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SEISMIC AND WIND LOAD ANALYSIS OF NATURAL DRAUGHT HYPERBOLIC COOLING TOWER

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ABSTRACT

The present study looks at the impact of seismic and wind loads on hyperbolic cooling with different RCC shell. An existing cooling tower (BTPS, Karnataka) is used as a reference. The RCC shell thickness has been varied in relation to the reference cooling tower for comparison. Staad pro V8i software has been used to analyse the seismic and wind stresses on this cooling tower. The seismic analysis was performed using the modal analysis and response spectrum analysis methodologies, and in accordance with IS 875 (Part 3)-2015 the wind loads on these cooling towers were computed as pressures by employing wind pressures at different levels. The maximum deflection, the maximum principal stress, mode shapes, and their corresponding frequencies were obtained. Through the graphs, the variation in maximum principal stress and maximum deflection with respect to thickness is shown.

KEYWORDS: Cooling Tower; Wind Load; Seismic Load; Varying Shell Thickness; Deflection; Stresses

INTRODUCTION

Large, thin-shelled reinforced concrete structures called hyperbolic cooling towers improve the efficiency and dependability of power generation while also protecting the environment. Large amounts of water are frequently cooled using hyperbolic reinforced concrete cooling towers in thermal power plants, refineries, atomic power plants, steel plants, air conditioning, and other industrial sites. Nuclear power plants make use of natural-draft cooling towers as heat exchangers. These shell structures are subjected to stochastic environmental forces like seismic, wind and temperature gradients. The majority of cooling towers have a hyperbolic design. They are constructed in this manner because the large base provides more surface area to promote evaporation and then narrows to quicken air movement. Then it gently opens to help the atmosphere get mixed up with the moisture-filled air.

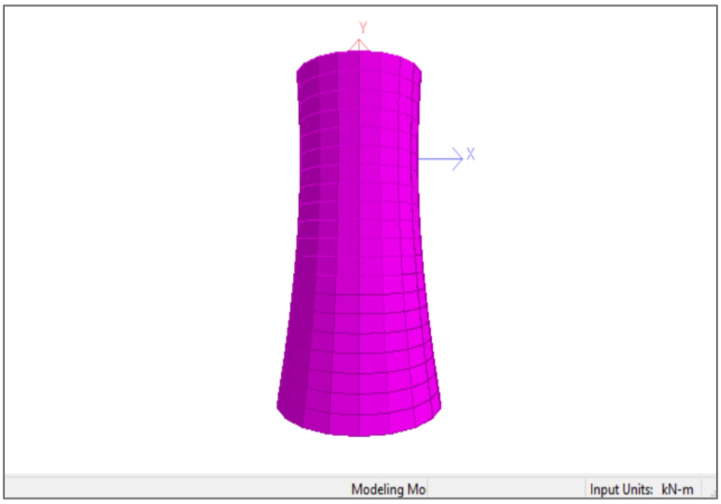

Fig. 1 (a): Geometric modal in staad. Pro

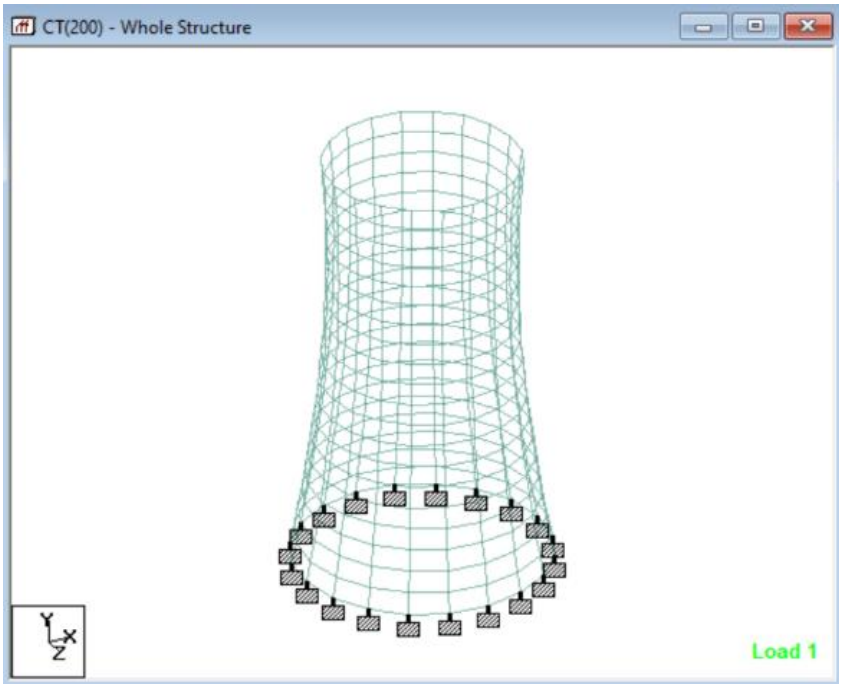

Fig. 1 (b): Boundary conditions

The hyperbolic structures have different mechanism from other structural forms. They have negative curvature which makes them to spread out more than the structures based on traditional Euclidean geometry. Forces are transmitted through its curvature in these structures which makes their analysis complex. They show non-linear behavior due to their surface geometry, hence responses to the forces is harder to predict.

A lot of research work has been done on hyperbolic cooling towers till date. El Ansary at. el. (2011) created a numerical programme that combines an internal, non-linear finite element model with a genetic algorithm optimisation technique to get the best possible shape and design for hyperbolic cooling towers. The elastic buckling movement of a tower subject to wind pressure and dead weight is modelled using the finite element method. There are two key sections to the study. The first section looks into the ideal tower shape that minimises weight while assuming constant thickness. In order to get the best shape and design, the study is expanded in the second section by including the thickness of shell as one of the design factors. Constraints related to design, functionality, and utility are used.

Murali at. el. (2012) conducted the analysis of two cooling towers that are 122 and 200 meters tall above the ground. By assuming fixity at the shell base, these cooling towers have been examined using Ansys software for wind loads. The circumferentially distributed design wind pressure coefficients from the IS: 11504-1985 code and the design wind pressures at various levels from the IS: 875 (Part 3)-1987 code was used to compute the wind loads on these cooling towers in the form of pressures. The findings of analysis include membrane forces, such as hoop and meridional forces, and bending moments, such as meridional and hoop moments.

In another study by S. Kulkarni and A. Kulkarni (2014), using the 8-noded SHELL 93 element and the 4-noded SHELL 63 element, static analysis has been conducted. ANSYS 10 (SHELL 93) element is used to analyse the behavioural changes caused by the cooling tower's stress concentration while adjusting the tower's thickness. Seismic analysis is performed for ground accelerations of 0.5g, 0.6g, and 0.7g using the modal & response spectrum approach. Wind loads have been estimated as pressure using the design wind pressure coefficient from the IS 11504-1985 code and the design wind pressure at various levels from the IS 875 (Part 3)-1987 code. For both of the cooling towers, eigen buckling analysis has been done.

