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Structural Performance Evaluation of Cooling Towers through Non-Linear Analyses Located in Mexico

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Abstract **-** Natural draft cooling towers are hyperbolic reinforced concrete shell structures designed to induce airflow through a large chimney to reduce the temperature of water used in various industrial processes. In Mexico, the construction of such cooling towers has been proposed to enhance the efficiency of refinery operations. However, the country lacks regulations and guidelines for special structures, particularly thin-walled shell structures. As a result, combined with uncertainties in structural demand and response, the construction of hyperbolic cooling towers has been discouraged, leading to the rejection of projects that could provide significant economic and environmental benefits compared to alternative solutions. This study aims to advance the understanding of these structures through numerical simulations, proposing more detailed analyses than those included in simplified procedures previously used in the country. A cooling tower proposed for the refinery in Tula, Hidalgo, Mexico, is presented as a case study. The tower's behaviour under seismic actions, wind loads, creep, and temperature distribution across its walls is evaluated, demonstrating its efficiency and structural safety.

Keywords**:** dynamic behaviour, seismic analysis, shell structures, creep, buckling, wind forces, temperature distribution.

1. Introduction

During certain industrial processes, water is required to cool specific stages of the process or the final product. This water cannot be discharged due to the environmental damage it would cause, making its reuse a priority. Generally, the cooling system consists of sprinklers that discharge hot water onto grids, where the water comes into contact with air, resulting in cooling through the loss of latent heat. It is estimated that this type of tower can achieve efficiencies of up to 98% in returning the water volume to the system, enabling significant conservation of this vital resource [1].

The geometric characteristics of the towers are defined by thermodynamic analysis and the adaptation of the industrial equipment considered. The use of reinforced concrete offers several advantages, as it not only allows for a greater volume of water but also enables the structure to operate within a wider temperature range compared to other materials used [2].

Throughout history, valuable information has been gathered regarding the performance of these structures due to numerous cases where they sustained significant damage or even collapsed. Some of the main reasons for the failure of these projects include underestimating wind forces, the vortex effect in grouped towers, insufficient steel reinforcement, lack of stiffness at the top, and the formation of cracks in the first third of the height [3].

Today, constructing this type of tower with adequate durability has been made possible thanks to international efforts to address the uncertainties that arise from in-depth studies of these structures. However, in many regions, quasi-empirical formulations that lack regulatory support and fail to ensure structural safety or an adequate level of reliability are still used. Mexico is an example of this, as the few hyperbolic towers that have been built have faced various issues, which are addressed through costly and frequent maintenance. The country lacks a code that governs the analysis and design of these structures; as a result, industrial companies have opted to disregard them in favour of alternative cooling methods that are more expensive and reduce production efficiency [4].

This study aims to evaluate the proposed project for a refinery in Tula, Hidalgo, Mexico, using nonlinear behaviour methods to assess the proposed design. The dynamic behaviour is analysed through a modal-spectral seismic analysis, a time-history method review, an evaluation of buckling effects, and nonlinearity considering the creep effect in the concrete due to the presence of high-temperature distribution on the tower walls. In this way, the study seeks to promote the use of this type of structure in the country.

2. Materials and Methods

The case study presented is a hyperbolic shell with a variable thickness along its height, supported by 80 V-shaped columns. The columns rest on a rigid foundation.

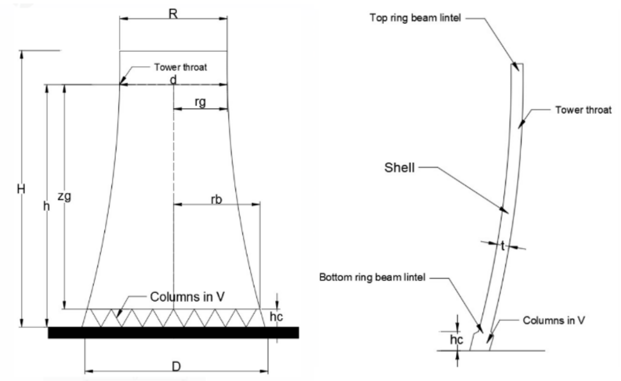


Fig. 1: Cooling tower general geometry

2.1. Geometric characterization

The geometry of the cooling tower in the case study is dominated by a revolve element that follows the characteristics of a hyperboloid. The expressions that define the geometry are governed by the following equations [5]:

