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Linear and Nonlinear Behaviour of R. C. Cooling Tower under Earthquake Loading

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Abstract- Cooling tower is a device which converts hot water into cold water due to direct air contact. It works on the temperature difference between the air inside the tower and outside the tower. Natural draft cooling tower is one of most widely used cooling tower. Hyperbolic shape of cooling tower is usually preferred because of its strength and stability and large available area at the base due to shape. As it is very important structure in nuclear and chemical plants, it should be continuously assessed for its stability under self-weight, and lateral loads like wind load and earthquake load. Therefore, self-weight analysis, static wind analysis and both linear and nonlinear analysis under earthquake loading of cooling tower with different column supporting systems are carried out.

Keywords- Cooling tower, Linear and nonlinear, Dynamic analysis

I. INTRODUCTION

Cooling tower is a device which converts hot water into cold water due to direct air contact. Cooling tower can be classified based on pattern of air flow through water and drafting of air. Natural draft cooling tower is one of most widely used cooling tower. It works on the temperature difference between the air inside the tower and outside the tower. Hyperbolic shape of cooling tower is usually preferred because of its strength and stability and large available area at the base due to shape. Cooling tower is supported on columns of different shapes such that A, V, X, and I. And these columns are rested on annular beam. These supporting columns behave as air inlets.

Natural draft cooling tower is a structure which is mostly found at nuclear and chemical plants. Cooling towers are used for evacuation of heat from these plants. It is very tall and slender structure. Shutting down of this structure due to any of reason causes great inconvenience and loss of revenue. Therefore, cooling tower should be analyzed for loads expected to act on it. Cooling tower should be analyzed self-weight, wind loading, and earthquake loading. As it is very tall structure it is normally assumed that wind analysis is important. But there are some locations where stresses developed due to wind are less than stresses developed by earthquake force. Therefore the predominance of lateral force (either wind or earthquake) depends on location of cooling tower. In this paper, dynamic analysis of cooling tower under earthquake load is carried out.

Many researchers have investigated the structural behavior of hyperbolic cooling towers under dynamic loading. Gupta A. K. (1976) presented different methods of seismic analysis. Different methods of analysis such as direct integration of equation of motion, and modal superposition method, response spectrum method, and random vibration method are discussed briefly. They mentioned advantages and disadvantages of these methods over each other. Finite element based program was used for analysis purpose.

Gran C. S. (1980) carried out analysis of cooling tower under earthquake loading for natural frequencies and mode shapes and results for the time history response of deflection. For analysis purpose the column supports were represented by beam elements and shell was modeled as orthotropic quadrilateral plate elements. In finite element method different element mesh sizes were used and two beam elements were used for representing individual column. This analysis was carried out based on linearly elastic assumptions; the max steel stresses have exceeded the yield point.

Wolf J. P. (1984) carried out seismic analysis of hyperbolic cooling tower in time domain. Higher order finite element frusta with isoparametric expansion in meridional direction and a Fourier expansion in circumferential direction. The stiffening ring beam, foundation ring beam, and supporting columns were synthesized into dynamic stiffness matrix with axisymmetric shell element. The model of soil was represented as spring and damper.

Prabhakar N. (1990) mentioned different features of R. C. hyperbolic cooling tower. Castiau T. (1998) compared the cooling tower on meridional supports to equivalent tower supported by diagonal columns. Two types of diagonal columns were used V and A. For earthquake analysis three normalized response spectra were considered. The behavior of supports was different because earthquake shear induces large bending moments in columns.

Ghomi S. S. (2005) assessed the stability of R. C. column supported hyperbolic cooling tower for seismic loads. They performed finite element analysis for finding stress concentration, nonlinear behavior, stability or safety factor of R. C. cooling tower due to earthquake load. Nonlinear finite element analysis was carried out due to two kinds of earthquake records to define stability factor of R. C. cooling tower with long X supporting columns. Ghomi S.S. (2006) carried out both linear and nonlinear analyses of R.C. cooling towers under earthquake excitation. The cooling tower supporting on X-type column support was analyzed under seismic excitation. Raju V.S.N. carried out analysis of a hyperbolic natural draught cooling tower using Quad8/Quad4 elements of MSC/NASTRAN. Results were compared by varying mesh size and aspect ratio of Quad8/Quad4 elements. Tabeshpour M. R. (2012) performed nonlinear dynamic analysis of chimney–like towers. These mega-structures are of vital importance in their field. Idealization of these mega-structures numerically may not consider all the mechanical characteristics particularly nonlinear properties of material.