The objective of this research is to study the linear static analysis (i.e., self-weight) of the cooling tower for maximum principal stress and its wind load analysis for maximum principal stress and its deflection pattern with varying shell thickness. Also, to carry out the modal analysis and response spectrum analysis for finding out the frequencies and modes of the cooling tower and finding out the dominant load.

RESEARCH METHODOLOGY

The cooling tower is analyzed using staad.pro v8i software in accordance with IS codes. IS 875:2015 (Part-3), IS 1893:2016, IS 11504:1985 were used. Three loads are considered for the analysis of cooling tower i.e., dead load, seismic load and wind load.

On the basis of the objectives, following analysis have been done:

1. Linear static analysis
2. Dynamic analysis

1. Seismic Load

It has been carried out in accordance with IS 1893:2016 by modal analysis and response spectrum analysis. Following factors are considered for the analysis:

Zone (Z): III (i.e., 0.16)

Importance factor (I): 1.5

Response reduction factor (R): 3

Type of soil: soft soil

Damping ratio: 0.05

2. Wind Load

These loads are applied in the form of wind pressure on the tower, which will be theoretically calculated in accordance with IS:875-2015 by the formula given below.

$$P_z = 0.6 \text{ x } (V_z)^2 \quad (1)$$

where

$$V_z = V_b \text{ x } K1 \text{ x } K2 \text{ x } K3 \text{ x } K4 \quad (2)$$

where, P_z is the wind pressure at height z in KN/m²

V_z is the design wind speed at height z in m/s

V_b is the basic wind speed in m/s

K1 is the probability factor (risk coefficient)

K2 is terrain roughness and height factor at height z

K3 is the topography factor

K4 is the importance factor for cyclonic region

Following values are taken as per the IS 875:2015 (Part-3) for the bellary region,

V_b = 33m/s

K1 = 1.05

K2 = interpolated from Table-2 (for terrain category-2)

K3 = 1

K4 = 1

Concrete used: M20 grade

Steel used: Fe500 grade

3. Description of the Structure

For the purpose of analysis an existing cooling tower of Bellary Thermal Power Station (BTPS), Karnataka has been used. The tower is 143.5 metres tall overall. The tower measures 55 metres in radius at the base, 30.5 metres at the throat level, and 31.85 metres at the top, with the throat being 107.75 metres above the base. Its shell wall is 200 mm thick. The top end is free and the bottom end is fixed as per the boundary conditions of the tower. For the purpose of analysis, the original structure is compared with increasing the shell thickness of the structure i.e, 250mm, 300mm, 350mm and 400mm. Also, its comparative performance analysis has been done in different seismic zones.

Table 1: Input geometry values to create model in staad. pro

Dimensions	Values (in meters)
Top Diameter	64
Throat Diameter	61
Height of Tower	143
Distance of top from throat	36
Division along circumference	20
Division along height	20

ANALYSIS & RESULTS

The structure has been analysed in Staad.pro V8i (select series-6) by modelling it through the provided option of run structure wizard and inputting the dimension values in the software. Boundary conditions of top end of the tower considered as free and bottom end being fixed, loads definition and required load case details are applied for the analysis.

1. Static Analysis

For static analysis, self-weight factor of -1 is applied under dead load. The results are then obtained for different shell thickness of cooling tower i.e., 200mm, 250mm, 300mm, 350mm and 400mm for comparative analysis of deflection and stress. The values of the deflection shown in the graph in Figure 3 are the average deflection values of the top twenty nodes of the tower.

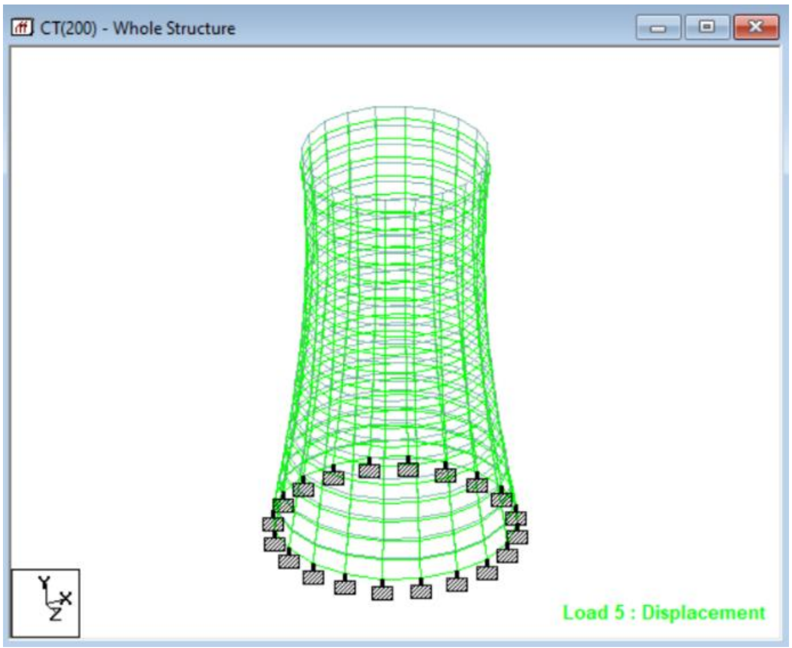

Fig. 2 Deflection due to dead load for cooling tower with 200mm shell thickness

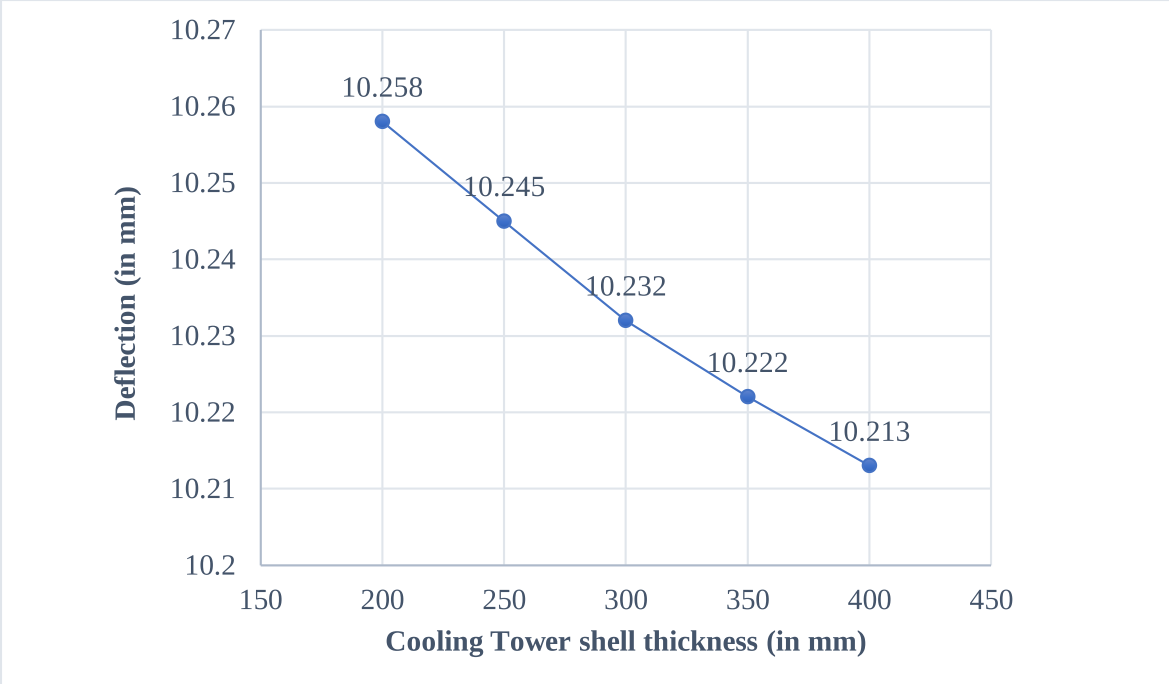

Fig. 3 Deflection (due to dead load) v/s varying the shell thickness of the cooling tower

