THEORETICAL STUDY OF EARTHQUAKE RESPONSE OF A COOLING TOWER

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SYNOPSIS

A cooling tower in the 1200 MW fossil fuel steam generating plant at Paradise, Kentucky, USA (TVA) is studied. The hyperboloidal reinforced concrete shell is modeled by using 3-D orthotropic quadrilateral flat plate finite elements. The top ring beam and the bottom supporting columns are modeled by 3-D beam finite elements. Natural frequencies and normal modes are first found. Time history responses of 30 seconds to the N-S component of the 1940 El Centro earthquake are then computed by the method of modal superposition. Only the modes with one circumferential wave are excitable by horizontal motion. The effect of viscous damping is considered. Results are discussed.

INTRODUCTION

In the early static analyses of cooling towers, membrane theory and fixed base were assumed (see, for example, Ref. 1). Bending theory and simply-supported base were later considered (Ref. 2). It was pointed out in Ref. 2 that although the bending stresses are not large, the corresponding hoop stresses near the base are significantly different from those obtained by membrane theory.

In the early dynamic analysis of cooling towers, membrane theory and fixed base were also assumed (see, for example, Ref. 3). The bending theory was later applied to the free vibration analysis of cooling towers with fixed bases. Among the methods of analysis were numerical integration method (Ref. 4), finite difference method (Ref. 5), and curved rotational shell finite element method (Ref. 6).

Efforts to include the realistic effect of discrete column supports for both the static and dynamic cases were made in Refs. 7 and 8 by using the curved rotational shell finite elements. In both references, the discrete columns were modeled by a rotational shell element with appropriately modified stiffness and mass properties. The free stress state between column joints was modified by applying a system of self-equilibrated edge loadings to the base of the shell.

In this study, the 3-D orthotropic quadrilateral and triangular plate finite elements are used to model the shell. The top ring beam and the discrete columns are modeled by 3-D beam finite elements. Such modeling provides some advantages: (1) The discrete supporting columns can be modeled in a more precise manner; (2) Quadrilateral element modeling of the shell provides nodal points rather than nodal circles to connect the column

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elements; (3) The circumferential wave numbers are not prescribed during the computation of natural frequencies. They are obtained in ascending sequence. Also, the present computations reveal that the use of such elements is not expensive.

DESCRIPTION OF THE SYSTEM

The subject reinforced concrete cooling tower is described in Fig. 1. The top of the tower is stiffened by a ring beam that provides a walk way. The footings of the supporting columns are buried into the excavated limestone rock. They are assumed to be rigidly fixed in this study.

The circumferential and meridional reinforcements vary along the meridional direction but remain constant along the circumferential direction. The details of the reinforcement distribution are given in a separate report, Ref. 9. In the present modeling, each quadrilateral element is orthotropic and represents the actual elastic properties of its location.

RESULTS AND DISCUSSIONS

The first example chosen is the concrete cooling tower with fixed base analyzed previously in Refs. 4-6. Three meshes (4x16, 6x20, and 8x20) were used in this study. Natural frequencies were obtained and compared with results given in Refs. 4-6. The comparisons were presented in Ref. 9. It was found that the 8x20 model provided the same accuracy as that given in Refs. 4-6 and the 4x16 model provided reasonable accuracy. Thus it was decided to use the 4x16 model for the present study of the time-history response.

The second example is the cooling tower analyzed by Gould et al. (Ref. 8) by using rotational shell finite elements. The tower was analyzed with base fixed as well as supported by columns. The columns were modeled by an equivalent rotational shell element. The results for natural frequencies obtained from both Ref. 8 and this study are shown in Table 1. The two sets of results are in close agreement.

Finally, the Paradise cooling tower is analyzed. A set of lowest natural frequencies were found and are given in Table 2. Since only the modes with one circumferential wave are excitable by horizontal motion, such modes were found. The first two mode shapes are shown in Fig. 2.

The N-S acceleration component of the El Centro earthquake was used in the response analysis. The first 30 seconds were broken down into 1500 equal time intervals. The method of superposition was used. The example used in Refs. 4-6 was first analyzed with results presented in Ref. 9. The Paradise cooling tower was then analyzed. The shell was modeled by 4x16 mesh and the columns were modeled by 32 pairs of equivalent beam finite element. All the modes up to the one with one circumferential and one longitudinal wave are included in the analysis. The mode with two meridional waves should have a small contribution to the response behavior. However, it is not included in this study because the emphasis is on the general dynamic behavior rather than extreme accuracy in displacements and stresses.