In this paper both linear and nonlinear analyses of cooling tower with different parameters are carried out and results are compared.

II. GEOMETRY OF TOWER

Consider a cooling tower [8] of height 125m supported on 44 pairs of diagonal column which are racked in the vertical plane being tangential to the meridional plane of the shell at its bottom. The shell has thickness of 720mm at base, 350mm at top and a throat level thickness of 230mm with the thickening at the top and bottom affected gradually. Geometry is shown in figure 1

The equation of hyperbolic shell is,

$$\left[\frac{z}{27.6}\right]^2 + \left[\frac{r}{68.82}\right]^2 = 1$$

Elevational mean radius of cooling tower is defined in table 1 ,

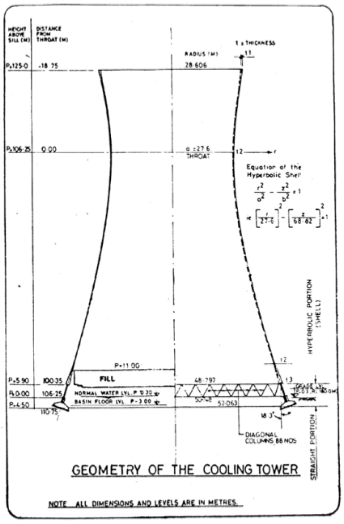

Figure 1. Geometry of cooling tower

Table 1. Elevational mean radius of cooling tower

Height in m	Z in m	Mean radius in m
124.500	-18.25	28.55
123.000	-16.75	28.40
119.125	-12.875	28.07
111.250	-5	27.67
101.250	5	27.67
91.250	15	28.24
81.250	25	29.36
71.250	35	30.96
61.250	45	32.97
51.250	55	35.33
41.250	65	37.96
31.250	75	40.82
21.250	85	43.86
14.350	91.9	46.04
10.550	95.7	47.27
7.825	98.425	48.16
6.500	99.75	48.60

III. METHODOLOGY

Finite element method is most widely used method for analysis of complex structures like cooling tower. In the process of finite element analysis a body is divided into an equivalent system of smaller units interconnected at points common to two or more elements and/or boundary lines and/or surfaces is called discretization. Instead of solving the problem for entire body in one operation equations for each finite element are formulated and then they are combined to get solution for whole body.

Here cooling tower is discretized using 4 -noded and 3-noded plate elements. 3 noded elements are used in at the interconnection of shell structure and column and remaining shell is discretized using 4- noded elements. There are 6 degrees of freedom at each node of element. They are u, v, w, θ_x, θ_y ,$\theta_{z.}$. And columns are discretized as 2-noded beam element having same number of degrees of freedom as plate element.

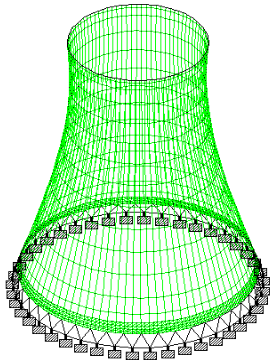

Figure 2. Finite Element Representation of Cooling Tower

IV. LINEAR DYNAMIC ANALYSIS OF COOLING TOWER

For the linear dynamic analysis of cooling tower time history modal analysis method is used. Cooling tower is subjected to strong earthquake motion like Northridge and El-centro and displacement at top node and bottom node, base shear of cooling tower considering both supporting systems are represented in graphical format. This analysis is done with SAP software.