As seen in the above graph Figure 3, the deflection due to self-weight decreases significantly as the shell thickness increases. This is expected because a thicker shell increases the stiffness of the structure, making it less susceptible to deformation. However, beyond 350mm, the rate of reduction in deflection becomes marginal, indicating diminishing returns in structural rigidity with increased material use. This suggests that optimal thickness should balance between strength and cost-efficiency.

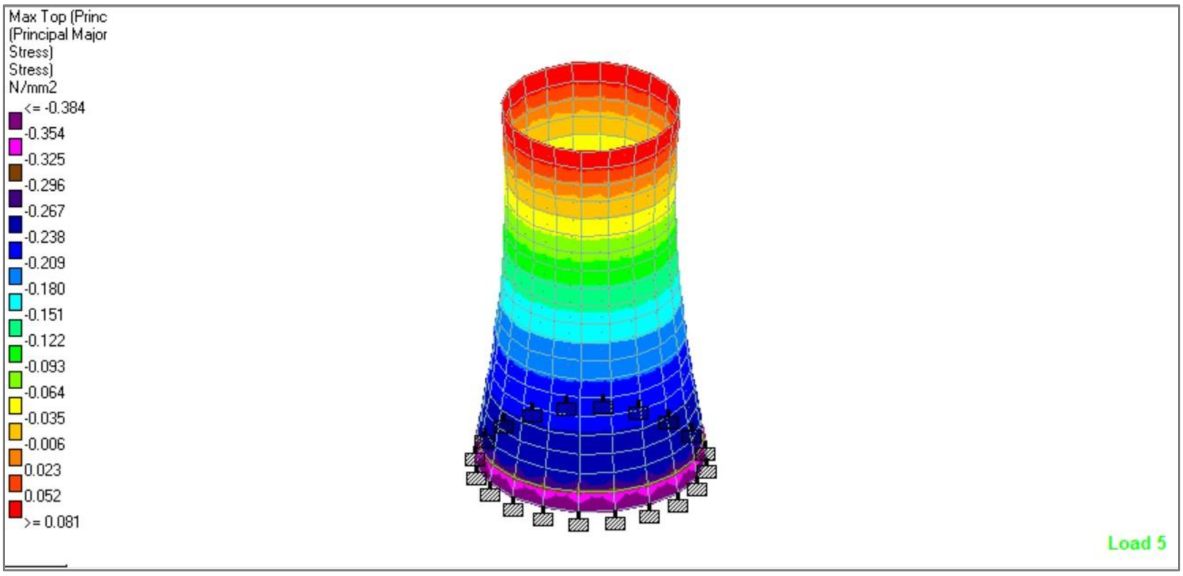

Fig. 4 Maximum principal stress due to dead load for cooling tower with 200mm shell thickness

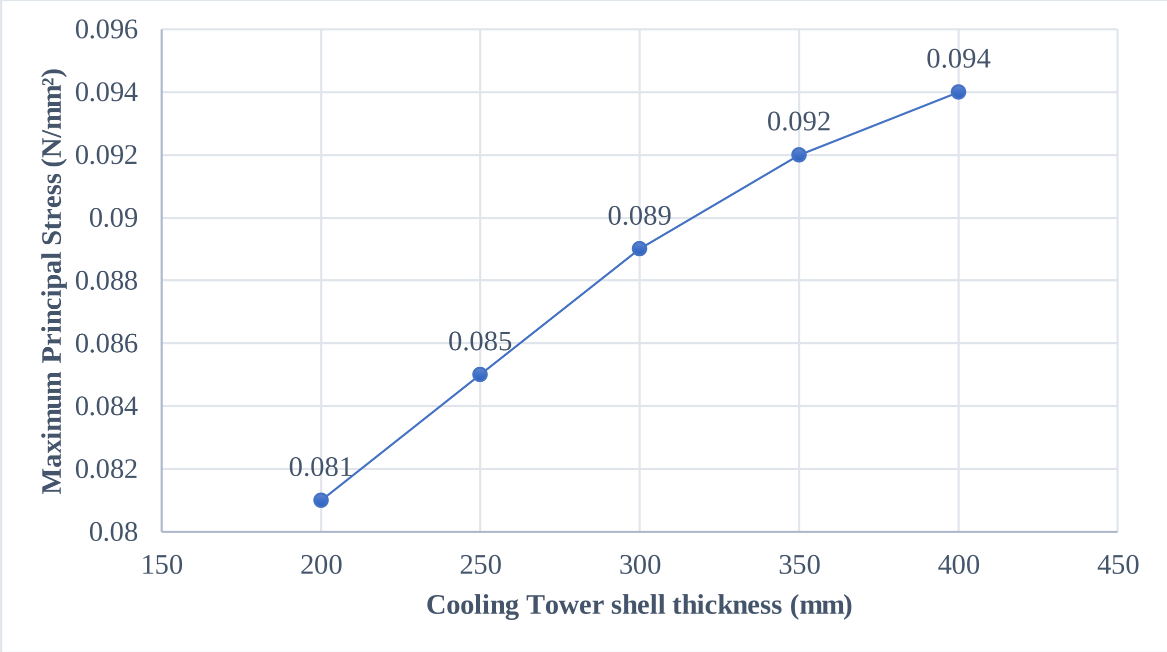

Fig. 5 Maximum principal stress at top (due to dead load) v/s varying shell thickness of cooling tower

Here, Figure 5 shows the maximum principal stress increases with increasing shell thickness. Although thicker shells reduce deflection, this pattern implies a need for careful consideration when increasing thickness solely to reduce deflection, as it may accidentally lead to higher stress concentrations and potential cracking if not reinforced adequately.

2. Wind Analysis

The wind load is applied in the form of design wind pressure at different levels as per IS 875:2015 (Part 3) using the eq^{n} (1). The maximum deflection obtained due to wind load at the top of cooling tower as shown in Figure 6 is 43.775 mm at the 16th node. The graph of deflection v/s varying thickness shown in Figure 7 shows the average deflection values of all twenty nodes at the top of cooling tower.

