_{ref} the size factor, correcting for structure dimensions relative to the reference area.

This approach allows the wind load on the tank to be estimated in accordance with EUROCODE recommendations, even in the absence of detailed local wind measurements.

H4: The self-weight of pipelines attached to the structure is neglected.

H5: The acceleration due to gravity is taken as 10 m/s^2.

H6: The design temperature is set at 50 ˚C, as specified in the project requirements.

H7: For the seismic analysis, the site is assumed to be located in a "normal risk" seismic zone (zone A; class B, type C), as recommended by the CODRES code when no specific site data are available.

H8: Design internal pressure [8] [10]. $P_d = 60$ mbar.

H9: $P_v = -5$ mbar; Design external pressure [8] [10].

H10: Density of diesel fuel [8] [11] [12]. $\rho = 860\,\text{kg/m}^3$.

2.2. Shell Plate Course Length

Ideally, each course of the tank shell would be made from a single plate, which would minimize welding work and reduce erection time. However, due to technical constraints related to manufacturing, forming, and transportation, the plate length is selected so as to obtain an integer number of plates of identical length per course. Using plates with a length of 5338 mm, a total of 5 plates per shell course is obtained.

2.3. Design Methodology Adopted by the Three Standards

During the design of any structure, the designer must deal with several sources of uncertainty. These may arise from variability in material properties or from the magnitude and combination of loads [1]-[4] [7] [9]. Among the evaluated standards, two design methodologies are identified:

The Allowable Stress Design (ASD) method.

The Load and Resistance Factor Design (LRFD) method.

2.3.1. Allowable Stress Design (ASD) Method

This method, adopted by CODRES and API 650, accounts for uncertainties by applying a single global safety factor to limit the allowable stresses in the structure.

2.3.2. The Load and Resistance Factor Design (LRFD)

Method is specified in the Eurocodes and addresses uncertainties by using multiple partial safety factors [2] [5]-[7]. In Eurocode, the limit state design (LSD) approach is adopted, in which separate factors are applied to both actions (loads) and resistances. In general, when a limit state in terms of strength or deformation is considered, the design value of the effect of actions must be verified to remain less than the corresponding design resistance. The applied factors are calibrated using structural reliability theory, which is based on the probability of failure.

2.4. Shell Thickness Design Equations

2.4.1. Shell Thickness According to API 650

For vertical cylindrical tanks, API 650 recommends a minimum shell thickness of 5 mm for tanks with a diameter less than 15 m.

$$\begin{cases} T_d = \dfrac{4,9xDx\left(H-0,3\right)xG}{S_d} + C_A \\ T_t = \dfrac{4,9xDx\left(H-0,3\right)}{S_t} \end{cases} \tag{2}$$

with T_d is the theoretical thickness, T_t the hydrostatic thickness, D: tank diameter, H: filling level height, Sd, theoretical allowable stress, St hydroallowable stress, G: density of the sorted product and CA corrosion allowance thickness.

2.4.2. Calculation Formulas for Shell Course Thicknesses According to the CODRES Code

The CODRES code defines a minimum thickness of 5 mm to be used for carbon steel shell plates [10].

$$\begin{cases} e_c = \dfrac{D}{20f}\left(96\rho\left(H_c - 0,3\right) + P\right) + C \\ e_t = \dfrac{D}{20f}\left(96\rho\left(H_c - 0,3\right) + Pt\right) \end{cases} \tag{3}$$

with e_c is required shell thickness under design conditions in mm, e_t required shell thickness under test conditions in mm, H_c vertical distance between the bottom of the considered shell course and the tank height in m, ρ maximum density of the stored product under normal operating conditions, D diameter of tank in m, p the design pressure in mbar, p_t the test pressure, f allowable stress under test conditions and C the corrosion allowance in mm.

All these requirements are defined according to the CODRES design provisions.

2.4.3. Formula for Calculating Shell Course Thicknesses According to the EUROCODE Standard

The EUROCODE standard recommends using a minimum thickness of 6 mm for tanks with a diameter D ≤ 33 m, 8 mm for 33 m < D ≤ 60 m, and 10 mm for D > 60 m.

$$t = \frac{\left[\gamma_F \rho g\left(H_j - 0.3\right) + P_0\right.}{f_{yd}} \tag{4}$$

t: thickness of the considered shell course, ρ density of the contained liquid, g: gravitational acceleration, P_O design value of the pressure above the liquide, f_{yd} design yield strength of the material, γ_F partial safety factor, H_j: filling level height.

The design procedure is based on the limit state design philosophy adopted by the Eurocodes.

2.5. Determination of the Equivalent Height

2.5.1. For the CODRES Construction Code

The equivalent height H_e of each shell course is given by [10]:

$$H_e = h\left(\frac{e_{\min}}{e}\right)^{5/2} \tag{5}$$

With $e_{\min}$: nominal thickness of the top shell course e: nominal thickness of the considered shell course, in mm, h: height of each shell course above the main beam, in m, D: tank diameter

$$H_E = \sum H_e \tag{6}$$

1. Determination of the coefficient K

The coefficient (K) is determined using the following expression [10]:

$$K = \frac{95000}{3,563v^2 + 580P_v} \cdot \frac{E_t}{E} \tag{7}$$

With P_v: design vacuum in absolute value, in mbar, v: wind speed, in m/s E: modulus of elasticity at ambient temperature, in MPa, E_t modulus of elasticity at maximum design temperature, in MPa.

