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Investigation of behavior of cooling tower structure under external loads

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Abstract

Cooling towers are high and thin structures which are widely used at the industry and nuclear facilities. These structures are built on column elements as reinforced concrete. Determining the behavior of the buildings affected by the dynamic loads such as wind and earthquake is very important in terms of preventing the loss of life and property. In this study, hyperbolic cooling with 117m height tower was examined and the behaviors of the structure in earthquake and wind effects were investigated. During the application of the wind load, 25m / sec wind velocity was applied and three ground motion records were applied to the structures in the course of the earthquake analysis. The wind load was calculated in accordance with the ASCE 7-10 standard and it was given as angular. As a result of the analysis, the values of the displacement and stress were obtained and examined. According to the results of the wind load analysis; As the height of the tower increases, the values of wind load increase and the displacement values occurring in the building increase. The values of displacement and stress vary angularly depending on angular wind load. It is seen that the highest values of displacement and stress values were obtained in Kobe earthquake. Displacement values were examined depending on the height and the largest displacement values were obtained at the top part.

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1. Introduction

Cooling towers are buildings heights of which are more, thicknesses of which are low, diameters of which are more and they are used at industrial plants such as oil refineries, energy and nuclear power plants. These important facilities can be affected by forces such as earthquakes and wind. Therefore, it is necessary to examine the resistance of these structures in the impact of earthquake and wind. The intended use of cooling towers is to remove the heat taken from the cooling water in the system. Since the heat present in the water is provided to cool under the influence of the atmosphere, these structures are constructed as high in order to benefit from the effect of air. The sliding mold technique is used during the construction of these structures and the construction of these structures is carried out part by part [1].

The cooling tower is designed by the engineer as more slender and thinner for the purpose of increasing the dead load. The relationship between height and shell thickness is of great significance in terms of the stability problem occuring due to the loads such as wind and dead load [2]. It is very important to determine the situation of stress, durability, elastic stability, vibration values in such big structures because of the interaction of loading condition with the meridian shape of the cooling towers [3]. Three from eight cooling towers located in Ferrybridge power stations in the UK collapsed due to the aerodynamic effects which are about wind velocity 19m/s in 1965. In 1973, the cooling tower situated in Scotland Ardeer Power Plant collopsed because of the strong wind effect [4].

There are many studies related to the behavior of cooling towers under the influence of wind and earthquake. Karakas et al. [5] examined the static and dynamic behavior of cooling tower and wind turbine structures by considering soil-structure interaction in their study. They considered Vlasov soil model in the analysis of the soil-structure interaction. Based on the results of the study performed by Karakaş, it was seen that the frequency values decreased depending on the cooling tower height and wall thickness, according to the results of the structure-soil interaction analysis; the frequency values decrease by the rigid base situation. It was observed that there were large increases in tensile strength and small increases in meridian

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strength due to the wind effect, and also changes in displacement values occured as a result of wind and earthquake effects. Karakas et al. [6] examined the behavior of the cooling tower structure under the effect of wind by using the Vlasov soil model. It was seen that shear forces, bending and torsional moments at the columns increased when the structure-soil interaction was taken into consideration. Karakas et al. [7] analyzed the soil structure interaction by modeling the cooling tower using the SAP2000-OAPI program. They dealt with the cooling towers with different H / a ratio and evaluated the results obtained by performing the analysis by using the Vlasov soil model. It was observed that the frequency values decreased when the soil structure interaction was compared in terms of the rigid situation, in addition to when the height of the tower and the slenderness rates increased, the frequency values decreased and the frequency values increased with the increasing of the curvature. Ghomi and Kharrazi [8] examined the behavior of cooling tower which were exposed to the earthquake effect. The big displacements and stresses occurred in the columns and the structure as determined by Ghomi and Kharrazi. Yu et al [9] analyzed the behavior of the tower under the influence of wind by applying angular wind load to a cooling tower. G. Murali et al. [10] examined two cooling towers with 122m and 200 m height. They studied the behavior of these towers under the wind effect. They applied the wind load to the structures angularly and compared the values obtained as a result of the analysis. It was shown that the values of the bending moment and membrane force were different for three towers. Greiner and Derler investigated the behavior of cylinder shell structures under the effect of wind pressure by considering geometric nonlinearity and material plasticity. The results of the test and numerical studies performed by Greiner and Derler were compared [11]. Afshari and Dehghanpour [12] explained the types of cooling tower and its cooling principles. The working principles of the cooling tower were compared in terms of the mechanical and natural draft. In addition to these, A fluent simulation was performed. Asadzadeh et al. [13] performed in the modal and nonlinear time history analysis of the cooling tower structure. The columns supporting the cooling tower were designed as I and Λ type. The effect of the angle of inclination in the columns was investigated. The angle variation of the columns is affected by the analysis results. Dehghanpour et. al. [14] examined the behavior of a cooling tower under the wind load effect in the cases of before and after reinforcement by reinforcing with CFRP (carbon fiber reinforced polymer) material with different thicknesses. The obtained stress and displacement values are compared.