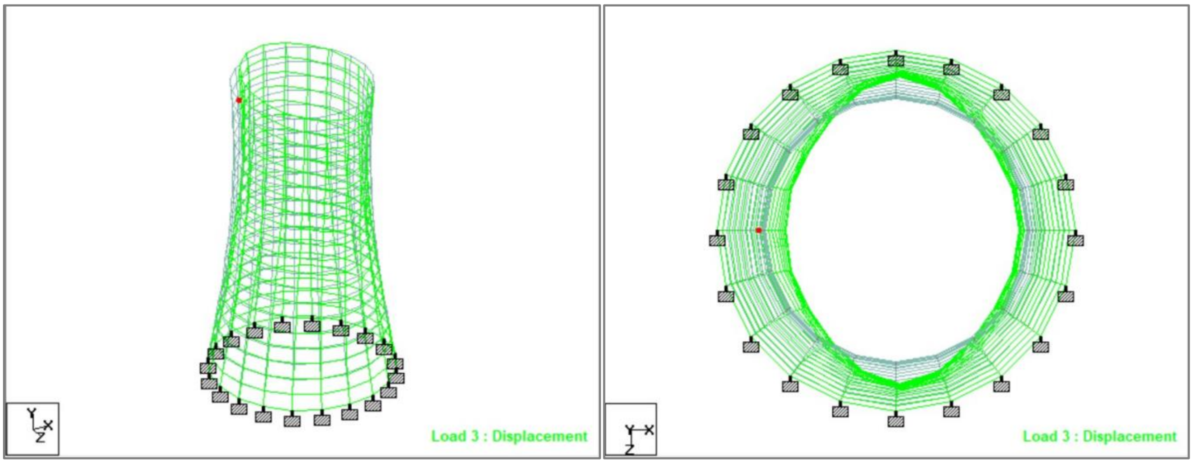

Fig. 6 Deflection at top due to wind load in cooling tower with 200mm shell thickness

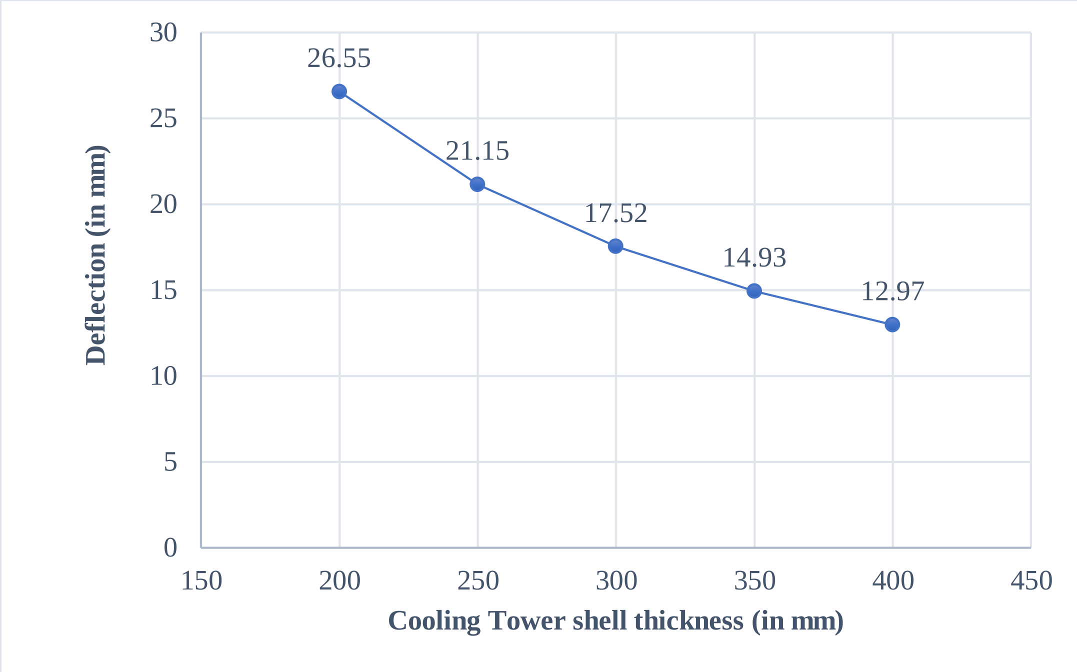

Fig. 7 Deflection (due to wind load) v/s varying shell thickness of cooling tower

In Figure 7, wind-induced deflections follow a similar decreasing pattern as seen with dead loads. This shows that increasing shell thickness enhances the tower's lateral stiffness.

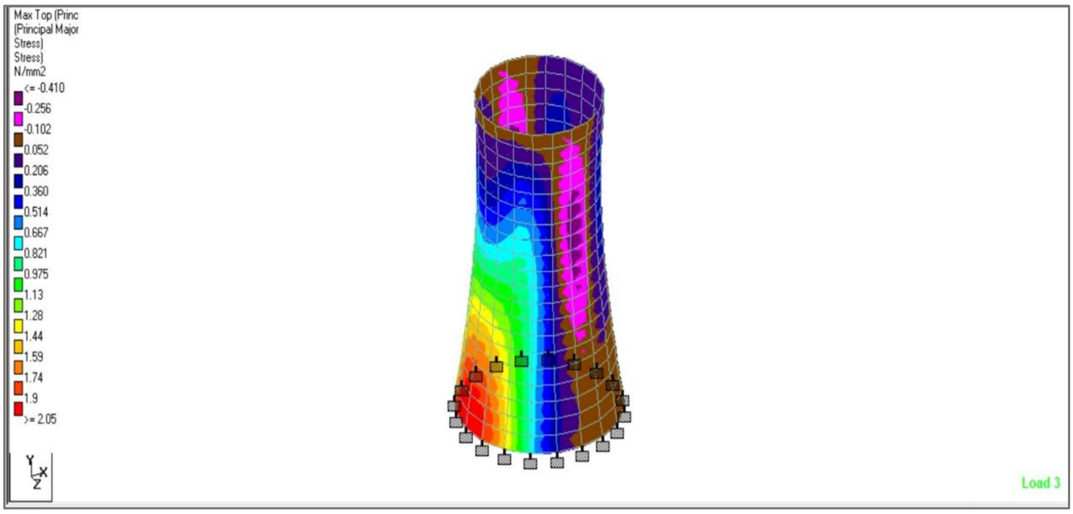

Fig. 8 Maximum principal stress due to wind load for cooling tower with 200mm shell thickness

