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Experimental and analytical studies of a smokestack

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ABSTRACT: Based on the model tests and theoretical analysis, the research of the seismic resistance capacity of a smokestack has been performed. This research provides the detailed test and analytical results for smokestack seismic resistance design.

1 INTRODUCTION

A set of power plant will be built in eastern Guangdong Province, China, in which the earthquake intensity is 8 . The 210m high reinforced concrete smokestack is one of the structural project in this engineering. In order to provide evidences of the test and theory, we do the test of the structure model and the research of the seismic resistance, windproof capacity of the smokestack to verify it safety and economy.

The dynamic and static test of the model have been performed. By means of the finite element method, the free vibration and the seismic response of the smokestack have been analysed.

The effect of the vertical seismic motion on the smokestack has been discussed.

2 MODEL TEST

A perspex model on the scale of 1:67 was prepared for static test and excited vibration test. The prototype of the smokestack and the model of the smokestack are shown in Figure 1.

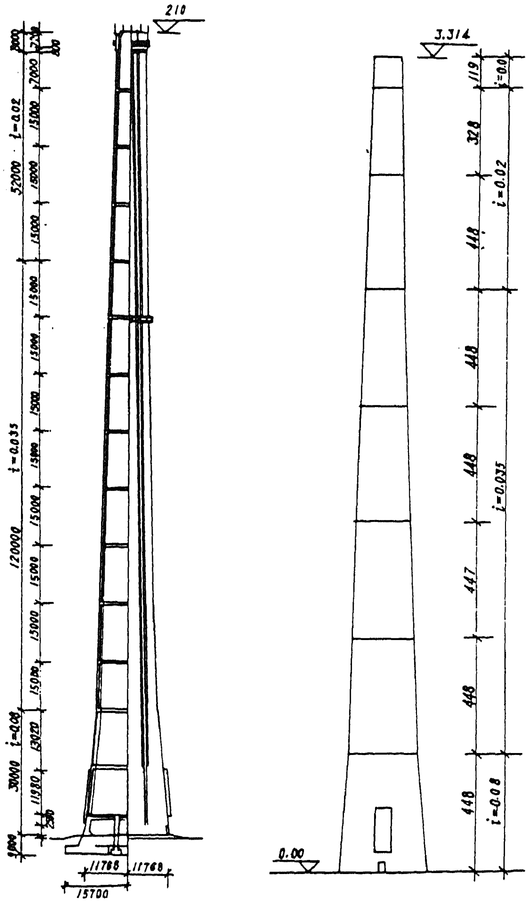
According to the test of perspex material, we obtained the physical and mechanical properties shown in Table 1.

Table 1. Properties of perspex material

Unit weight (KN)	11.28
Static elasticity modulus (MPa)	2432
Dynamic elasticity modulus (MPa)	3187
Poisson ratio	0.39

2.1 Dynamic test

In order to obtain the natural frequencies as well as the corresponding vibration modes



Smokestack Model

Fig. 1 Prototype and model of the smokestack excited vibration tests were performed. The resonance curve is shown in Figure 2. The natural frequencies of the model are listed in Table 2. The mode shapes of the model are shown in Figure 3.