2. Determination of the maximum allowed spacing between stiffeners

This spacing is given by the following formula:

$$H_p = K\left(\frac{e^s_{\min}}{D^s}\right)^{2.5} \tag{8}$$

2.5.2. For the EUROCODE Construction Standard

1. Primary stiffeners

According to the EUROCODE, fixed-roof tanks with a supporting roof structure can be considered sufficiently stiffened at the top of the shell by the roof structure itself. Therefore, the use of primary stiffeners is not required.

2. Secondary stiffeners

The equivalent height h_e of each shell course is given by:

$$h_e = h\left(\frac{t_{\min}}{t}\right)^{2.5} \tag{9}$$

With $t_{\min}$: thickness of the thinnest shell course, t: thickness of the considered shell course, h: height of the considered shell course.

3. Determination of the maximum allowed spacing of stiffeners

This spacing is given by the following formula:

The maximum stiffener spacing is calculated using the following expression

$$H_p = 0.46\times\left(\frac{E}{P_{sd}}\right)\times\left(\frac{t_{\min}}{t}\right)^{2.5} Rxk \tag{10}$$

E: Young's modulus; E = 2.1 × 10^5 N/mm^2;

$t_{\min}$: minimum thickness of the shell courses;

R: tank radius;

p_{sd}: pressure due to wind and partial vacuum.

2.5.3. For the API 650 Construction Standard

The transformed shell height is calculated using the following relationship:

The formula for calculating the transformed height of the shell is given by:

$$W_{tri} = \sum_{i=1}^{6} W_i x \sqrt{\left(\frac{t_{\text{uniform}}}{t_{\text{current}}}\right)^5} \tag{11}$$

Such as:

W_i: plate width = 1800 mm;

t_{uniform}: thickness of the last shell course = 5 mm;

t_{current}: thickness of each shell course, in mm.

2.6. Calculation of Bottom Plate Thicknesses

The tank bottom can be flat, convex, or concave. A slightly convex shape is generally given to the foundation to allow settlement during the hydraulic test of the tank.

2.7. Calculation of the Annular Flange

2.7.1. Calculation According to the CODRES Construction Code

The formula used for the calculations is as follows:

$$e_{annul} \geq \left\{3+\frac{e_1}{3};\ 6\ \text{mm}\right\} \tag{12}$$

Where:

e_1 : thickness of the bottom shell course, in mm, excluding corrosion allowance.

This annular flange plate must have a minimum width l_a, as indicated in the figure above and defined by [10]:

$$l_{annul} = \max\left\{\frac{240}{\sqrt{H}} x e_{annul}; 500\ \text{mm}\right\} \tag{13}$$

H : design height of the liquid, in m.

2.7.2. Calculation According to the API 650 Standard

The formula used is as follows:

$$e_{annul} = \max\left\{e_{annul,?test}; x e_{annul,hydro}\right\} \tag{14}$$

Where:

$e_{annul,test}$: thickness of the annular plate corresponding to the test stress;

$e_{annul,hydro}$: thickness of the annular plate corresponding to the hydrostatic stress.

The width of the annular flange is given by the following formula:

$$b = \max\left\{600; \frac{370 x e_{annul}}{\sqrt{HG}}\right\} \tag{15 (API 650)}$$

2.7.3. Calculation According to the EUROCODE Standard

The formula for calculating the thickness of the annular flange is as follows:

$$e_{annul} = \left(\frac{e_s}{3}+3\right) en\ \text{mm} \tag{16}$$

With: e_s : thickness of the first shell course of the shell.

Consequently, the width of the annular flange must be between 500 mm and the limiting value W_a, given by:

$$W_a = \left(\frac{f_y e_{annuel}^2}{\rho g H}\right)^{1/2} \tag{17}$$

Where:

f_y : yield strength of the material used, e_{annul} : thickness of the annular plate, including corrosion allowance;

ρ : density of the contained liquid, g : gravitational acceleration, H : maximum liquid height.

2.8. Calculation of Stresses and Shell Deformation Modeling

We will determine the characteristic stresses around a point of each shell course constituting the tank, in order to use them for the tank's design or for regulatory verification of its dimensions [1]-[4].

2.8.1. Stress Modeling and Calculation

The determination of the characteristic stresses is based on thin-shell theory. As illustrated in the shell segment under study (Figure 1), the cylindrical wall is defined by its mean radius R and its thickness e.

Longitudinal stress: This stress is obtained by isolating a section of the shell. The force diagram acting on this isolated segment is shown in Figure 2.

Circumferential (hoop) stress: The transfer of hydrostatic pressure to the shell wall requires rigorous verification. Analysis of the second shell segment (Figure 3) allows the formulation of the Von Mises failure criterion.

The calculation of shell thickness depends on the design philosophy of each standard: API 650: Uses the One-Foot Method, based on the Allowable Stress Design (ASD) approach.

CODRES: Specifies a minimum thickness of 5 mm for carbon steel plates.

Eurocode: Applies the Limit State Design (LRFD) approach with partial safety factors (γF).

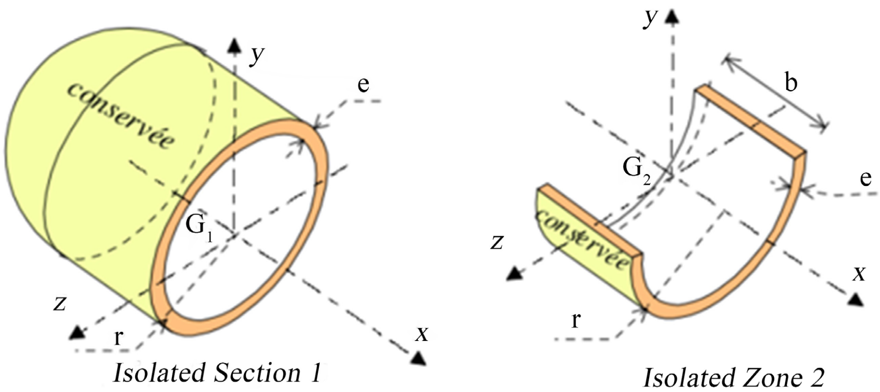

Figure 1. Section to be studied.