$$R = \pm\sqrt{\left(1+\frac{(z-z_g)^2}{b^2}\right){r_g}^2} \tag{1}$$

Where:

$$b = \sqrt{\frac{{z_g}^2}{\frac{(D'/2)^2}{{r_g}^2}-1}} \tag{2}$$

And: r_g is throat radius, z_g throat height, D' diameter in the base and R radius of the circumference varying in height.

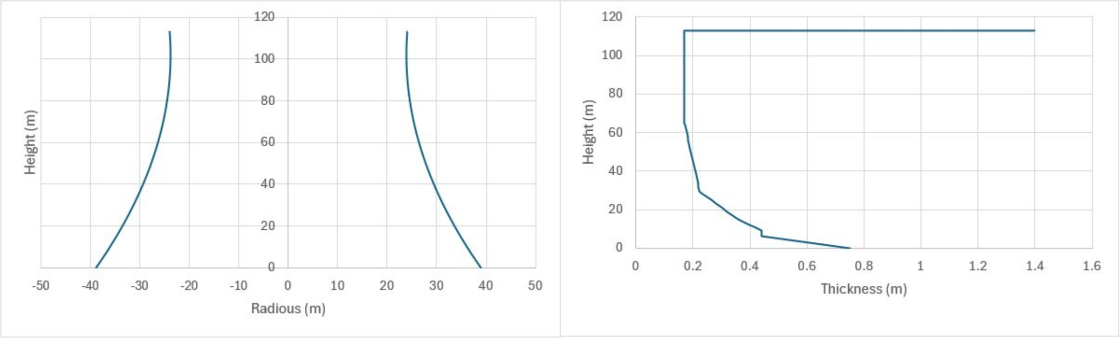


Fig. 2: Elevation profile and shell thickness

Table 1: Geometric characteristics of the tower

Parameter	Dimension (m)
r_g	24.1
H	113
D’	77.76
b	87.73
hc	6.4

2.1. Tower structuring

The tower is discretized into shell-type elements based on its height, forming horizontal rings, which are further refined circumferentially every 3°, allowing for a good numerical approximation of the ring beam, the wall, and the lintels due to the uniformity of the mesh.

Table 2: Cross-section of beams and columns

Element	Section (m x m)
Ring beam	1.05 x 1.35
Columns	0.75 x 0.75

2.2. Material properties

The corresponding properties are assigned to the concrete elements. It is worth noting that, according to international recommendations, the Poisson's ratio will be zero for shell-type elements. Additionally, the constants for the creep behaviour laws used are specified, Time Hardening Law for primary stage and Norton´s power law for secondary stage.

Table 3: Concrete properties

Elastic modulus (MPa)	23780	C_2	0.794
Density (kg/m^3)	2400	C_3	-0.894
Coefficient of thermal expansion (1/°c)	1.43×10^{-5}	C_4	0
Poisson´s ratio for columns	0.15	C_5	$1X10^{-12}$
Compressive strength (kg/cm^2)	300	C_6	0.794
C_1	$1.05X10^{-7}$	C_7	0

The creep constants are identified through uniaxial compression tests on cylinder samples prepared according to ASTM standards.