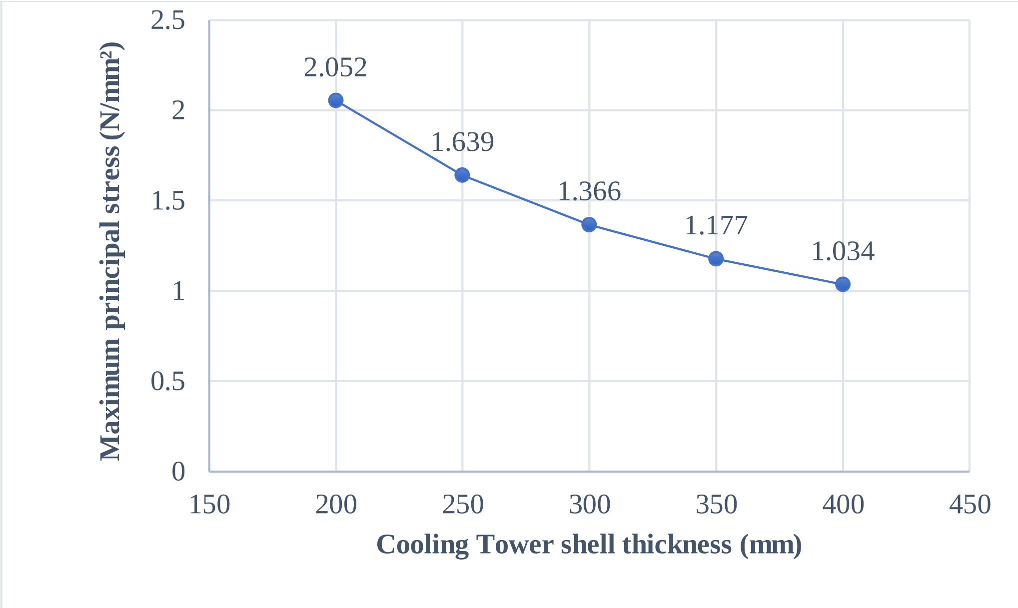

Fig. 9 Maximum principal stress (due to wind load) v/s varying shell thickness of the cooling tower

Unlike the dead load case, Figure 9 shows that the wind-induced stress decreases with increasing shell thickness. This indicates that the increased stiffness helps in distributing the wind load more uniformly, thereby reducing localized stress peaks. This result supports the use of thicker shells in high-wind regions, especially where stress reduction is more important than minimizing material cost.

3. Modal Analysis

The natural frequencies, time period, and their mode shapes are determined using modal analysis. It is the study of the system's dynamic characteristics. Staad.pro has been used to carry out this analysis. The requested number of modes is six. Below is the Figure 10 showing the mode shapes of the 200mm thick cooling tower.

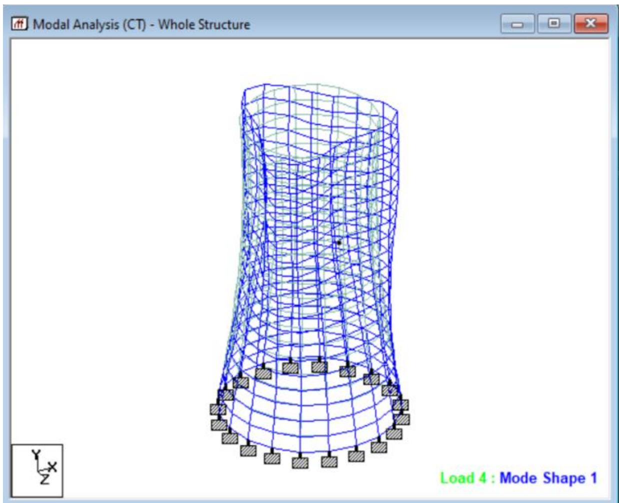

Fig. 10 (a) Mode 1

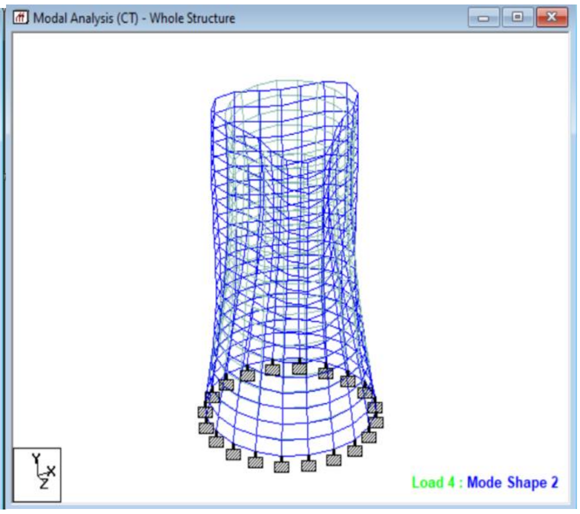

Fig. 10 (b) Mode 2

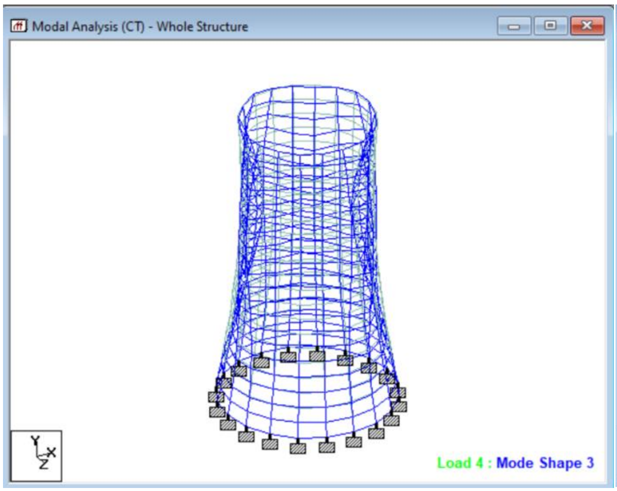

Fig. 10 (c) Mode 3

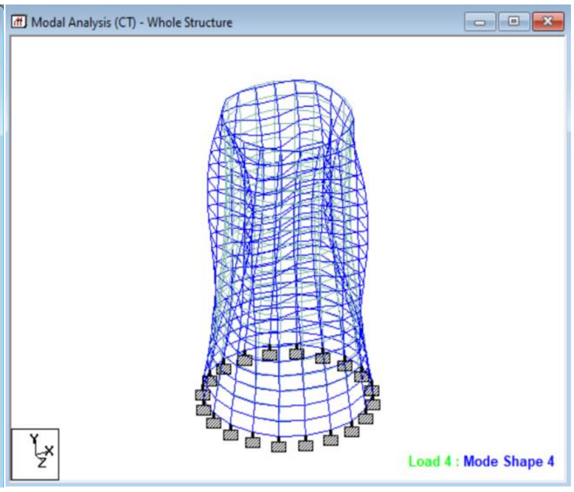

Fig. 10 (d) Mode 4

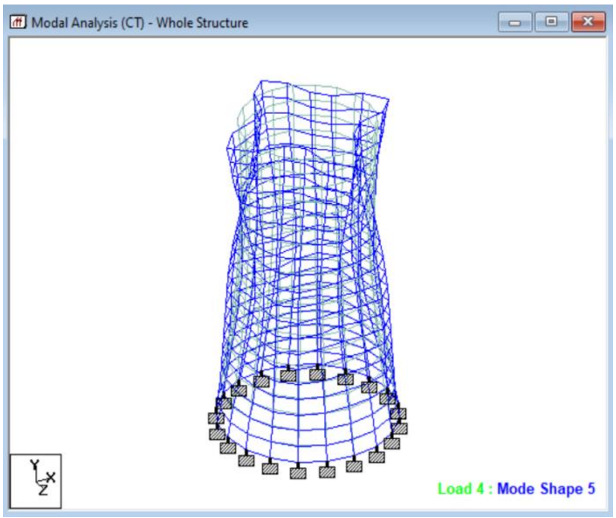

Fig. 10 (e) Mode 5

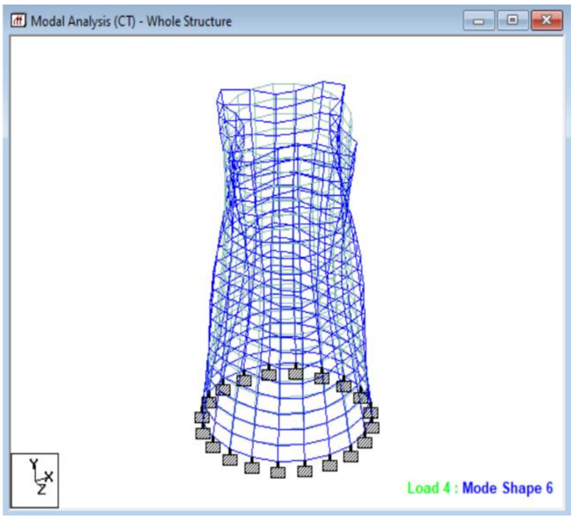

Fig. 10 (f) Mode 6

Fig. 10 Mode shapes for modal analysis for cooling tower with 200mm shell thickness