The maximum pressure in our tank has a magnitude of $\|P_{\max}\|$. The cylindrical part of the tank (cylindrical shell) is characterized by a mean radius "R" and a thickness "e". This pressure is given by the following formula:

$$P_{\max} = \rho g h_{\max} \tag{18}$$

here: is the density of diesel fuel (kg/m^3), is the gravitational acceleration (9.81 m/s^2), $h_{\max}$ is the maximum liquid height in the tank (m).

For a thin-walled cylindrical shell subjected to internal pressure, the analytical circumferential (hoop) and axial stresses can be estimated using:

$$e_\theta = \frac{P_{\max}}{e} R,\ e_x = \frac{P_{\max}}{2e} R \tag{19}$$

where:

R is the mean radius of the cylindrical shell,

e is the shell thickness.

e_θ is the circumferential stress,

e_x is the axial stress.

$$P_{\max} = \rho g h_{\max} \tag{20}$$

With

ρ: is the density of the liquid stored;

g: is the acceleration due to gravity;

h: is the considered liquid height.

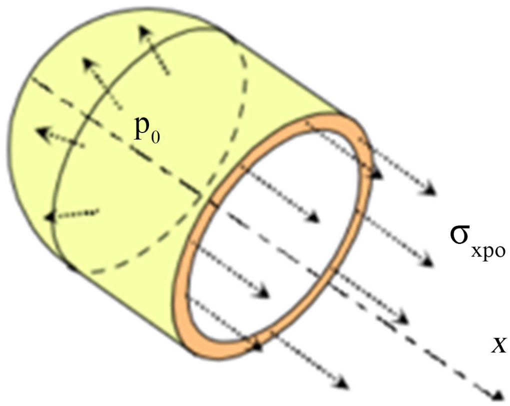

Figure 2. Isolated section (1).

2.8.2. Circumferential Stress

It is given by the following formula:

The circumferential stress is calculated using the following expression:

$$e_{xpo} = \frac{N_{xpo}}{S_{annul}} = \frac{PxR}{2e} \tag{21}$$

$$S_{annul} = 2\pi e r$$

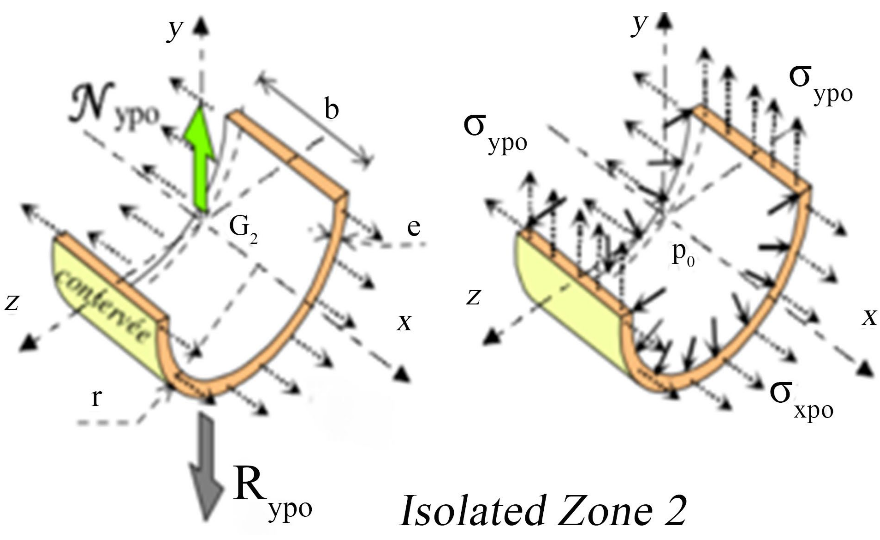

Figure 3. Section (2).

2.8.3. Resistance Condition

The shell wall is considered safe if the following conditions are satisfied.

The wall resists if:

$$\sigma_{eq,miss} \leq f_{eq,Rd} \tag{22}$$

$$\sigma_{eq,v,miss} = \sqrt{\sigma_{xpo}^2 + \sigma_{ypo}^2 - \sigma_{xpo} x \sigma_{ypo} + 3\tau_{xy}} \tag{23}$$

with $\tau = 0$ because σ_{xpo} and $\sigma_{ypo} \gg P$.

2.9. Verification of Tank Stability under Wind Loads

2.9.1. Stability According to the API 650 Standard

According to API 650 §5.11.2.1, an unanchored tank is considered stable under wind loading when the overturning moments do not exceed the stabilizing moments generated by the tank self-weight and the stored liquid

$$0.6M_w + M_{pi} < \frac{M_{DL}}{1.5} + M_{DL} \tag{24}$$

$$M_w + F_p\left(M_{pi}\right) < \frac{\left(M_{DL} + M_F\right)}{1.5} + M_{DLR} \tag{25}$$

$$M_{ws} + F_p\left(M_{pi}\right) < \frac{M_{DL}}{1.5} + M_{DLR} \tag{26}$$

Where:

M_{pi} : is the moment about the shell-to-bottom joint due to design internal pressure = 0.