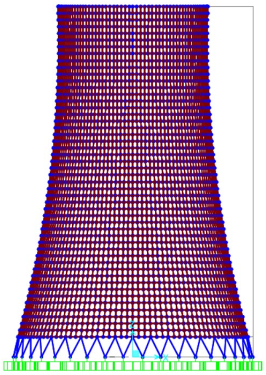
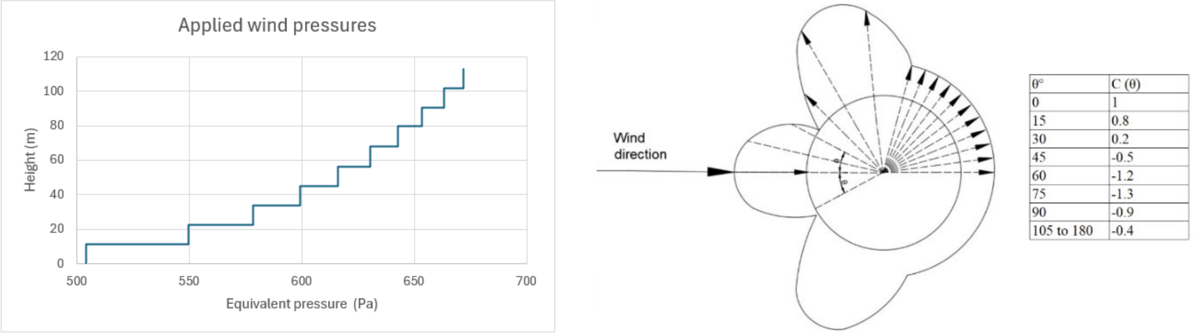


Fig. 3: Colling tower mesh.

3. Loading

3.1. Wind Loads

The calculation of the applied pressures is carried out in accordance with the Civil Works Manual of CFE, developed by the Mexican government. The applied values are obtained considering a structure of importance from group A, type considering adjustment factors for topography and dynamic amplification for a regional wind speed of 123.35 km/h. structure is discretized into 10 parts based on its height. The circumferential pressure distribution is shown to consider effects of windward and leeward [6].



θ°	C (θ)
0	1
15	0.8
30	0.2
45	-0.5
60	-1.2
75	-1.3
90	-0.9
105 to 180	-0.4

Fig. 4: Applied wind pressures over height (right), Circumferential distribution (left).

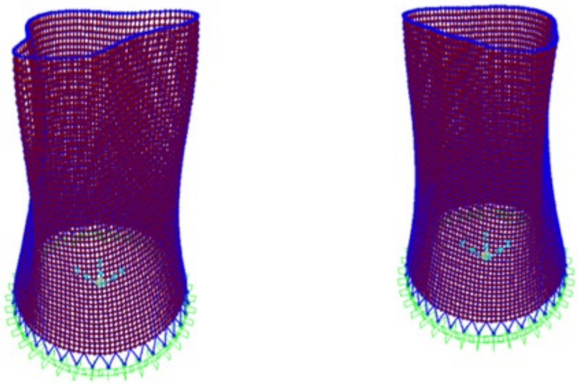


Fig. 5: Deformed shape due to wind loads, X direction (right), Y direction (left).

3.2. Temperatures Loads

There are three loading conditions due to temperature variations along the structure. The first is caused by seasonal loads, the second by operating conditions, and the third by solar radiation [7]. A linear gradient is considered along the shell's thickness. For this, it is necessary to estimate the maximum annual temperature variation (V_{ma}), expressed as the difference between the maximum summer temperature and the minimum winter temperature [8].

Table 4: Temperature loads.

Wall thickness, e (cm)	Average temperature increase	Mean temperature gradient increase
10<e<50	Exposed face: 0.6 V_{ma}	0.3 V_{ma}/e
	Opposite face: 0.45 V_{ma}	0.3 V_{ma}/e

Parameters values corresponding to Tula, Hidalgo, Mexico being operation temperature 60°c, maximum temperature in summer 28 °c and minimum temperature in winter 9°c.

Table 5: Temperature conditions

Case	Description
T1	ΔT increment, left hemisphere exposed to solar radiation
T2	Increase temperature gradient due to solar radiation exposition
T3	Temperature gradient, operation in summer
T4	Temperature gradient, operation in winter
T5	ΔT, quit no solar radiation exposition