The aim of the study is to examine the behavior of the cooling tower exposed to the external loads such as earthquake and wind effects . For this reason, while the wind loading analysis was performed in accordance with ASCE 7-10 regulation, earthquake analysis was performed by using time history analysis by taking into account of a cooling tower being 117m [15]. The wind loads were angularly applied to the cooling structure and the values obtained from the results obtained angularly. In the earthquake analysis, The earthquakes having different characteristics were applied to the cooling tower. One of the earthquakes applied to the structure is Kobe earthquake whose magnitude, ground acceleration, ground velocity are quite high.

2. Materials and Methods

In our country, many earthquakes causing a number of losses of lives and property occurred. Many buildings were damaged in the August 17, 1999 earthquake. Earthquakes occurred before and after 1999 earthquake show that examination of the industrial buildings is very important in terms of the earthquake engineering. It is necessary to determine the behavior of the structures under earthquake effect in order to be able to prevent these losses.

The wind, earthquake and temperature effects are of great importance when internal forces occurring in cooling tower structures are determined. Hyperbolic design of cooling towers increases the strength of the structure, however fewer material is used [16]. The meridional shape of a hyperbolic cooling tower comprises of lower and upper hyperbola parts and these parts join in throat. The curve varies along the height of the tower because the tower axis with the axis of the hyperbola does not need to match, and the greatest value is usually seen in the throat part [3]. Hyperbolic shell geometry is shown in Figure 1 [16].

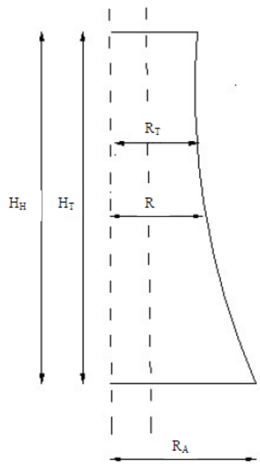


Figure 1. Hyperbolic shell [16]

$$R = c + a\sqrt{1 + \frac{z^2}{b^2}} \quad (1)$$

$$b = \frac{H_T}{\sqrt{\left(\frac{R_A - C}{R_T - C}\right)^2 - 1}} \quad (2)$$

R is determined according to the equation 1-2. Hyperbolic shell design can be performed with the equations [16]. The geometric properties of the cooling tower are presented in Figure 2a. The dimensions of tower designed are as follows; the total height of the cooling towers is 117m, column height is 9m, the base diameter is 103.5m, shell base is 98m, diameter of throat is 54m, diameter of top part is 58.5m.