V. NONLINEAR DYNAMIC ANALYSIS OF COOLING TOWER

To understand the exact behavior of structure under seismic excitation nonlinear analysis of structure is necessary. When subjected to strong ground shaking, most of the structures are expected to deform beyond the limit of linearly elastic behavior. Whenever the structural system has any or all reactive forces (linear inertia, damping and restoring forces) having non-linear variation, a set of non-linear differential equations are evolved and to be solved. The most common non-linearities are stiffness and damping non-linearities. In the stiffness non-linearity, there are two types of non-linearities, first one is geometric non-linearity and second one is material non-linearity. Here material nonlinearity is considered.

Engineering materials display non-linear stress-strain relationship. The behavior of stress-strain curve depends on the type of material such as steel, concrete, rocks, and soil. Stress-strain curve defined by Hognestad is popularly used by researchers. A series of tests were conducted by a team of people headed by Hedao. The stress-strain curve derived by him is having same character similar to that of Hognestad. The data is as below:

Table 2. Relationship between Stresses and Modulus of Elasticity

Strain	**Stress ($N\backslash mm^2$)**	**E_c Modulus of Elasticity of Concrete ($N\backslash mm^2$)**	**Nature of Curve**
0.000178	4.55244	25720.00	Linear
0.000307	7.89604	25720.00	Linear
0.000484	12.44848	25720.00	Linear
0.000615	15.81780	25720.00	Linear
0.000835	21.47620	25720.00	Linear
0.000924	23.76528	25720.00	Linear
0.001120	26.03000	23241.07	Non-Linear
0.001240	27.70000	22338.70	Non-Linear
0.001360	29.43000	21639.70	Non-Linear
0.001620	32.78000	20234.56	Non-Linear
0.001800	33.95000	18861.11	Non-Linear
0.002260	36.22000	16026.54	Non-Linear
0.003360	38.48000	11452.38	Non-Linear
0.003570	38.94000	10907.56	Non-Linear
0.003990	38.96000	9764.41	Non-Linear

Above table 2 gives relationship between stresses and modulus of elasticity. And stress-strain curve is plotted in figure 3.

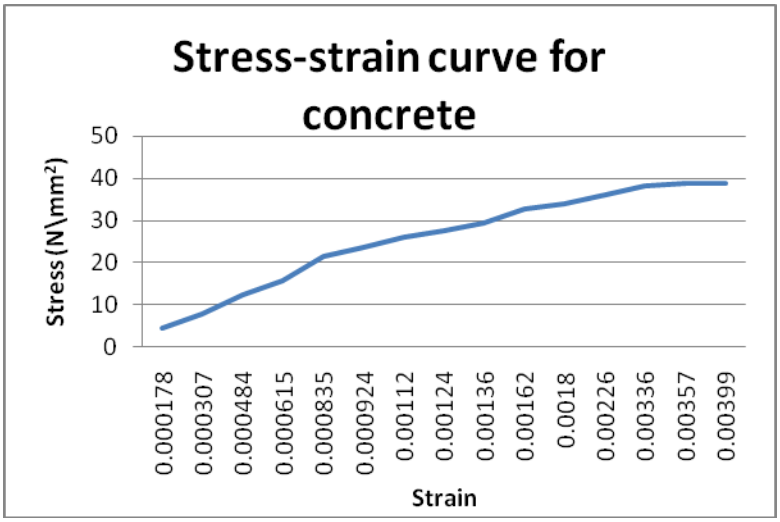

Figure 3 Stress-strain curve for concrete

The comparison of results obtained from both linear and nonlinear analysis for cooling tower supported on V shaped columns is as shown in fig. 4 to fig. 27 below.

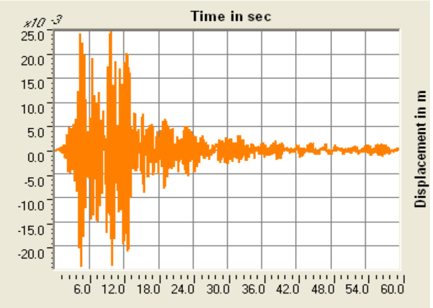

Figure4. Plot of top displacement versus time under Northridge earthquake (linear)