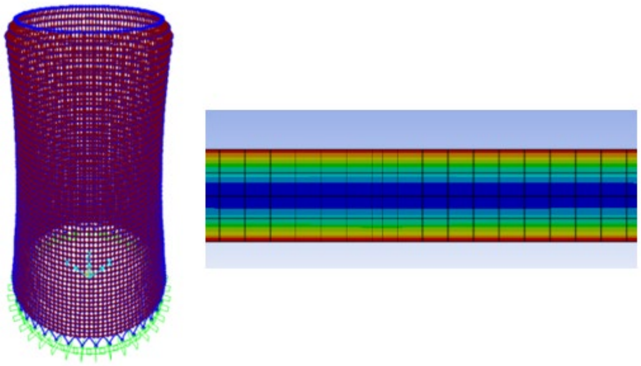


Fig. 6: Deformed shape due to T3 case (right) and temperature distribution across thickness wall at ring beam (left).

3.3. Seismic loads.

Due to the importance level of the structure, the goal is to maintain it at an immediate occupancy performance level, meaning it exhibits linear behaviour. Therefore, the structure is analysed with a seismic behaviour factor Q=1. The terrain characteristics correspond to hard soils of the volcanic axis located in seismic region #38, so soil-structure interaction is neglected. The seismic design spectrum is obtained using CFE's Prodisis software. Additionally, a synthetic time-history signal corresponding to this spectrum is generated [2].

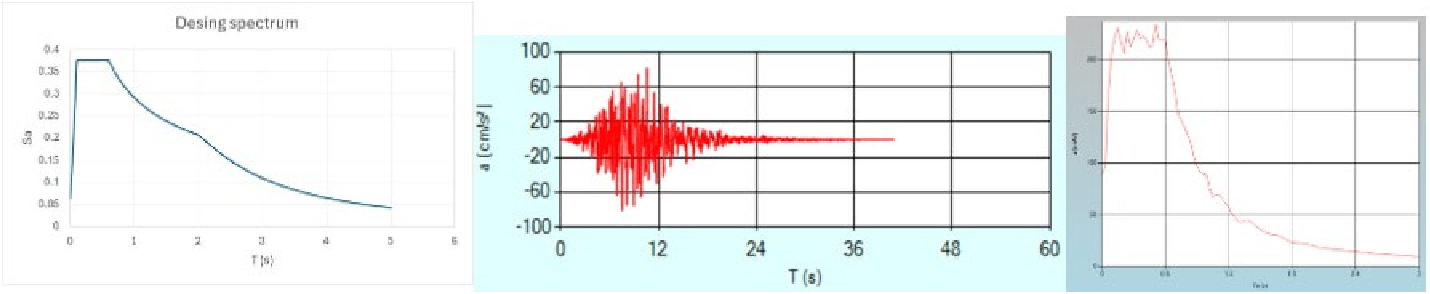


Fig. 7: Desing spectrum, synthetic seismic signal and response spectrum.

The spectral modal analysis provides the main vibration modes of the structure. Enough modes are considered to achieve a mass participation factor of at least 90%.