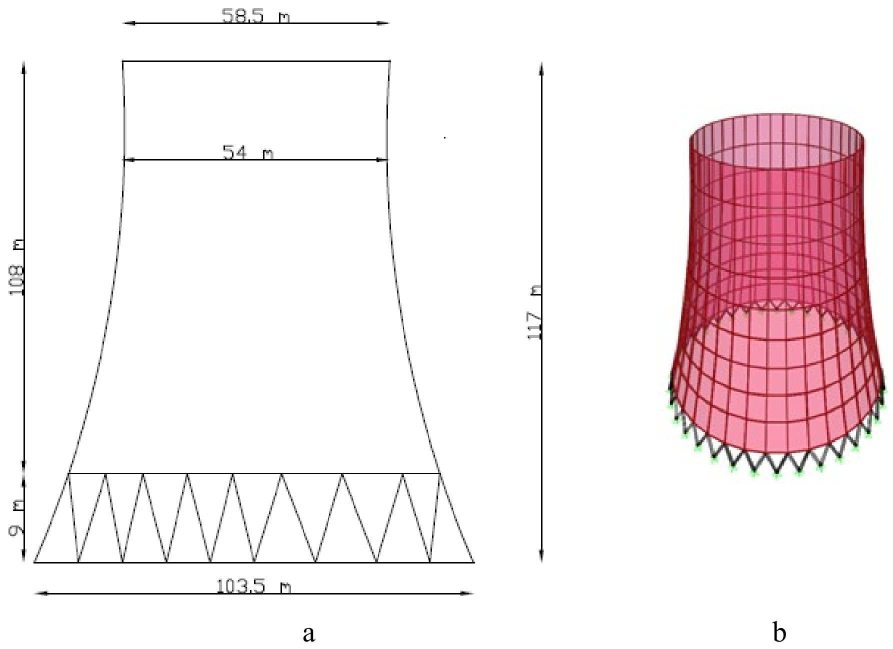


Figure 2. a) The geometric properties **b)** mesh shape of the cooling tower building

The cooling tower structure was modeled as a shell element with the SAP 2000 finite element program [17]. The finite element model of the cooling tower in Figure 2b. Cooling towers are supported by columns. V shaped columns consisted of line element with 2 noded were designed. Columns gave 6 degrees of freedom at each node. The columns carrying the cooling tower consist of reinforced concrete elements and their diameters are 90 cm. In the structure designed, 32 columns were used and the cooling tower wall was divided into 324 shell elements. The tower is divided into 36 parts in the radial direction. The wall thickness of cooling tower was designed as 700mm in lower parts and 250mm in other parts. C30 concrete was used in the shell walls of the cooling tower structure and supporting columns.

2.1. Wind load analysis

The effect of the angular distribution with the vertical effect of the wind loads formed in symmetrical circular structures such as cooling tower is very important. Wind loads formed in the vertical direction depend on climatic conditions and soil surface roughness, and wind loads formed angularly depend on the structure surface roughness [5].

Wind loads are determined according to ASCE 7-10 standard in order to examine the behavior of cooling tower structures under the effect of wind. Wind load calculation is made by using equation 3 - equation 6 [15].

$$P(z) = q_z G\, C_{pe}(\theta) \quad (3)$$

$$q_z = 0.613.K_z K_{zt} K_d.I.V^2 \quad (4)$$

q_z	Wind pressure
G	Storm effect factor
$C_{Pe}(\theta)$	Angular pressure distribution
K_z	Speed pressure effect coefficient
K_{zt}	Topography factor
K_d	Wind direction coefficient
I	Importance factor

$$G = 0.925\left(\frac{1 + 1.7\, I_{\bar{Z}} \sqrt{g_Q^2\, Q^2 + g_R^2\, R^2}}{1 + 1.7 g_v I_{\bar{z}}}\right) \tag{5}$$

Q; Ground response factor is calculated by equation 6.

$$Q = \sqrt{\frac{1}{1 + 0.63\left(\frac{B+h}{L_{\bar{Z}}}\right)}} \tag{6}$$

$I_{\bar{z}}$	Turbulence density at $\bar{z}$ height
$\bar{z}$	Equivalent height of the structure ($\bar{z} = 0.6h$)
g_Q	Peak factor for soil response
g_V	Peak factor for wind response
Q	Ground response factor

The value of design wind pressure at any height value is determined by multiplying the values of the wind pressure, storm effect factor and the angular pressure distribution. Wind pressure (q_z) is calculated based on the values of K_z, K_{zt}, K_d, I by using equation 3. K_z, K_{zt}, K_d and I coefficient values are provided in the regulation. The storm effect factor can be taken as 0.85 in rigid and other structures and it is also obtained by using equation 4 [5, 15, 18, 19].

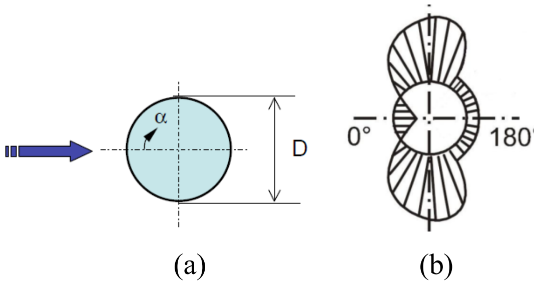


Figure 3. (a) Wind flow in circular sections [20] **(b)** Pressure distribution in circular structures [18;21]

The condition of the effect of wind in one direction to the circular cross-sectional structures is shown in Figure 3a and the pressure distribution resulting is shown in Figure 3b [18; 20; 21]. C_{pe} coefficient for circular cross-section conditions is determined according to the equation 7 which belongs to Greiner. In the Formula 7, α is the angle that the wind load makes with the circular cross section [18; 22].