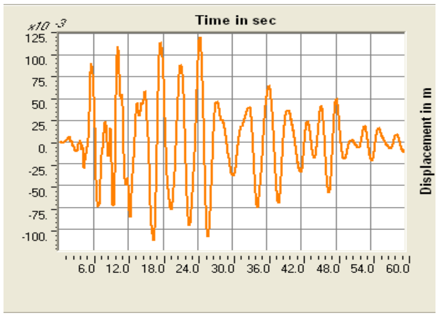

Figure 5. Plot of top displacement versus time under Northridge earthquake (nonlinear)

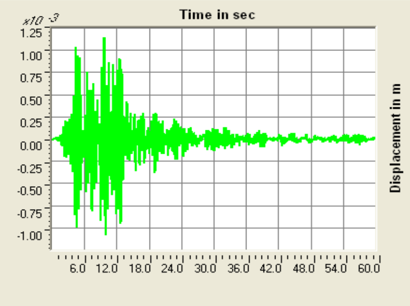

Figure6. Plot of bottom displacement versus time under Northridge earthquake (linear)

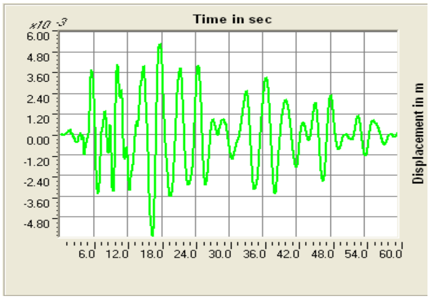

Figure 7. Plot of bottom displacement versus time under Northridge earthquake (nonlinear)

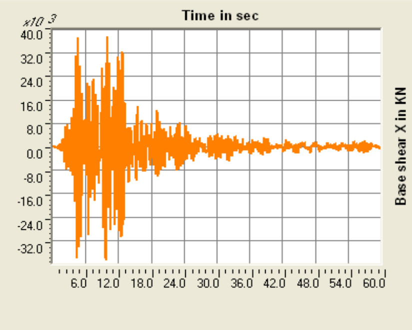

Figure 8. Plot of base shear versus time under Northridge earthquake (linear)

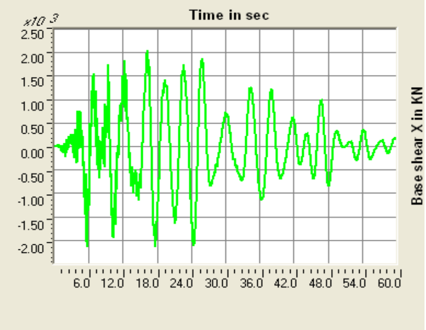

Figure 9. Plot of base shear versus time under Northridge earthquake (nonlinear)

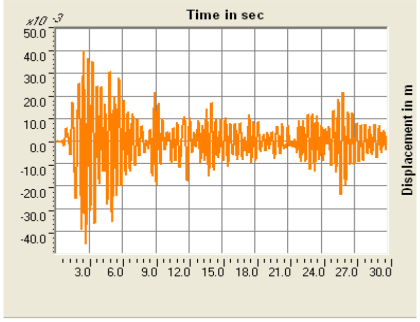

Figure 10. Plot of top displacement versus time under El-centro earthquake (linear)

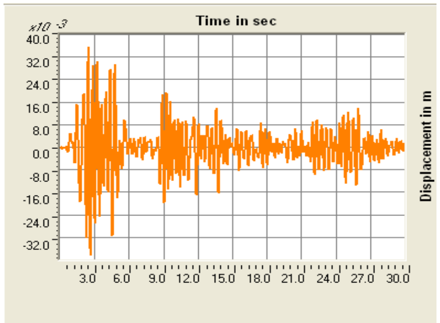

Figure 11. Plot of top displacement versus time under El-centro earthquake (nonlinear)

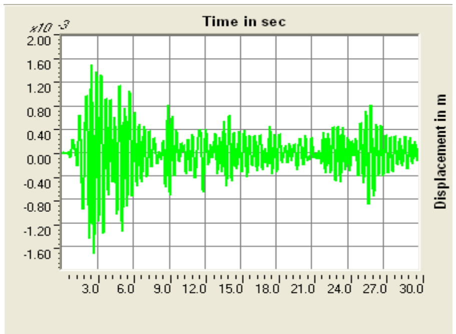

Figure 12. Plot of bottom displacement versus time under El-centro earthquake (linaer)