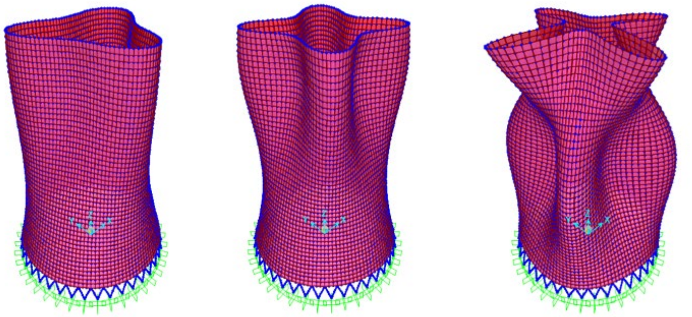


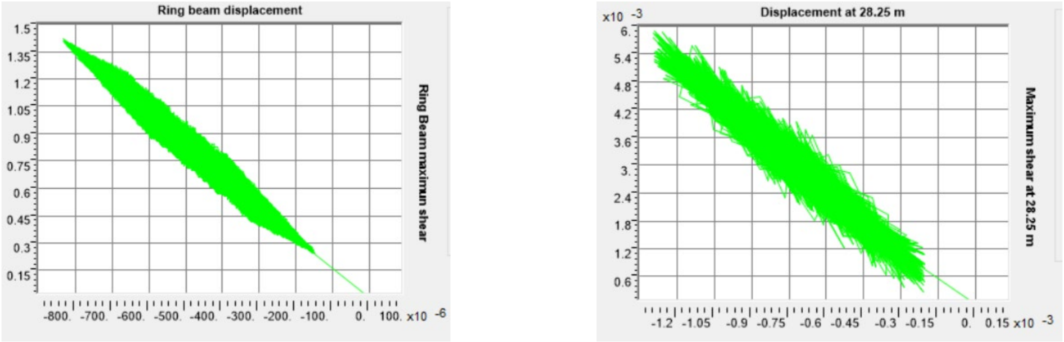
Fig. 8: Principal mode shapes, T=0.86, 0.85, 0.78 seconds respectively

To ensure the linear behaviour of the structure, a transient time-history analysis is performed based on the presented synthetic signal. The signal is obtained from a time-history series in which the response spectrum matches the design spectrum. The general motion equation which solves the transient structural equilibrium is [9]:

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=-[M]\{\dot{u_g}\} \tag{3}$$

Where: [M] is mass matrix, [C] damping matrix, [K] stiffness matrix {x} displacement vector and {üg} ground acceleration.

The Takeda hysteresis curves are presented at the most critical points of the structure to evaluate its nonlinear seismic behaviour. The maximum shear force (T) is plotted on the y-axis, and the displacement (m) is plotted on the x-axis.



. Fig. 9: Takeda hysteresis curves at 6.4 m (right) and 28.25 m (left) over height.

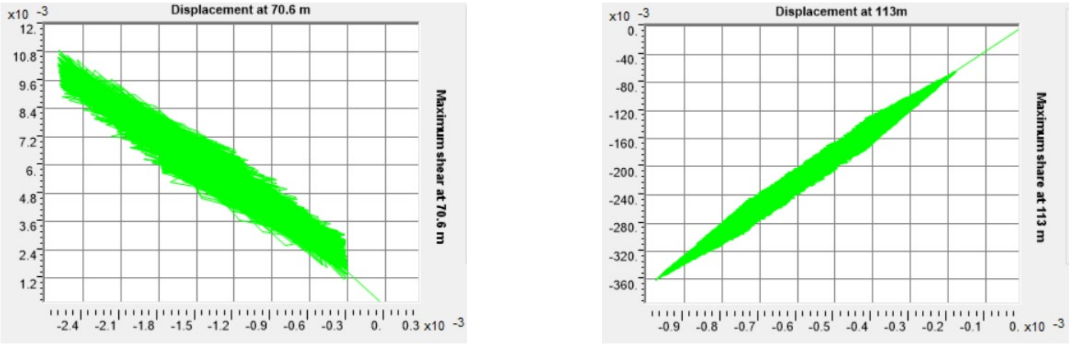


Fig. 10: Takeda hysteresis curves at 70.6 m (right) and 113m (left) over height.

4. Buckling analysis

Hyperbolic cooling towers with direct draft are shell-type structures highly efficient from a structural point of view, but their design must account for buckling due to their thin geometry and high height-to-thickness ratio [10].

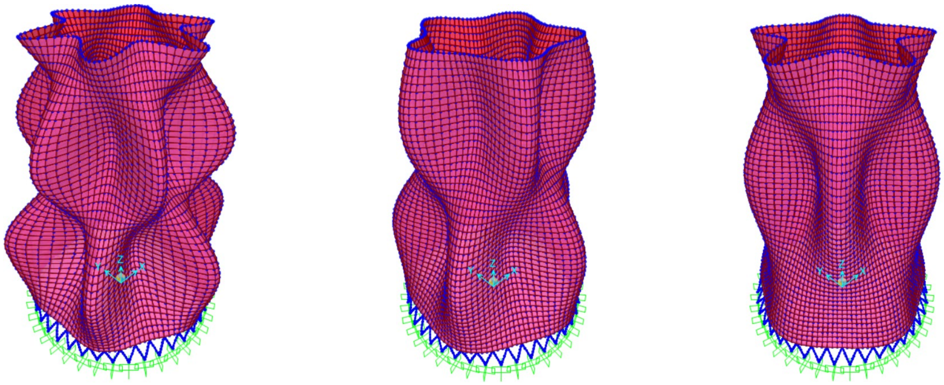


Fig. 11: Principal buckling shapes, Load multipliers=29.63, 30.07, 34.13 respectively