$$C_{pe} = -0.55 + 0.25 * \cos\alpha + 1.0 * \cos 2\alpha + 0.45 * \cos 3\alpha - 0.15 * \cos 4\alpha \tag{7}$$

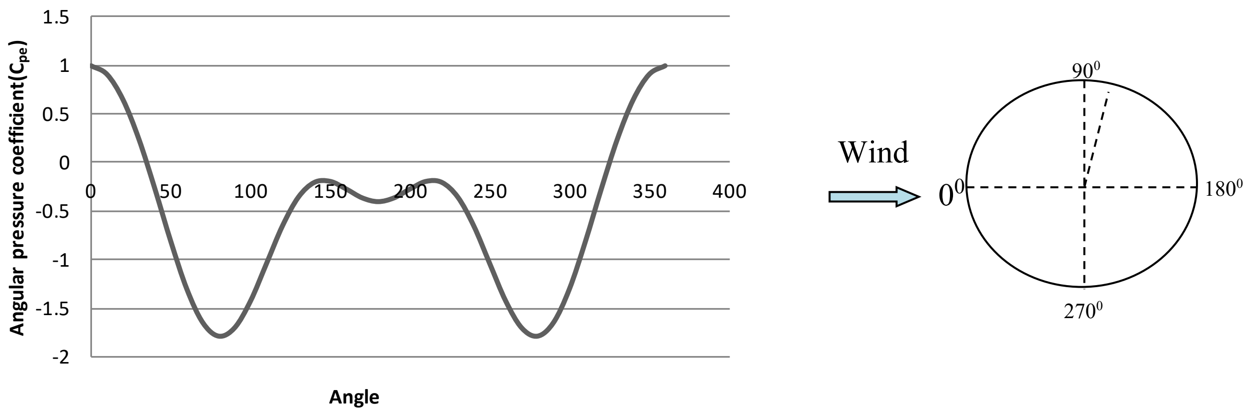
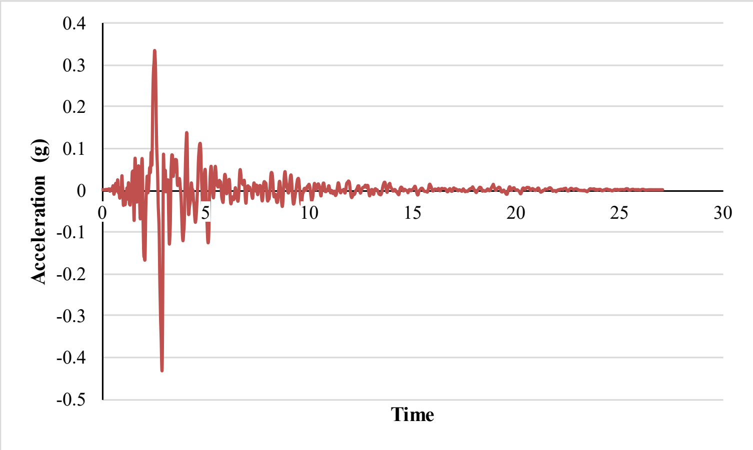


Figure 4. Angular pressure coefficients

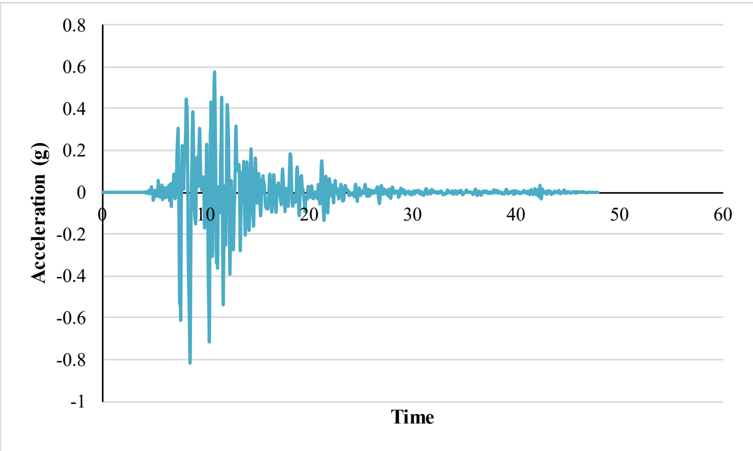
In this study, 25m/sec wind speed is applied to the cooling tower building and since these structures are circular cross-section, the values of the wind pressure are calculated as angular according to the equation 3-equation 7. The values of the angular pressure coefficient used in the calculations are shown in Figure 4. The values of wind load applied to the tower were obtained by multiplying with the wind pressure values determined for each z height by establishing values of C_{pe} according to the angles.