A detailed report of the results was presented in Ref. 9. The plots included the time-history responses of deflections at different levels, bending and membrane stresses in the shell, and bending, axial, and shear forces in the columns. Viscous damping coefficients with 4, 7, and 10 percent of the critical value were included. Selected results are presented in Figs. 3-6. The symbol θ is the angle measured from the diameter parallel to the direction of the earthquake.

It was found that the column supports reduced the natural frequencies of a cooling tower originally with fixed base. Ref. 8 also gave the same conclusion. It was found that the column top deflected substantially during earthquake excitation. The fixed base assumption is inadequate. Fig. 5 shows that the meridional moment is large at the column top but away from the columns the membrane behavior dominates. Fig. 6 shows the effect of the magnitude of the damping coefficient on the results.

ACKNOWLEDGMENT

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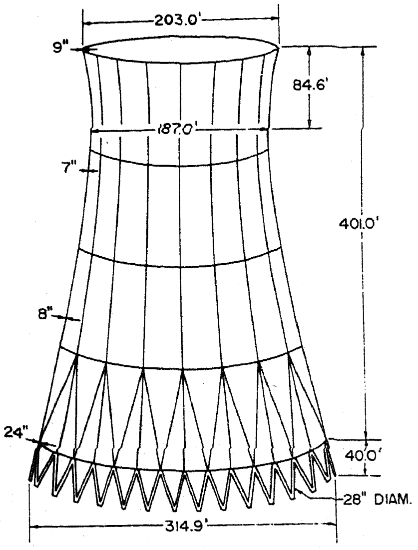

FIG. 1 THE COOLING TOWER AT PARADISE, KENTUCKY, U.S.A. AND THE FINITE ELEMENT MESH.

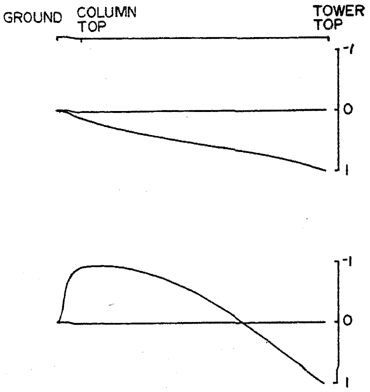

FIG. 2 THE FIRST TWO MERIDIONAL MODE SHAPES (WITH ONE CIRCUMFERENTIAL WAVE).

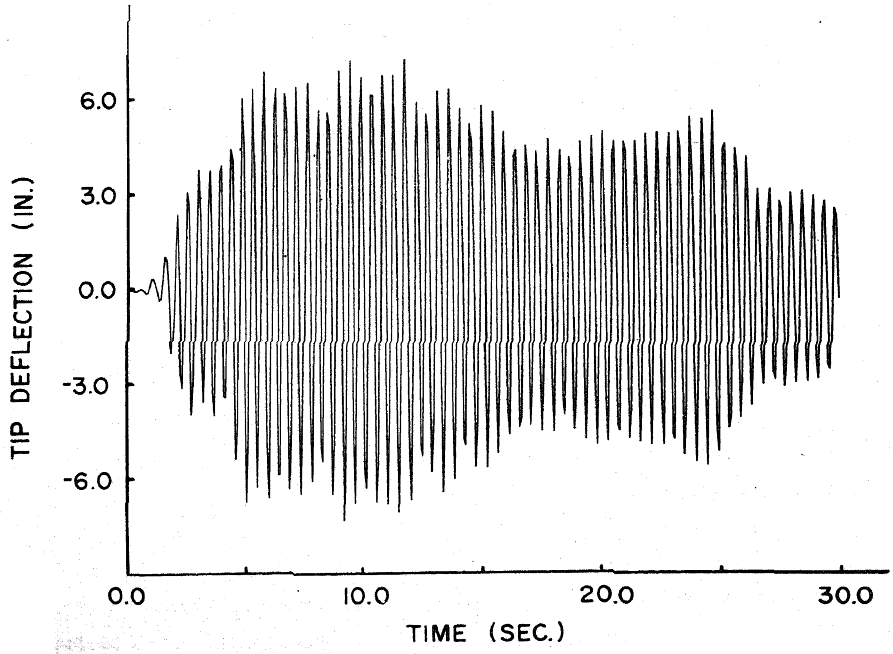

FIG. 3 TIME HISTORY RESPONSE OF TIP DEFLECTION (AT $\theta=0°$).