M_w : is the overturning moment about the shell-to-bottom joint due to horizontal and vertical wind pressures.

M_{DL} : is the moment about the shell-to-bottom joint from the nominal weight of the shell and roof structure supported by the shell (excluding roof plates).

M_F : is the moment about the shell-to-bottom joint from the weight of the contained liquid.

M_{DL} : is the moment about the shell-to-bottom joint from the nominal weight of the roof plate plus any attached structural elements.

M_{ws} : is the overturning moment about the shell-to-bottom joint from horizontal wind pressure alone.

F_P : is the pressure combination factor.

2.9.2. Stability According to the EUROCODE

1. Plastic Limit State

Condition to be verified.

$$\sigma_{eq,Ed} \leq f_{eq,Ed} \tag{27}$$

With:

$f_{eq,Ed}$ It is the Von Mises design resistance, which is given by the following expression:

$$f_{eq,Ed} = \frac{f_y}{\gamma_M} \tag{28}$$

$\sigma_{eq,Ed}$ It is the equivalent design stress calculated separately, also known as the Von Mises equivalent stress.

2. Limit State: Buckling

a) Buckling under Meridional (Axial) Compression

The verification condition is:

$$\sigma_{eq,Ed} = \frac{1}{t}\sqrt{n_x^2 + n_\theta^2 - n_x n_\theta + 3n_{x\theta^2}} \tag{29}$$

n_x : Meridional membrane force.

n_θ : Circumferential Membrane Force.

$n_{x\theta}$: Shear Membrane Force.

It is necessary here to verify at every point of the structure that the following condition is satisfied:

$$\sigma_{x,sd} \le t\ x\ \sigma_{xEd} \tag{30}$$

With σ_{xEd} Which is the ultimate meridional stress defined by:

$$\sigma_{xEd} = \frac{\sigma_{xRk}}{\gamma_{Mo}} \tag{31}$$

Furthermore, the characteristic buckling stress is calculated from the relation below:

$$\sigma_{xRk} = \chi_x x f_y \tag{32}$$

The reduction factor χ_x is determined by:

$$\begin{cases} X_x = 1 & if\ \overline{\lambda_x} \le \overline{\lambda_0} \\ X_x = 1 - 0.6x\left((\frac{\overline{\lambda_x} - \overline{\lambda_0}}{\overline{\lambda_p} - \overline{\lambda_0}} \right) & if\ \overline{\lambda_0} \le \overline{\lambda_x} \le \overline{\lambda_p} \\ X_x = \frac{\alpha}{\overline{\lambda_0}^2_x} & if\ \overline{\lambda_p} \le \overline{\lambda_x} \end{cases} \tag{33}$$

b) Buckling under Circumferential Compression

Our calculations will be carried out for an unstiffened cylindrical shell with variable wall thickness in steps. Thus, for each shell course thickness t_j, it must be verified that the following condition is satisfied:

$$\sigma_{\theta Rd,j} \le \sigma_{\theta Rd,j}$$

$$\sigma_{\theta Rd,j} = \frac{n_{\theta Rd,j}}{t_j} \leftrightarrow n_{\theta sd} \le n_{\theta Rd,j}\ x t_j \tag{34}$$

2.9.3. Stability According to the CODRES Construction Code

According to the CODRES construction code, the tank is stable under wind loading if the following conditions are satisfied:

$$0.6\times M_{vent}+M_{\text{pression}}\leq\frac{M_{\text{weight}}}{1.5} \quad (35)$$

$$M_{vent}+0.4M_{\text{pression}}\leq\frac{M_{\text{weight}}+M_{\text{produit}}}{2} \quad (36)$$

with, M_{vent} : Moment due to wind pressure on the shell of the tank; M_{pression} : Moment due to internal pressure; M_{produit} : Moment due to the weight of the residual product; M_{weight} : Moment due to the weight of the entire structure including its accessories.

3. Results and Discussion

In this section, we compare the results obtained according to API 650, EUROCODE, and the CODRES construction code. The comparison focuses on the following aspects:

1) Wind studies;

2) Structural components of the tank;

3) Ease of use of each standard;

4) Structural reliability;

5) Manufacturing cost of the tank;

6) Methods employed by each standard [1]-[4] [7]-[9].

3.1. Wind Study

Presentation of Methods

Wind loading is treated according to EN 1991-1-4 for the Eurocode approach, ASCE 7-10 (2015) for API 650 calculations, and the NV65 regulation for the CODRES construction code.

All three standards agree on a reference height of 10 meters, from which wind speed is calculated, as well as on an annual exceedance probability of 2%, corresponding to an average return period of fifty years. However, the reference wind speed duration differs:

1) Eurocode and NV65 use the 10-minute mean wind speed;

2) ASCE 7-10 uses the 3-second gust wind speed.

A similarity among the standards lies in the calculation of the longitudinal wind load: it is obtained by multiplying the wind pressure by the projected area of the section (i.e., the horizontal cross-section of the reservoir perpendicular to the wind direction) and by other relevant factors.

The difference lies in the distribution of dynamic pressure:

1) In ASCE 7-10 (2015), it is uniform along the structural section;

2) In EUROCODE and CODRES, it varies with height. Once the dynamic pressure is determined, the wind pressure is calculated in the same manner for all three codes.

3.2. Structural Components of the Reservoir

Table 1 below lists the structural components of the reservoir. An analysis of this table allows us to draw the following conclusions:

Table 1. Summary of the reservoir's characteristic elements according to the three standards.