2.2. Earthquake analysis with the time history method

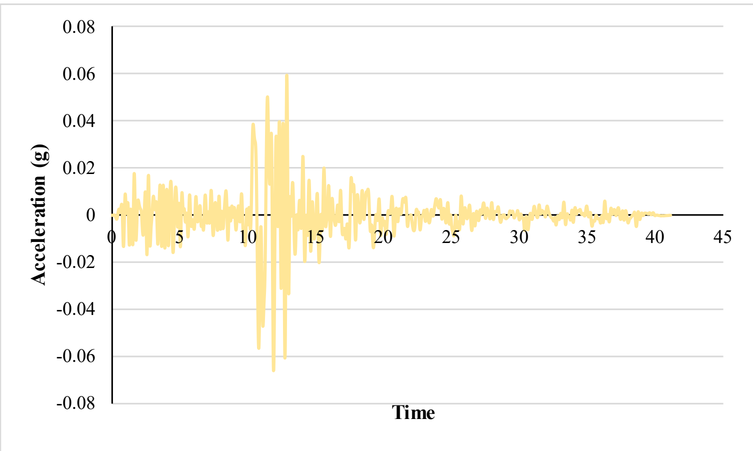
The dynamic analyses were performed with the time history method by applying three ground motion records to the cooling towers. The features of the earthquakes used in the analyzes are presented in Table 1 [23]. Time-dependent acceleration recordings of earthquakes are shown in Figure 5.



a) 1979 Coyote Lake Earthquake



b) 1995 Kobe Earthquake



c) 1980 Anza Earthquake

Figure 5. Time-dependent acceleration records of **(a)** 1979 Coyote Lake, **(b)** 1995 Kobe, **(c)**1980 Anza Earthquake

Table 1. The features of earthquakes used in the analysis [23]

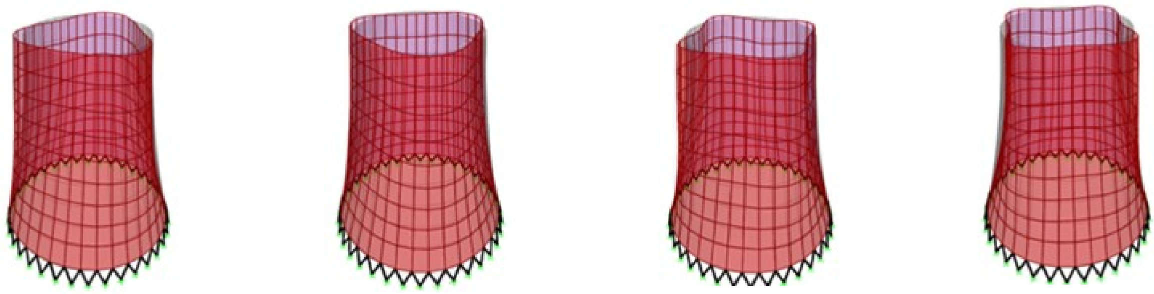
Earthquake	Date	Magnitude (M_w)	Record	Ground Velocity (cm/s)	Ground Acceleration (g)	Focus Depth (km)
Coyote Lake	06/08/1979	5.8	G06230	49.2	0.4339	3.1
Kobe	16/01/1995	6.9	KJM000	79.3	0.8213	6.9
Anza (HorseCany)	25/02/1980	4.9	AZF315	2.6	0.066	12.1

3. Results and Discussion

In this study, cooling tower structure is modelled and analysis are performed under the effect of earthquake and wind. Firstly, The period values of the cooling tower structure were obtained by performing modal analysis. Secondly, The wind analysis was made according to ASCE 7-10 regulation [15]. Then, the ground motion records with different properties were applied to the cooling tower structure.

3.1. Mode shapes and frequency values

Mode shapes and frequency values obtained by using SAP 2000 finite element program. There are mode shapes and the value of frequency in the analysis result of the modal analysis made in Figure 6. The first four frequency values in the cooling tower structure are 1.14Hz., 1.14Hz., 1.30Hz. and 1.30 Hz.



f_1=1.14 Hz. f_2=1.14 Hz. f_3=1.30 Hz. f_4=1.30 Hz.

Figure 6. The mode shapes and period values in cooling tower

The math model of the cooling tower structure can be designed as a single degree of freedom system. The first natural frequency value of a single degree system with fixed supported.