Table 2: Modal Analysis Results

Shell thickness of Cooling Tower (mm)	**Modes**	**Frequency (cycles/sec)**	**Period (sec)**
200	1	0.676	1.47978
	3	0.741	1.34970
	5	0.837	1.19410
250	1	0.699	1.43101
	3	0.818	1.22323
	5	0.895	1.11743
300	1	0.726	1.37784
	3	0.898	1.11397

	5	0.902	1.10896
350	1	0.756	1.32224
	3	0.901	1.10998
	5	0.992	1.00854
400	1	0.790	1.26586
	3	0.905	1.10546
	5	1.085	0.92144

4. Response spectrum analysis

The analysis has been carried out for varying shell thickness of cooling tower i.e., 200mm, 250mm, 300mm, 350mm and 400mm. SRSS (square root of the sum of squares) method used for mode combination. Spectral acceleration of 0.538g is and 5% damping ratio is used. Number of modes requested are six. Mode shapes are shown in Figure 11.

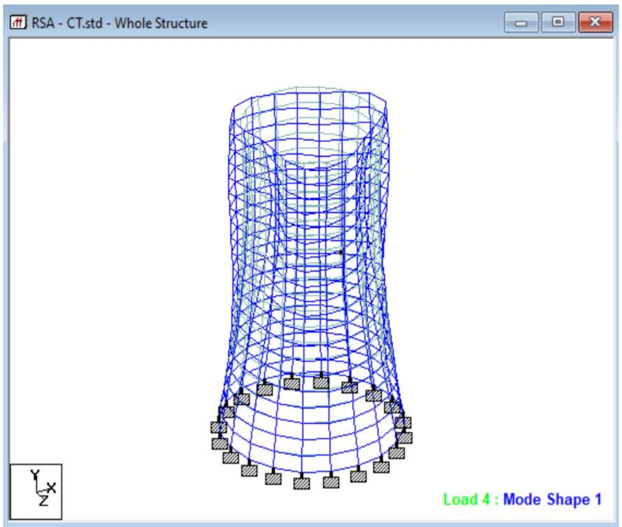

Fig. 11 (a) Mode 1

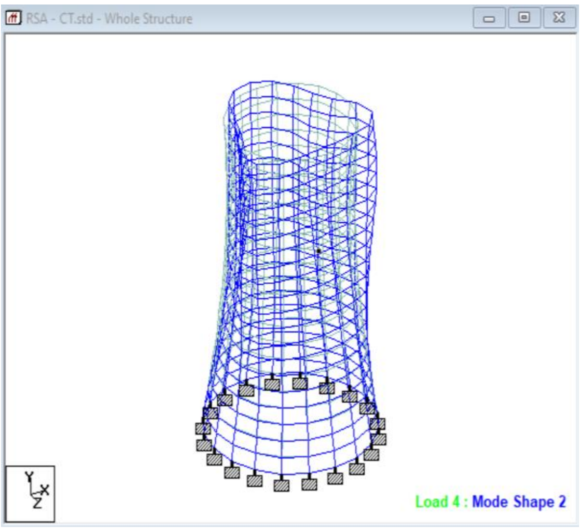

Fig. 11 (b) Mode 2

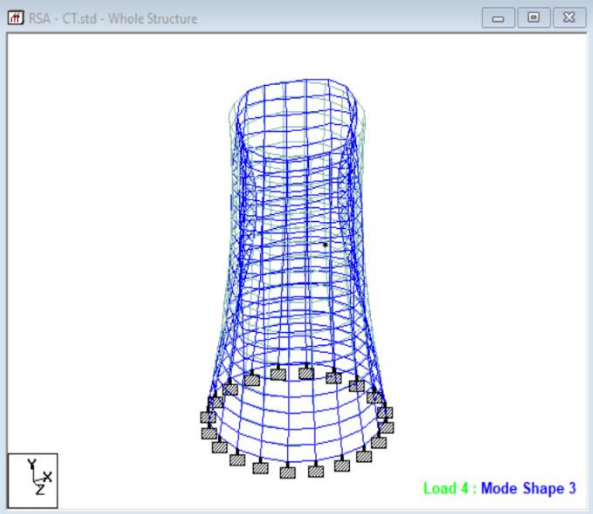

Fig. 11 (c) Mode 3

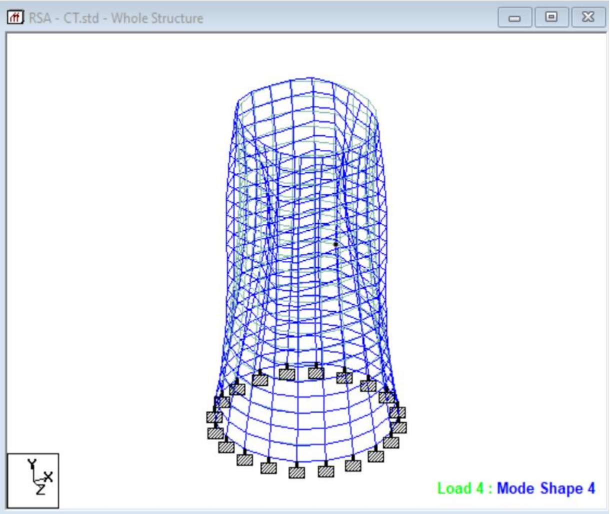

Fig. 11 (d) Mode 4

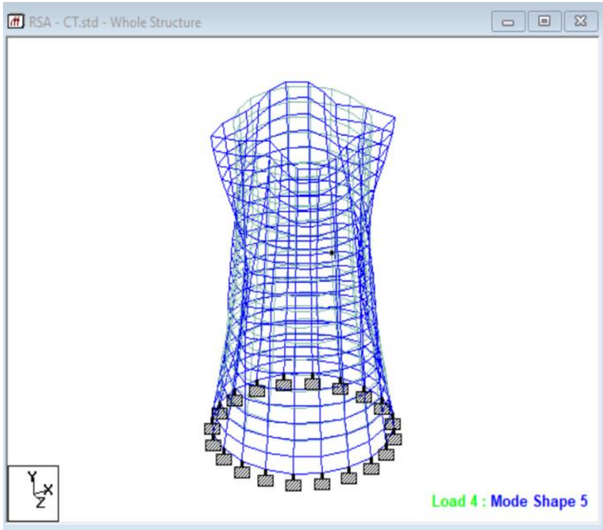

Fig. 11 (e) Mode 5

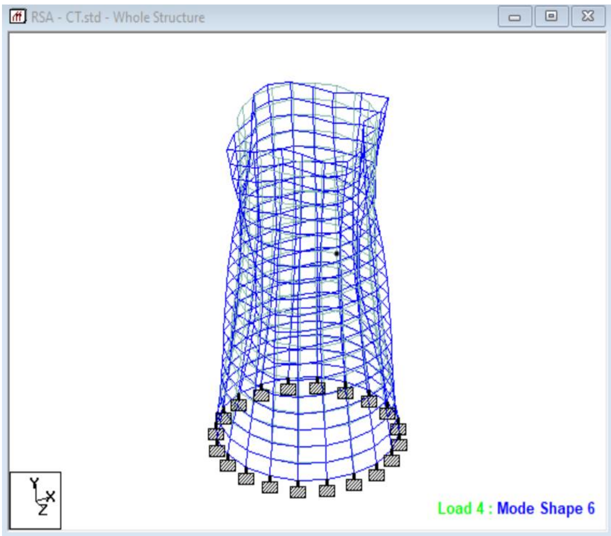