		EUROCODE	API 650	CODRES
Shell plate thickness	Shell Number	Calculated thickness (mm)	Calculated thickness (mm)	Calculated thickness (mm)
	1st Shell Course	7.21	5.94	5.18
	2nd Shell Course	6.86	4.49	4.70
	3rd Shell Course	5.51	4.03	3.40
	4th Shell Course	5.16	3.58	3.01
	5th Shell Course	4.81	3.12	2.48
	6th Shell Course	4.46	2.66	2.37
Shell plate thickness				
Bottom plate thickness		6	No annular plate	No annular plate
Annular plate thickness (W_a)		784	600	500
Annular overlap width		60	60	60
Distance of projected annular plate outside		50	50	50
Edge angle		$L80\times80\times6$	$L50\times50\times5$	$L50\times50\times5$
Secondary stiffeners		None	None	None
Roof thickness		6	6	6
Primary stiffeners		stiffeners. none	stiffeners. none	stiffeners. none
Wind stability		Not wind-stable: anchoring required	Wind-stable: anchoring not required	Wind-stable: anchoring not required

1) All three standards agree on the need to use a 60 mm annular overlap;

2) For reservoirs with a diameter less than 12.5 m, as in this study, EUROCODE and CODRES do not recommend the use of an annular flange, whereas API 650 does;

3) Shell plate thicknesses obtained using EUROCODE are 1 cm greater than those obtained using CODRES or API 650;

4) According to CODRES and API 650, the reservoir is wind-stable and does not require anchoring; however, EUROCODE indicates that the reservoir is not wind-stable and requires anchoring;

5) All three standards agree that primary and secondary stiffeners are not required;

6) CODRES and API 650 recommend a minimum annular flange width of 600 mm, whereas EUROCODE recommends a minimum width of 784 mm.

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The estimates of the tank manufacturing cost, including the painting/coating, lead to the results summarized in Table 2 below:

Table 2. Summary of tank manufacturing costs.

Designation	EUROCODE	API 650	CODRES
Estimated Manufacturing Cost of the Tank	28.535.113,88	28.389.712,58	25.986.131,6

3.3. Ease of Use of Each Standard

3.3.1. Comparison of Ease of Use

A rigorous comparison of the ease of use between API 650, CODRES, and the Eurocode shows that the relative simplicity of the American and French codes is based on an integrated normative structure and a direct mathematical approach, in contrast to the more fragmented and probabilistic framework of the Eurocode [1]-[7].

3.3.2. Computational Complexity and Mathematical Density

The volume and nature of the calculations required vary significantly depending on the design philosophy adopted by each code:

API 650 and CODRES (ASD approach):

These standards employ the allowable stress design (ASD) method, which is based on a single global safety factor. The formulas used for shell thickness calculation, such as the API "One-Foot Method", are deterministic and straightforward, allowing for rapid and transparent design procedures.

$$t_d = \left(4.9 \times D \times \left(H - 0.3\right) \times G\right) / S_d + CA \tag{37}$$

The number of required iterations is limited, as these codes do not treat uncertainties related to loads and material properties separately.

Eurocode (LSD/LRFD approach): Limit state design imposes a significantly higher computational density. The engineer must evaluate multiple partial safety factors for actions and for materials, which vary according to load combinations. For instance, buckling analysis in accordance with EN 1993-1-6 requires the determination of several complex non-dimensional parameters through numerous intermediate steps, thereby increasing the risk of human error.

3.3.3. Normative Framework and Data Integration

The clarity of the provisions depends largely on the way information is centralized and organized:

API 650 and CODRES (standalone standards):

These codes are specifically dedicated to the design of storage tanks and their associated components. Engineers have access to a coherent and consolidated set of methodologies, functioning as a clear design guideline. Only a limited number of checks, such as wind load analysis in API 650, require consultation of an external standard (e.g., ASCE 7).

The Eurocode is a general-purpose structural code covering a wide range of structures, which requires users to navigate through multiple interrelated standards for the design of a single tank. Structural verification involves combining EN 1990 (basis of design), EN 1991 (actions, including wind), EN 1993-1-6 (shell structures), and EN 1993-4-2 (tanks). This fragmentation demands a higher level of cross-disciplinary expertise from the designer.

Table 3. Qualitative evaluation grid for claret.

Criterion	API 650/CODRES	Eurocode
Number of calculations	Low to moderate: deterministic calculations	High: statistical analysis and verification of multiple limit states
Formula complexity	Simple: direct linear or rational equations	High: formulas including probabilistic reduction factors
Normative clarity	High: trade-specific codes presented as practical guidelines	Moderate: general rules requiring interpretation for the specific case of storage tanks
Wind stability analysis	Direct: global overturning moment calculation	Complex: requires wind speed conversions (ISO 4354) and non-uniform pressure analysis

The comparison presented in **Table 3** highlights the fundamental differences in ease of use between API 650/CODRES and the Eurocode. The American and French standards rely on deterministic formulations and trade-specific guidelines, resulting in a lower computational effort, simpler equations, and greater normative clarity. This facilitates rapid design procedures and reduces the risk of implementation errors in practical engineering applications.

In contrast, the Eurocode adopts a probabilistic and limit-state-based framework, which significantly increases the number and complexity of calculations, particularly for wind stability and buckling analyses. The need to combine multiple standards and interpret general provisions for tank-specific applications requires a higher level of expertise and engineering judgment. While this complexity makes the Eurocode less straightforward to apply, it also provides a more rigorous and reliability-oriented design approach, offering improved control over structural safety at the expense of increased computational effort.

3.4. Stress in the Tank Shell

Table 4. The stresses in the shell.