The value of first frequency of vibration can be estimated according to Equation 9 [24,25].

$$\omega = \frac{1.875}{H^2}\sqrt{\frac{EI}{m}} \quad (9)$$

$$f = \frac{\omega}{2\pi} \quad (10)$$

Here, H; height of the tower; I; moment of inertia, E; elasticity modulus, f; first natural frequency, m; mass of the tower. The mass, height and weight of, volume of cooling tower are 117m and 24 KN/m^3. The average dimension is taken as 78m.

ω =7.91 s^{-1}

f=1.26 Hz

The frequency value obtained from equation 9 and equation 10 is very close to the value obtained from modal analysis performed with SAP 2000 finite element program.

3.2. The application of wind load to the cooling tower structure

The displacement and stress and their values were examined by considering the angular changes of the structure in case of wind load effect on cooling tower structure.

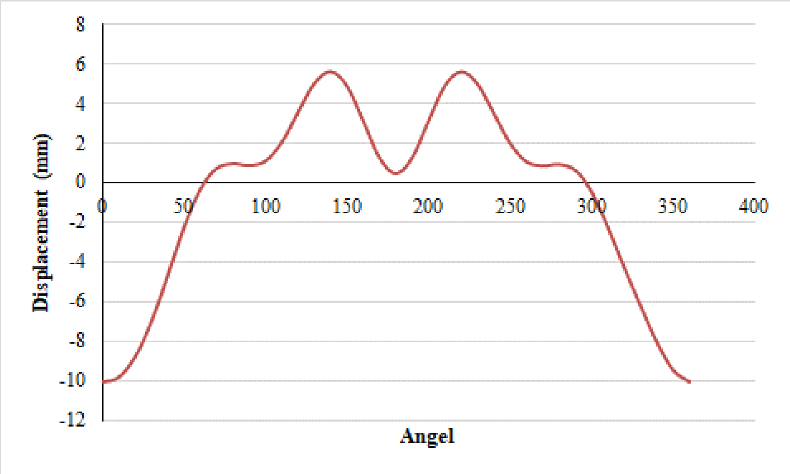


Figure 7. Angular displacement values

There are the graphics of displacement values occurring in the angular direction in Figure 7. The wind load comes to the structure as angular and is applied angularly by multiplying the wind load with the angular pressure coefficient at each height z. It was shown that the wind speeds are gradually decreasing 10mm at 0^0, 9.8mm at 10^0 and 8.8 mm at 20^0. While the largest values occur in the direction of the wind, the values decrease in the other direction.

Displacement values depending on the height are shown in Figure 8. The largest displacement is seen to be obtained at a height of 117 m. Since the wind load increases with the height of the floor, displacement values increase as the height of the structure increases.

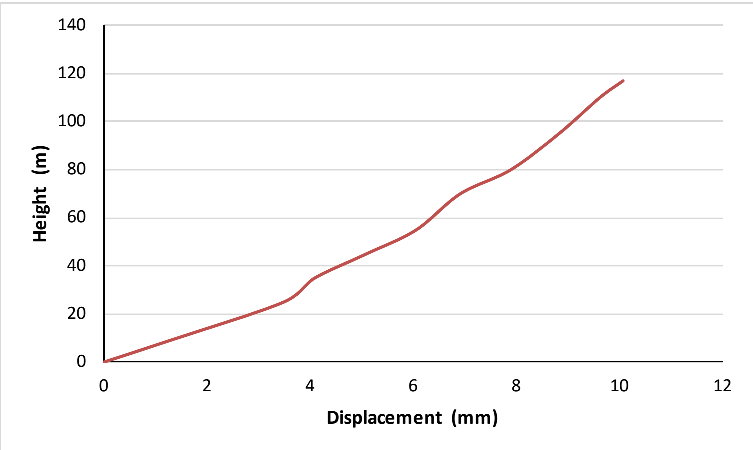


Figure 8. The values of displacement depending on the height

In Figure 9, there are stress shapes in which the pressure and tensile stresses occur in the structure when the speed of the wind is 25m / sec. It is seen that the stresses intensify in the parts close to the base and in the throat in the direction of the wind.