5. Creep strain

It is necessary to use the most appropriate behaviour law depending on the stage to be analysed. This work proposes the use of the Time Hardening Law for the primary phase and the Norton Power Law for the secondary phase.

The Time Hardening Law's main hypothesis is that the only factors involved in deformation are the stresses and the change in material properties, leading to a precipitated hardening that generates the primary phase [11].

$$\dot{\varepsilon_{cr}} = C_1\sigma^{C_2}t^{C_3}e^{-C_4/T} \tag{4}$$

The Norton Power Law, where under changes in proportional loads, the stress distributions are independent of the load magnitude [11]. The stationary stage is estimated, as the most noticeable effects of the stress function manifest at this point [12].

$$\dot{\varepsilon_{cr}} = C_5\sigma^{C_6}e^{-C_7/T} \tag{5}$$

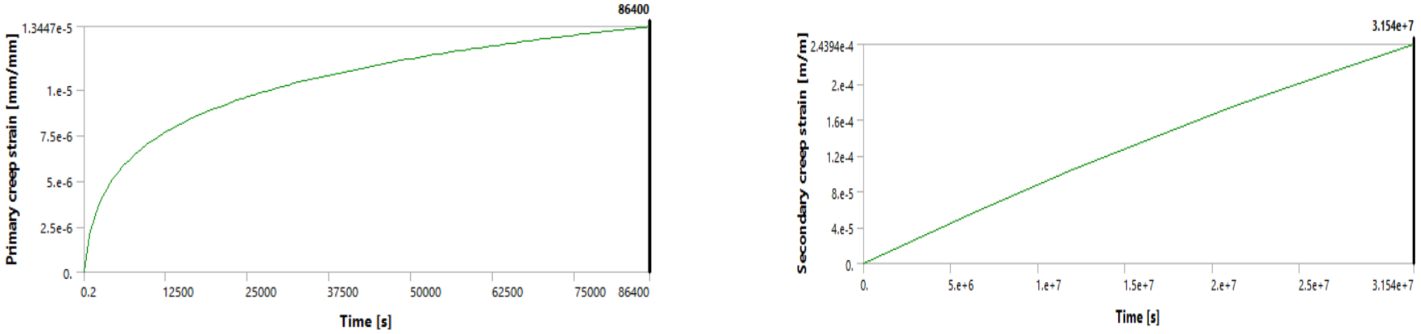


Fig. 21: Primary and secondary maximum creep strains

6. Conclusion

In this case study, it is demonstrated through non-linear seismic and material analyses that the design proposals for cooling tower exhibit adequate behaviour under seismic and wind loads. The buckling and creep analyses are as cracks have been identified in the walls due to changes in stress state, which generate instabilities due to these effects such structures.

The time history analysis supports the design obtained from the spectral modal analysis, as it shows that the structure maintains an immediate occupancy performance level, meaning minimal damage is expected in structural elements, such that no significant permanent deformations occur. If repairs are needed, they will be minor and will not affect the tower's operation, with no significant loss of stiffness observed. Although the structure shows good behaviour under wind loads, wind tunnel studies are suggested to better consider the interaction of towers in a group.

The presented case study demonstrates an adequate level of structural safety. However, due to the complexity of cooling structures with these geometric and mechanical characteristics, it is proposed to thoroughly study each case. Additionally, probabilistic reliability studies should be conducted to seek the optimal design of the structure in critical sections such as lintels and the ring beam, as it has been shown that lack of stiffness in these points can lead to collapse.

The construction of this type of tower is recommended because it represents a considerable cost-benefit advantage compared to other types of towers, in addition to improving industrial processes while safeguarding environmental impact.

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