Shell Course	$H_{red}(m)$	Thickness (mm)	σ_{xpo} (MPa)	σ_{ypo} (MPa)	$\sigma_{éq.VMi}(Mpa)$	$f_{eq.Rd}(MPa)$	Condition
V1	10	0.006	73.1	146.2	130.61	261	OK
V2	8.7	0.005	74.82	149.64	129.58	261	OK

Continued

V3	6.9	0.005	59.34	118.68	83.91	261	OK
V4	5.1	0.005	43.86	87.72	61.65	261	OK
V5	3 .3	0.005	28.38	56.76	40.13	261	OK
V6	1.5	0.005	12.9	25.8	17.66	261	OK

A summary of the stresses in the shell is provided in **Table 4**. The analytical stress values were obtained using classical thin-shell theory and hydrostatic loading assumptions.

3.5. Comparison of Analysis Result

The numerical analysis was carried out to verify the structural stability of the tank shell using Autodesk Robot Structural Analysis 2016. For shell modeling, the software employs the Finite Element Method (FEM), which discretizes the structure into a finite number of elements and solves the governing equilibrium equations in matrix form. This approach enables the evaluation of stress distribution, deformation patterns, and stability behavior under the applied loading conditions. The FEM formulation leads to the resolution of the following system of equations:

$$MQ + CQ + K_Q = F(t) + f(t,Q) \tag{38}$$

Where:

K_Q is the tangent stiffness matrix, defined as the sum of the following component matrices: $K = K_0 + K + K_{NL}$.

K_Q is the initial stiffness matrix, independent of the displacement vector Q.

K: is the stress (geometric) stiffness matrix, dependent on the collinearity factor of compressive stresses.

K_{NL}: denotes the nonlinear stiffness matrix, which depends on the displacement vector Q.

However, since the present study is restricted to linear static analysis, the nonlinear and stress-dependent components are neglected, and the governing equilibrium equation reduces to: $K_{Q0} = F$.

We employ a 3-node triangular mesh generated using the Delaunay method. This method is widely used to create finite element meshes on arbitrary planar surfaces, including those with complex or circular boundaries, while ensuring good element quality and avoiding overly distorted triangles.

The 3-node triangular mesh was selected because Autodesk Robot Structural Analysis recommends the use of surface elements with 3 or 4 nodes. Using higher-order elements, such as 6- or 8-node surface elements, for mesh generation may result in incorrect or unreliable behavior in certain software functions.

3.5.1. The Numerical Model

The structural stability of the tank was assessed using Autodesk Robot Structural Analysis 2016.

A three-dimensional numerical model was developed to accurately represent the actual structure. A Delaunay-type mesh composed of three-node triangular elements was adopted (**Figure 4**) to ensure accurate stress calculations and reliable structural analysis results. The 3D model of the variable-thickness storage tank, created using SolidWorks, is shown in **Figure 5**.

Figure 4. 3-node triangular mesh.

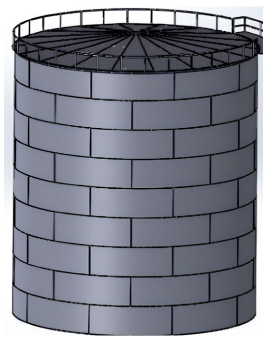

Figure 5. 3D model of the variable-thickness.

The final model consists of 56,145 nodes, each having six degrees of freedom, including three translational and three rotational components.

3.5.2. Stress Maps and Deformation Diagrams

1) The finite element analysis outputs highlight the distribution of stresses acting on the tank shell (courses), as illustrated in **Figures 6-9**.

2) The circumferential (hoop) stress distribution, evaluated along the X-direction, shows a continuous stress pattern over the entire height of the cylindrical shell. Under the self-weight loading case, the maximum circumferential stress reaches approximately 20.66 MPa.

3) The axial stress distribution, evaluated along the Y-direction, exhibits maximum values on the order of 16.61 MPa (**Figure 9**).

4) The deformation diagram illustrates the displacement field of the shell under loading, allowing the identification of potential bending zones, particularly at the roof-to-shell and shell-to-bottom junctions (**Figure 9**).

3.5.3. Quantitative Comparison: Analytical vs. Numerical Results

Table 5 below compares the analytical results (based on the maximum product pressure) with the numerical outputs obtained from the Finite Element Method (FEM) analysis.

Table 5. Quantitative comparison between analytical and fem results.

Parameter	Analytical Result (Maximum Load)	FEM Result (Robot Structural Analysis)
Circumferential stress e_θ	146.2 MPa (Course 1)	20.66 MPa (self-weight only)
Axial stress e_x	73.1 MPa (Course 1)	16.61 MPa (self-weight only)
Shell thickness	6 - 7 mm (depending on design codes)	Validated by the numerical model

Comparative Analysis:

Although the study demonstrates that the numerical analysis is capable of validating the analytically obtained results, a significant discrepancy is observed between the stress values. This difference arises from the fact that the FEM screenshots presented in Figures 6-9 correspond specifically to the loading case of the tank self-weight, whereas the analytical calculations account for the maximum hydrostatic pressure of diesel fuel (0.90 MPa).

The maximum internal pressure in the tank is denoted as $P_{\max}$. The cylindrical part of the tank (cylindrical shell course) is characterized by a mean radius R and a shell thickness e. The maximum internal pressure acting on the tank is given by:

$$P_{\max} = \rho g h_{\max} \tag{39}$$

where:

ρ : is the density of diesel fuel (kg/m^3);

g : is the gravitational acceleration (9.81 m/s^2);

$h_{\max}$: is the maximum liquid height in the tank (m).