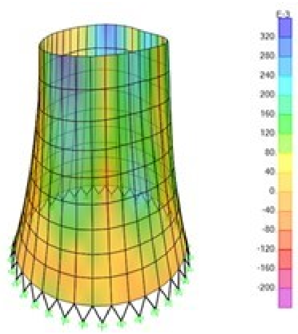


Figure 9. The tensile status of the building in 25 m/s wind speed

3.3. Application of earthquake load to the cooling tower structure

Three time dependent acceleration recordings were applied to the structure and displacement and stress values were obtained. The displacement and stress values are respectively shown in Figure 10 and 11. The biggest stress and displacement values were obtained in Kobe earthquake.

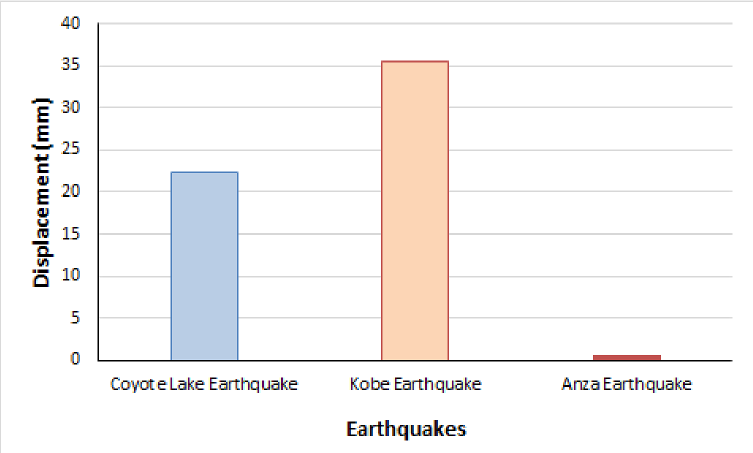


Figure 10. Displacement values found in the earthquake analysis

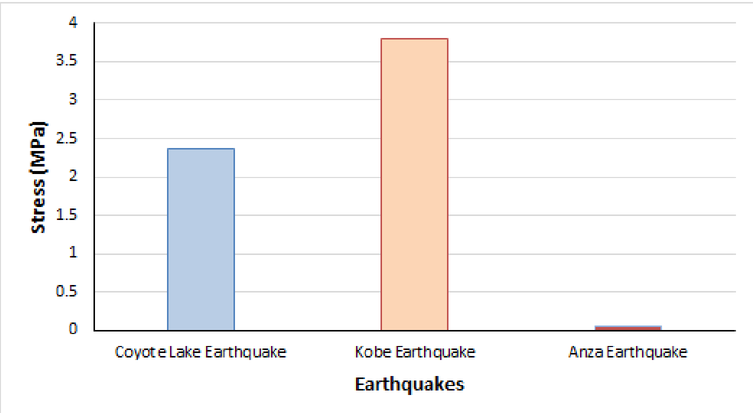
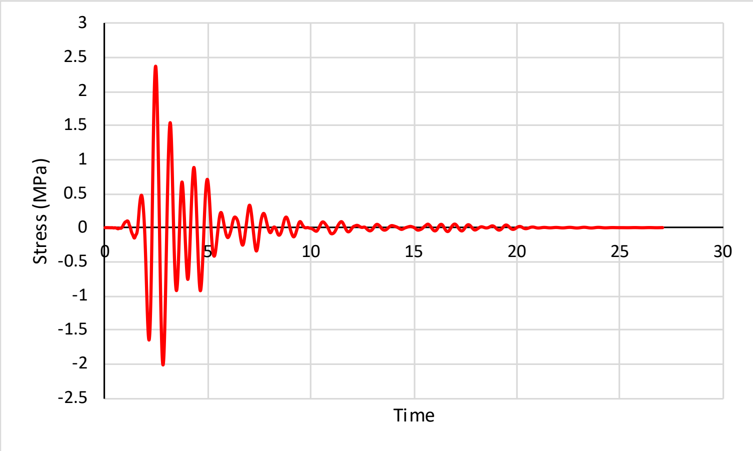


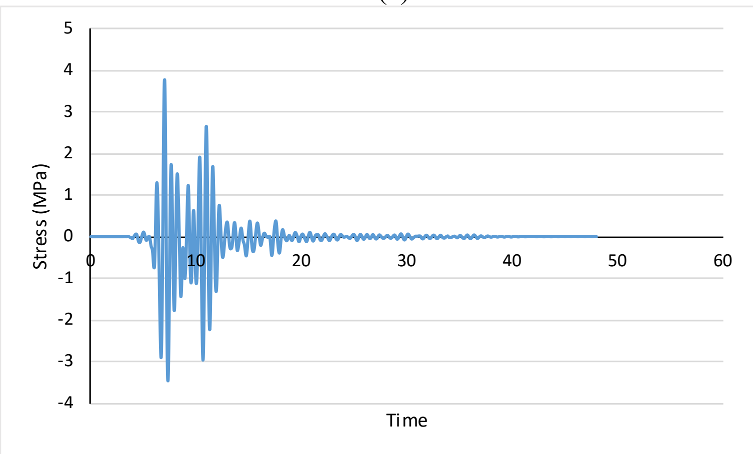
Figure 11. Stress values found in the earthquake analysis