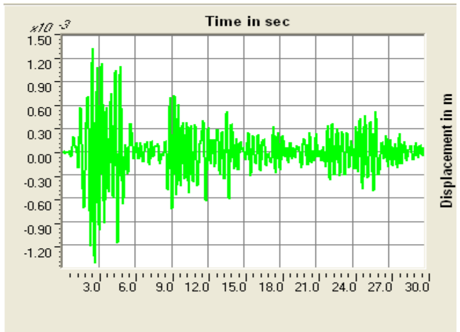

Figure 13. Plot of bottom displacement versus time under El-centro earthquake (nonlinear

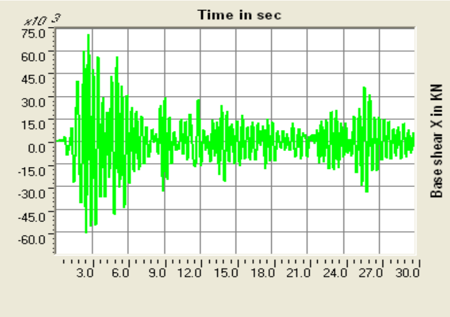

Figure 14. Plot of base shear versus time under El-centro earthquake (linear)

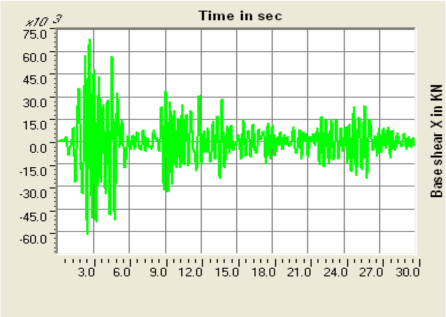

Figure 15. Plot of base shear versus time under El-centro earthquake (nonlinear)

Cooling tower supported on I shaped columns

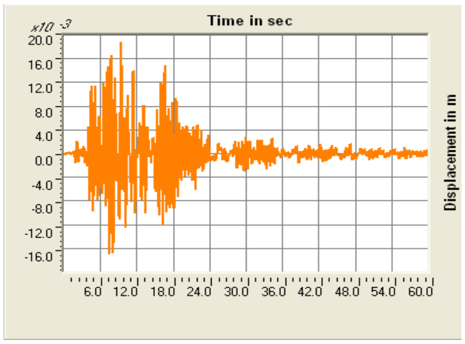

Figure 16. Plot of top displacement versus time under Northridge earthquake (linear)

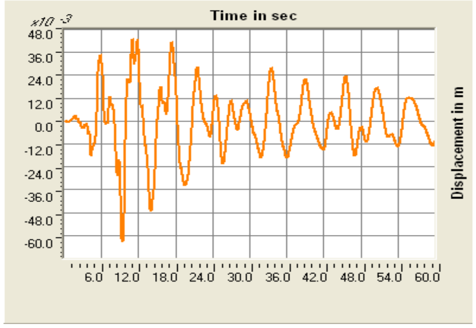

Figure 17. Plot of top displacement versus time under Northridge earthquake (nonlinear)

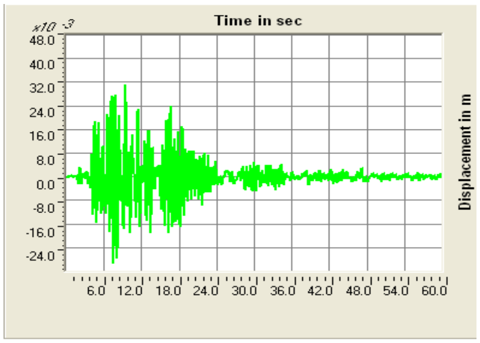

Figure 18. Plot of bottom displacement versus time under Northridge earthquake (linear)