For a thin-walled cylindrical shell subjected to internal pressure, the analytical circumferential (hoop) and axial stresses can be estimated using:

$$e_\theta = \frac{P_{\max}}{e} R,\ e_x = \frac{P_{\max}}{2e} R \tag{40}$$

where:

R: is the mean radius of the cylindrical shell;

e: is the shell thickness.

These equations correspond to classical thin-shell theory and form the basis for the analytical calculations compared with the FEM results.

$$P_{\max} = 0.90 \text{ MPa}$$

Since the mean radius of the tank satisfies $R \gg e$.

For shell thicknesses satisfying $e \gg 20$, the structural behavior is modeled based on the equilibrium of a small isolated tank element (an angular sector of thickness eee with infinitesimal dimensions) subjected to internal pressure pp and cohesive forces. The stress distribution is assumed to be constant across the shell thickness.

The figure below illustrates the details corresponding to small displacements of the element under loading.

3.5.4. Reliability Conclusion

The wind load analysis was carried out in accordance with the provisions of **ASCE 7-10** (for API 650), **Eurocode 1, Part 1-4**, and the **NV65 regulations** (for CODRES). The results indicate that the Eurocode imposes more stringent design requirements, leading to the conclusion that the tank is not wind-stable without anchorage. In contrast, both API 650 and CODRES classify the tank as stable under wind loading without the need for anchoring.

The finite element analysis (**Figures 6-9**) confirms the structural stability of the tank shell without the need for secondary stiffening rings. Detailed results showing the small displacements of a shell element subjected to loading, which are essential for verifying local stability, are presented in **Figure 10**.

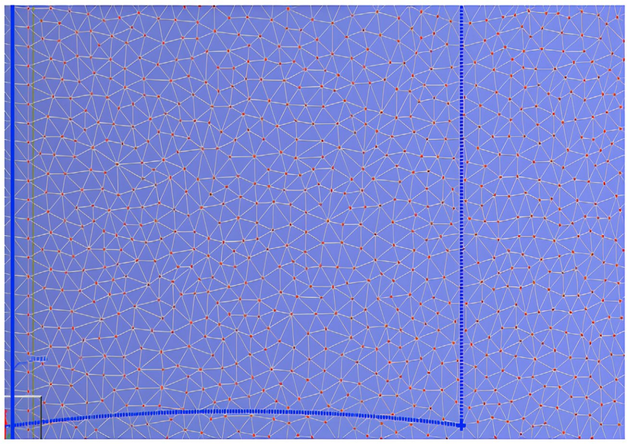

Figure 6. Detailed view.

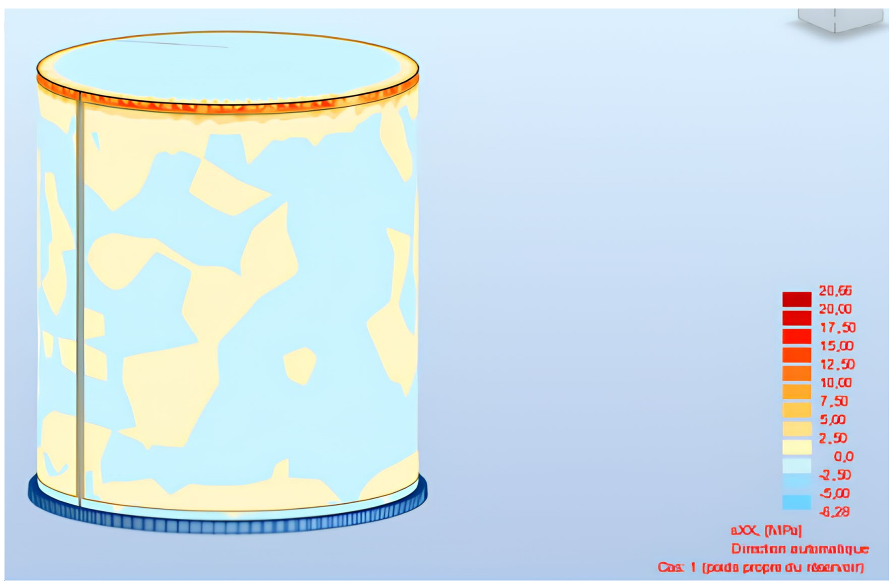

Figure 7. Circumferential stress of thank mesh along the X-direction.

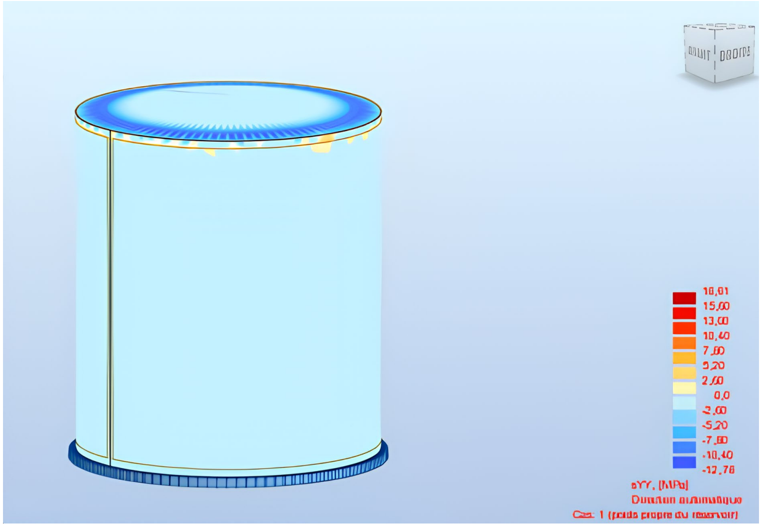

Figure 8. Axial stress distribution.