The stress graph dependent to time in the structure in the case of Kobe, Coyote Lake and Anza earthquakes are shown in Figure 12 a,b and c. While the biggest displacement and stress value were obtained in Kobe earthquake, the smallest values were obtained in Anza earthquake.

Displacement and stress values were obtained by applying time-dependent acceleration records of 3 earthquakes. The biggest displacement value was 35.51 mm and the maximum stress value was 3.7 MPa with Kobe earthquake, the smallest displacement value was 0.58mm and the stress value was 0.048 MPa in 1980 Anza earthquake. In 1979 Coyota Lake earthquake, 22.29 mm displacement and 2.3 MPa stress value was obtained. The Kobe earthquake is a quite big earthquake and its magnitude is 6.9. The magnitudes of Coyota Lake and Anza earthquakes are 5.8 and 4.9, respectively. Kobe earthquake has a ground velocity of 79.3 m / sec, an effective ground acceleration of 0.82 and a focal depth of 6.9 km. velocity and ground acceleration are quite higher than other earthquakes. The ground velocity and ground acceleration of Anza earthquakes have the smallest value and its depth of focus has the largest value. In Figure 12, It is seen that the values of the biggest stress occured in the duration when the effective ground acceleration of the earthquakes is greatest.



(a)



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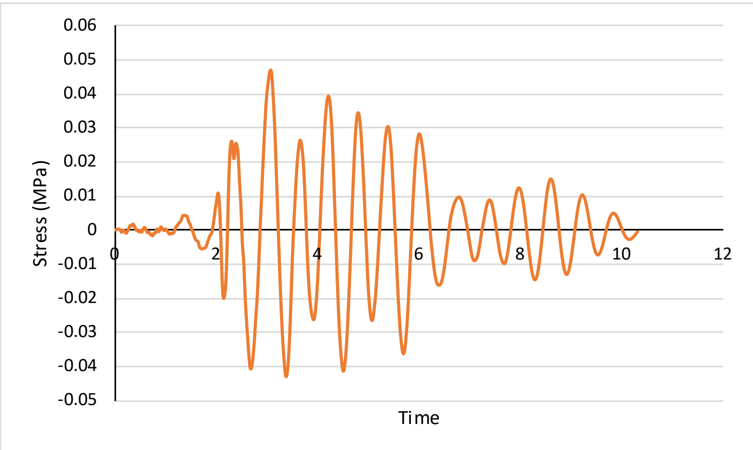

(c)

Figure 12. Maximum stress graph found in the earthquake analysis for **(a)** Coyote Lake Earthquake **(b)** Kobe Earthquake **(c)** Anza Earthquake

4. Conclusion

In this study, the behavior of the cooling tower under the influence of wind and earthquake was examined. ASCE-7-10 regulation was used for wind analysis [15]. Wind loads were determined by using angular coefficient values in circular cross-sectional systems. In earthquake analysis, three ground motion records were applied to the structure according to time history analysis.

As a result of the earthquake analysis; while the greatest displacement and stress values are obtained in Kobe earthquake, the values obtained in Coyota Lake and Anza earthquakes are gradually decreasing. Effective ground acceleration and ground velocity of Kobe earthquake is higher than other earthquakes. The earthquake effective ground acceleration and ground speed of which are the lowest is observed in Anza earthquake. Accordingly, it is seen that the smallest displacement and stress values are obtained from Anza earthquake. The largest displacement values in the structure occur at the top of the tower.

The structure was examined under the effect of wind speed of 25 m / sec and displacement and stress values were obtained. The wind pressure was applied at the maximum value in the wind direction and the wind pressure values changed according to the angle change. Displacement values were determined as angular and dependent on height. According to the values obtained depending on the height, the greatest value is at the top part. It is seen that the values changed according to the angular change in the values of the displacement obtained as angular.

Conflicts of Interest

The authors state that there is no conflict of interests.

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