Fig. 11 (f) Mode 6

Fig. 11 Mode shapes for response spectrum analysis for 200mm thick cooling tower

Table 3: Response spectrum analysis (RSA) results

Shell thickness of Cooling Tower (mm)	Modes	Frequency (cycles/sec)	Period (sec)
200	1	0.909	1.10008
	3	0.973	1.02840
	5	1.091	0.91689
250	1	0.953	1.04950
	3	1.054	0.94957
	5	1.194	0.83773
300	1	0.997	1.00256
	3	1.122	0.89331
	5	1.299	0.77001
350	1	1.045	0.95733
	3	1.170	0.85567
	5	1.411	0.70887
400	1	1.095	0.91348
	3	1.202	0.83016
	5	1.530	0.65368

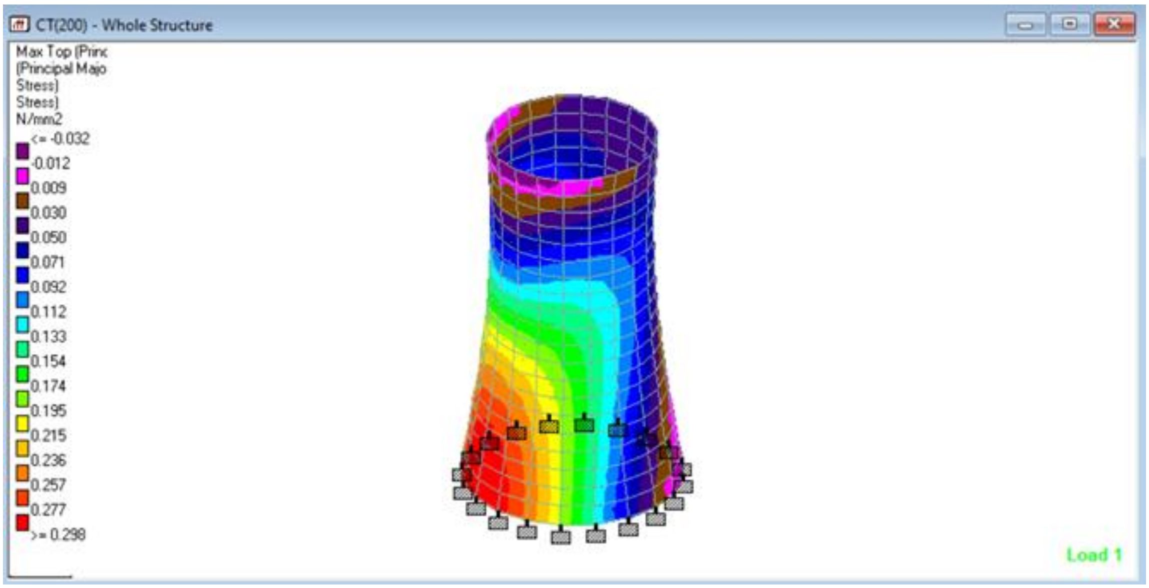

Fig. 12 Maximum principal stress due to earthquake load for cooling tower with 200mm shell thickness

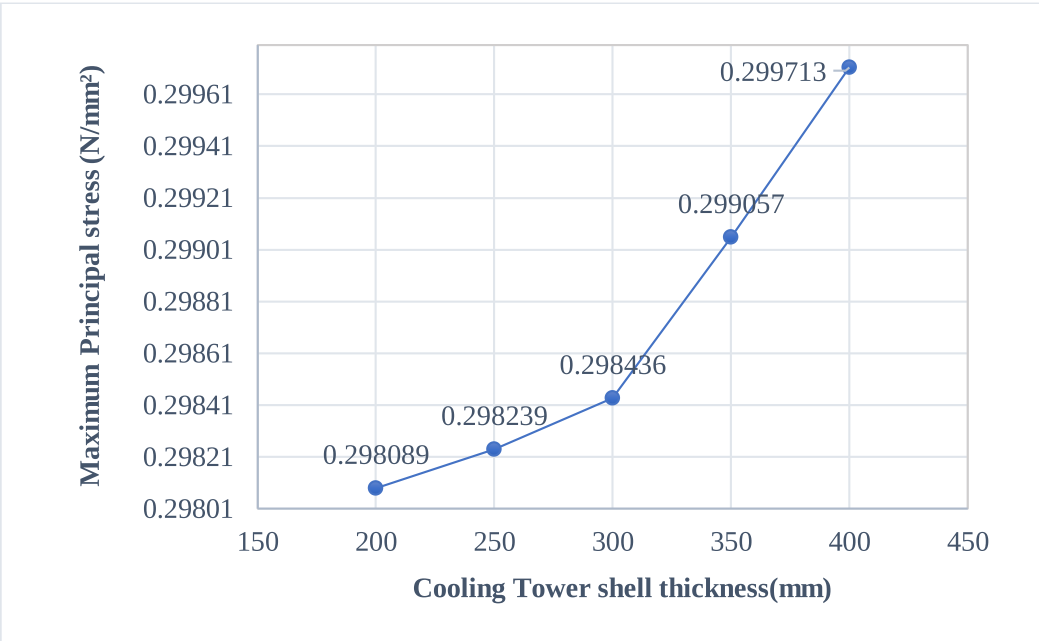

Fig. 13 Maximum principal stress (due to earthquake load) v/s varying shell thickness of cooling tower

Above graph in Figure 13 indicates, as shell thickness increases, the mass of the structure also increases which can amplify inertia forces during seismic events. So, instead of just thickening the shell, this observation highlights the necessity for optimal seismic design, either through base isolation or dampening.