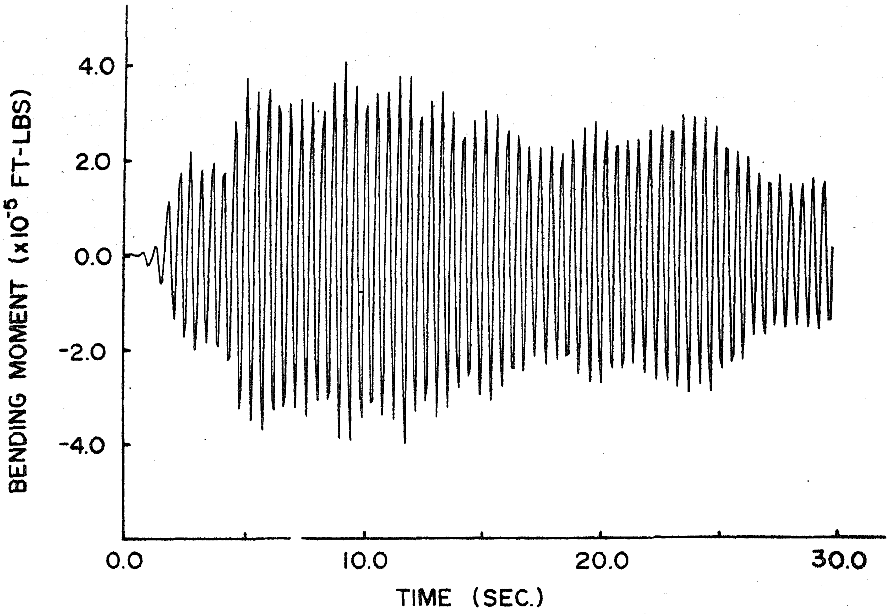

FIG. 4 TIME HISTORY RESPONSE OF BENDING MOMENT AT TOP OF COLUMN (AT θ=0°).

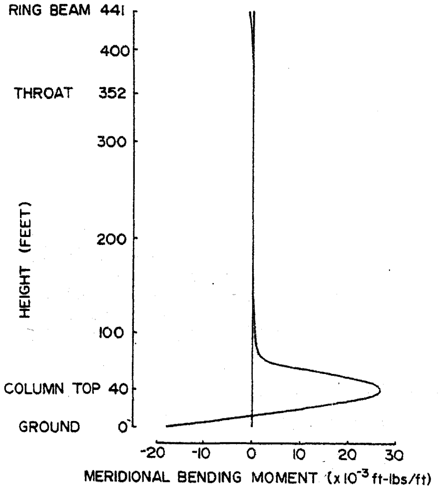

FIG. 5 DISTRIBUTION OF MERIDIONAL BENDING MOMENT (AT θ=0°) AT 9.2 SECONDS.

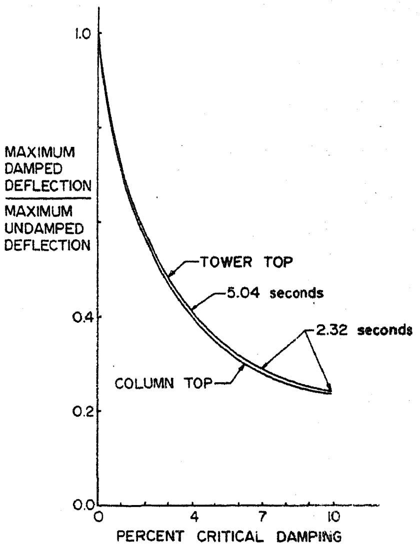

FIG. 6 VARIATION OF DEFLECTIONS VERSUS DAMPING COEFFICIENT.

Table 1. The Natural Frequencies (H_z) for a Cooling Tower

Circumferential Mode	Longitudinal Mode	Fixed Base		Column Base	
		Ref. 8	This Study 8x20 Mesh	Ref. 8	This study 8x20 Mesh
3	1	1.194	1.185	1.086	1.092
4	1	1.104	1.126	0.945	0.951
	2	1.302	1.304	1.204	1.169
5	1	1.131	1.147	1.032	1.025
	2	1.453	1.463	1.256	1.220
6	1	1.400	1.406	1.235	1.189

Table 2. The Natural Frequencies (H_z) for the Paradise Cooling Tower

Circumferential Mode	Longitudinal Mode	4x16 Mesh	6x20 Mesh	8x20 Mesh
1	1	2.195		
	2	4.262		
2	1	1.254	1.239	1.215
	2	1.988		
3	1	0.888	0.878	0.886
	2	1.626	1.532	1.451
4	1	0.985	0.931	0.906
	2	1.397	1.359	1.335
5	1	0.845	0.826	0.849
	2	2.043		
6	1	1.024	1.076	1.035
	2	1.916	1.669	
7	1	1.271	1.416	1.300
	2	1.936	1.753	
8	1	1.380	1.679	
	2	2.064		