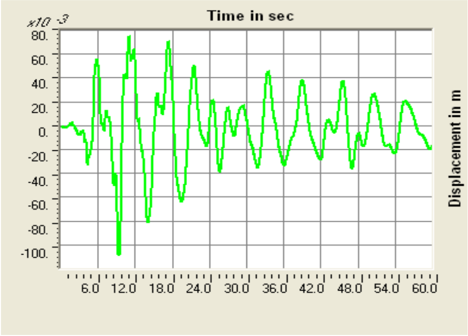

Figure 19. Plot of bottom displacement versus time under Northridge earthquake (nonlinear)

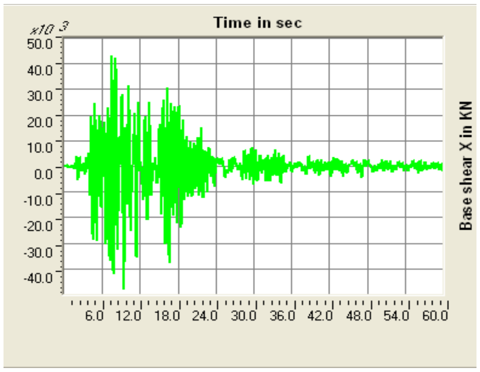

Figure 20. Plot of base shear versus time under Northridge earthquake (linear)

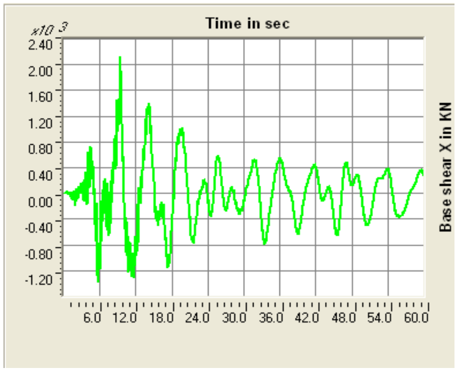

Figure 21. Plot of base shear versus time under Northridge earthquake (nonlinear)

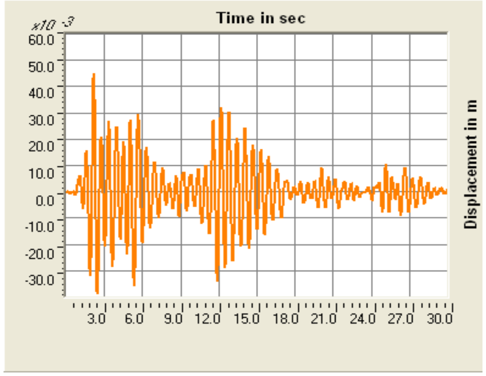

Figure 22. Plot of top displacement versus time under El-centro earthquake (linear)

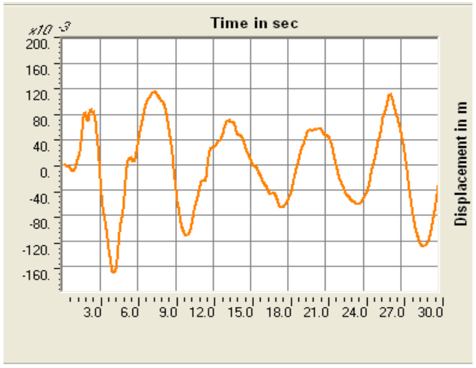

Figure 23. Plot of top displacement versus time under El-centro earthquake (nonlinear)

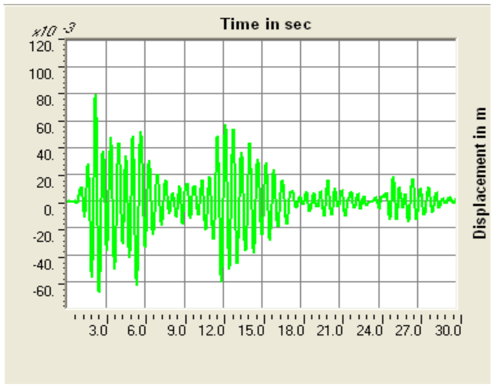

Figure 24. Plot of bottom displacement versus time under El-centro earthquake (linaer)