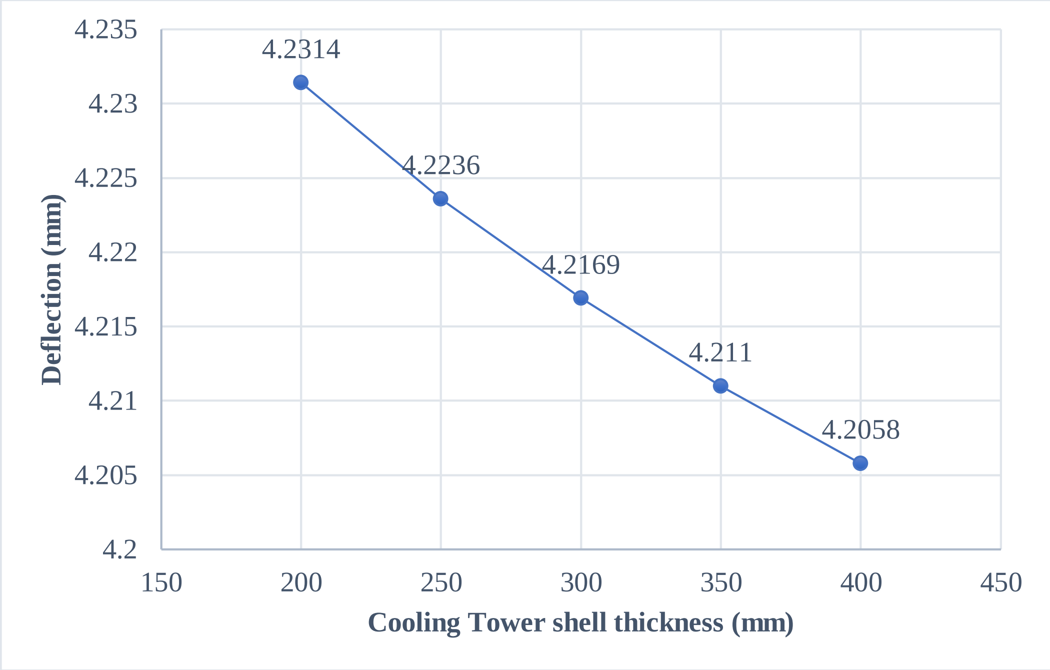

Fig. 14 Deflection (due to earthquake load) v/s varying shell thickness of cooling tower

The Figure 14, shows decrease in deflection with increasing shell thicknesses. However, the magnitude of reduction in deflection is less comparable to what we observed in case of wind loads. This implies that increasing thickness may not enough to reduce seismic displacements and highlights the importance of dynamic considerations.

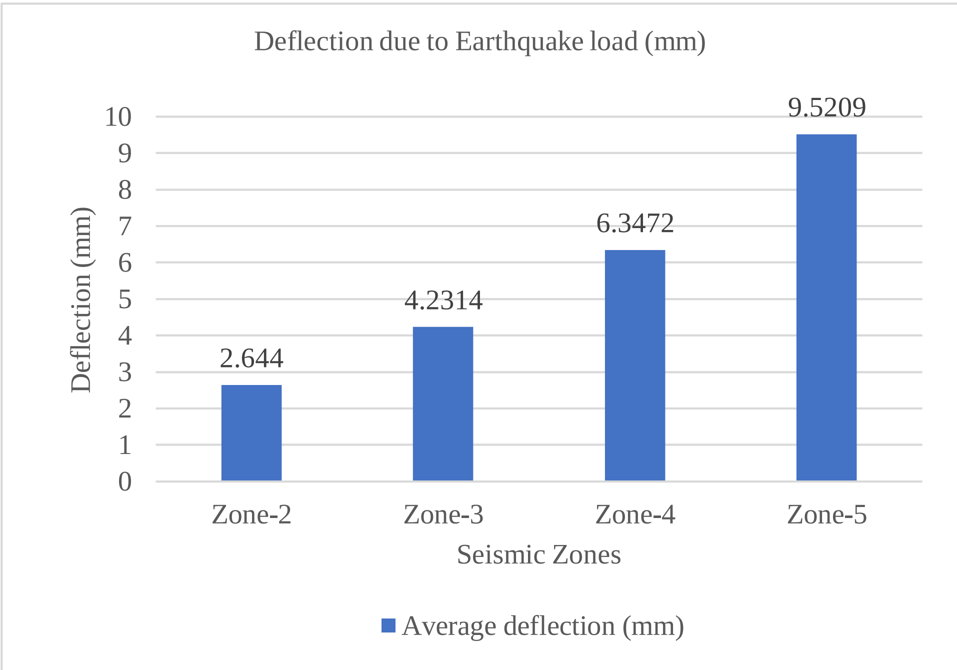

Fig. 15 Deflection (due to earthquake load) in different seismic zones for cooling tower with 200mm shell thickness

The Figure 15 shows increasing deflection values in higher seismic zones, validating the role of seismic zoning in structural analysis & highlights the importance of seismic zoning in civil engineering codes.

NOTE: In Figure 5; 9; 13 the weighted average value of stress shown in these graphs is represented in the form of weighted average stress which is calculated using the following formula:

$$\sigma_{avg} = (\Sigma\sigma i * Ai)/\Sigma Ai \quad (3)$$

where, σ_{avg} is the weighted average stress value, i is the stress value at a particular node or element, Ai is the area or volume associated with that node or element and Σ represents the sum of all values.

This calculation is used to determine the average stress value for a group of nodes or elements on a face or within a specific volume. The weights are determined based on the area or volume of the element or nodes that the stress values are associated with. Weighted average is a common method used in finite element analysis to provide a single stress value for a node that is shared by multiple elements. Each of these elements will generally have a different stress value at the shared node. The total principal stress acting on the entire tower would be a distribution of stresses, not a single value. It would be typically obtained from a detailed finite element analysis which requires knowledge of the stress state at every point in the structure.

CONCLUSION

The study clearly demonstrates that increasing the shell thickness of a natural draught hyperbolic cooling tower has a significant impact on its structural behaviour under various loading conditions. As the thickness increases, the overall deflection of the tower decreases across all load cases—dead, wind, and seismic—highlighting the direct correlation between shell stiffness and displacement resistance. However, the behaviour of maximum principal stress varies depending on the nature of the load. For dead and earthquake loads, the stress tends to increase with shell thickness due to the added mass contributing to higher internal forces. In contrast, wind load-induced stress decreases with increasing thickness, suggesting better distribution and absorption of lateral wind forces in thicker shells.

The dynamic analysis further supports the benefit of increased thickness, with natural frequencies rising consistently, indicating enhanced structural stiffness and improved resistance to dynamic excitation. Among all the loads considered, wind load emerges as the most dominant, particularly in Zone III, where it induces the highest deflections. This finding shows the necessity to prioritize wind load considerations in the structural design of such towers, especially in regions prone to high wind speeds. In conclusion, while increasing shell thickness can improve dynamic stability and reduce deflection, it also requires careful stress management, especially under seismic conditions. Thus, achieving an optimal balance between stiffness, mass, and cost remains significant factor in the efficient design of hyperbolic cooling towers.

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