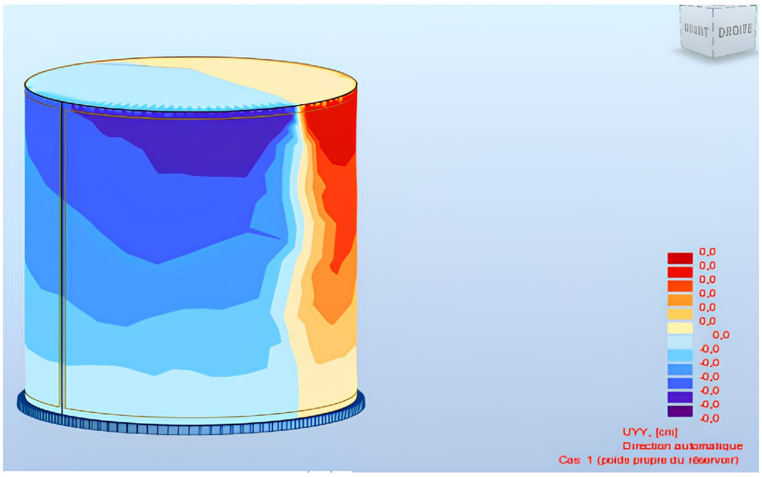

Figure 9. Displacement along the specified direction.

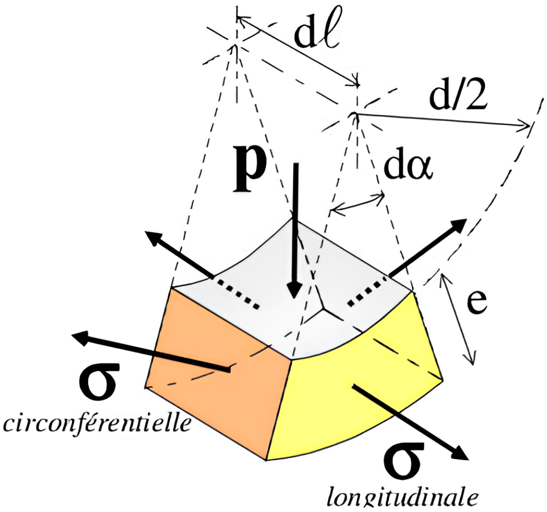

Figure 10. Detail of small displacements of the tank element.

The estimated fabrication cost according to the CODRES standard is 25,986,131 FCFA, which is approximately 3 million FCFA lower than the costs obtained using the Eurocode (28,535,113 FCFA) and API 650 (28,389,712 FCFA) design approaches. This difference highlights the economic advantage of the CODRES-based designs. The finite element simulations confirm the structural adequacy of the shell without the need for secondary stiffening rings. The deformation patterns remain within acceptable limits, and no critical stress concentrations exceeding the elastic limit of the material (S275JR, 275 MPa) are observed.

4. Conclusions

The comparative study for the design of the fixed-roof diesel storage tank at the LIMBE oil yard demonstrates that while the API 650, EUROCODE, and CODRES standards all ensure stability against plasticization and buckling, they differ fundamentally in their methodology and reliability [1]-[4] [7] [9].

The main findings of this comparison are as follows:

(i) Methodological Divergence: API 650 and CODRES utilize the Allowable Stress Design (ASD) method, which relies on a single global safety factor. In contrast, the EUROCODE employs the Limit State Design (LSD) approach, which is grounded in reliability theory and utilizes partial safety factors [1]-[4] [7].

(i) Superior Reliability: The EUROCODE is considered the most reliable standard among the three. Because it is based on a probabilistic approach, it offers a more transparent and accurate assessment of the actual structural risk, whereas the safety factors in API 650 and CODRES do not provide specific information regarding the probability of failure [4] [6] [7].

(iii) Stringent Design Requirements: The probabilistic rigor of the EUROCODE leads to stricter requirements, particularly concerning wind stability—which may necessitate anchoring—and a more conservative design for shell thickness to ensure a higher level of structural safety.

(iv) Economic and Technical Impact: Designing with the EUROCODE involves more extensive and complex calculations. Furthermore, the study indicates that the design and construction costs for a tank designed under EUROCODE or API 650 differ by approximately three million CFA francs compared to those derived from the CODRES code [1]-[4].

(v) Ultimately, although the EUROCODE is more complex and potentially more costly, it is the preferred standard for achieving a superior level of structural reliability and a better-controlled risk of failure.

The Limit State Design (LSD) method, as applied by the Eurocode in the study of the Limbe tank, offers several practical advantages over the Allowable Stress Design (ASD) approach:

(a) Improved risk control: Based on reliability theory and a probabilistic approach, LSD enables a much more precise control of structural failure risk. Unlike ASD, which relies on a single global safety factor, the limit state approach provides a more transparent and accurate assessment of the actual risk.

(b) Use of partial safety factors: Instead of a single overall coefficient, LSD applies partial safety factors to loads and material properties. This refinement enhances the reliability of the structure by tailoring the safety margins to specific uncertainties.

(c) Clear distinction of performance objectives: LSD explicitly differentiates between serviceability limit states (SLS), related to normal operation and durability, and ultimate limit states (ULS), associated with safety and collapse prevention.

(d) Enhanced structural safety: The probabilistic rigor of this method imposes stricter design requirements, such as more conservative shell thickness calculations and more demanding wind stability criteria, potentially including the need for specific anchoring, thereby ensuring a higher level of structural safety.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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