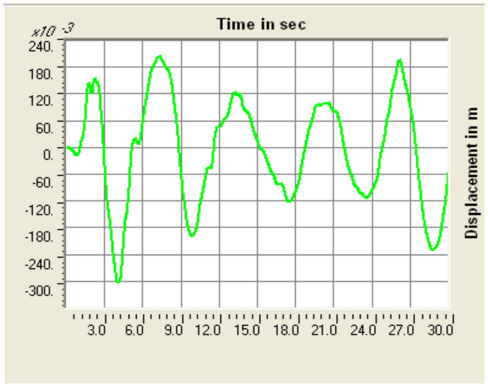

Figure 25. Plot of bottom displacement versus time under El-centro earthquake (nonlinear)

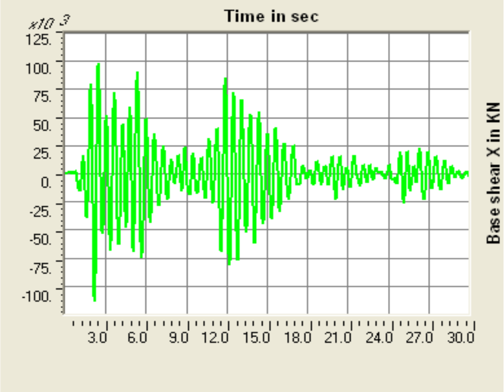

Figure 26. Plot of base shear
versus time under
El-centro earthquake (linear)

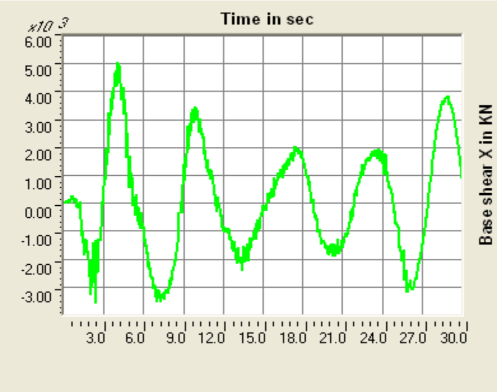

Figure 27. Plot of base shear
versus time under
El-centro earthquake (nonlinear)

Table 3.Comparison of results of linear and nonlinear dynamic analysis

Earthquake	Response / Force	V-shaped system		I-shaped system	
		linear	nonlinear	linear	nonlinear
Northridge	Max.top displacement in mm	24	121	18	42
	Max.bottom displacement in mm	1.1	5	31	42
	Max base shear in KN	37000	2056	43000	2133
El-centro	Max.top displacement in mm	40	35	44	131
	Max.bottom displacement in mm	1.5	1.3	79	131
	Max base shear in KN	71000	68720	98000	5035

Table 3 gives comparison of maximum values of displacement and base shear obtained from linear and nonlinear analyses. It can be observed from linear results that top displacement of shell on either of support remains nearly constant. But in case of bottom displacement oh shell there is large difference. The displacement at bottom of shell resting on I shaped column is very large as compared to the displacement at bottom of shell supported on V shaped column. It is observed from nonlinear results that there is not much difference in results (both linear and nonlinear) for cooling tower on V shaped columns and for El-centro earthquake. In case of cooling tower supported on V shaped supporting system under Northridge earthquake and cooling towers supported on both (V and I shaped)supporting systems under both earthquakes (El-centro and Northridge) there is large difference in maximum value of displacement and base shear. The value of displacement in case of material nonlinear analysis is higher than linear analysis and value of base shear in nonlinear analysis is lower than linear analysis. Therefore, base shear decreases and displacement increases.

VI. CONCLUSIONS

Cooling tower is very important structure for nuclear and chemical plants. It should be analysed for lateral load acting on it. Here, cooling tower is analyzed for earthquake loading both linearly and nonlinearly. Based on the above results and observations the following conclusions are drawn,

1. The value of displacement in case of material nonlinear analysis is higher than linear analysis and value of base shear in nonlinear analysis is lower than linear analysis. It means the structure becomes flexible in nonlinear analysis.
2. In case of nonlinear analysis stiffness of structure reduces. It absorbs large amount of energy under strong ground motion. Therefore, base shear decreases and displacement increases.
3. Under strong earthquake motion structure goes into inelastic state, therefore to know exact behavior of structure nonlinear analysis should be performed.

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