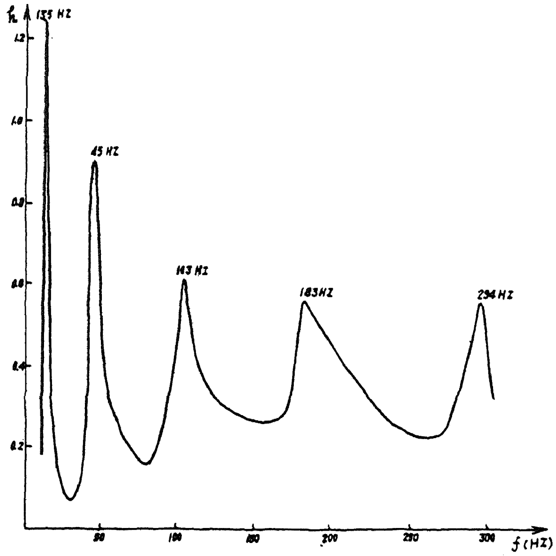


Fig. 2 Resonance curve of the model

Table 2. Natural frequencies of the model

	Natural frequencies (Hz)
f1	13.5
f2	45.0
f3	103.0
f4	183.0
f5	294.0

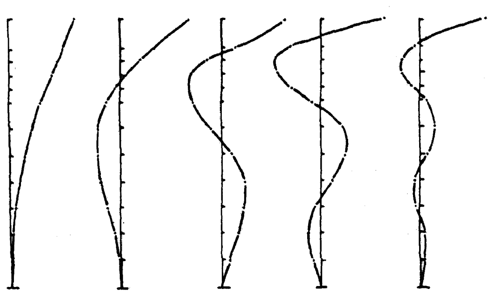
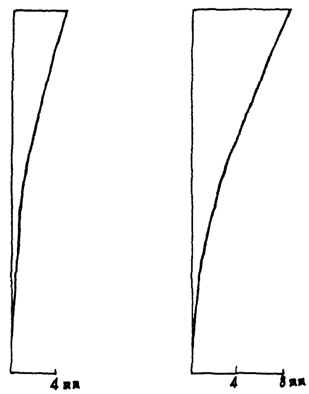


Fig. 3 Mode shapes of the model

2. 2 Static test

We have measured the deflection and strain of the model under earthquake and wind loads. The lateral deflections are shown in Figure 4.



Earthquake Wind

Fig. 4 Lateral deflection of the model

2. 3 Calculation the prototype structure according to the similarity theory

By means of the similarity theory, we can obtain the correlation physical quantities of the prototype structure from the results of the model tests. The calculated natural periods of the prototype smokestack by the similarity theory from the model test are listed in Table 3.

Table 3. Periods of the smokestack

	Periods (Second)
T1	2.644
T2	0.793
T3	0.346
T4	0.195
T5	0.121

3 THE SEISMIC RESISTANCE ANALYSIS OF SMOKESTACK

Using the finite element method, we do the analysis of seismic resistance of the smokestack and seismic response of the time history of the smokestack.

3. 1 Computation method

The smokestack is treated as a multidegree—of—freedom system. By means of the finite element method, the free vibration and the earthquake response of the smokestack have been analysed.

The equilibrium equation of vibrateion of multidegree—of—freedom system is

$$[M]\{A\}+[C]\{V\}+[K]\{X\}=\{P\} \qquad (1)$$

where

[M] the mass matrix of the structure

[C] the damping matrix of the structure

[K] the stiffness matrix of the structure

{A} the general acceleration vector of the nodes

{V} the general velocity vector of the nodes

{X} the general displacement vector of the nodes

{P} the load vector

when we study the problem of free vibration of the structure, equation (1) becomes;

$$[M]\{A\}+[K]\{X\}=\{o\} \qquad (2)$$

From equtation (2), we obtain eigenvalue equation:

$$([K]-F^2[M]\{X\}=\{o\} \qquad (3)$$

where F is the natural frequency of the structure.

Sloving abouve equation, we can get the natural frequency and the corresponding mode shape of the structure.

When we analyse the earthquake response of structure, the right term of equation (1) is $-[M]\{I\}Ag(t)$, the vibration equation becomes:

$$[M]\{A\}+[C]\{V\}+[K]\{X\}=-[M]\{I\}Ag(t) \quad (4)$$

where

Ag (t) the ground motion acceleration, {I} the vector whose elements are 1

The damping matrix which is used in calculation is linear combination of mass matrix and stiffness matrix:

$$[C]=A[M]+B[K] \qquad (5)$$

where

$$A=2(Ci\ Fj-Cj\ Fi)\ Fi\ Fj/(Fj+Fi)/(Fj-Fi)$$

$$B=2(Cj\ Fj-Ci\ Fi)/(Fj+Fi)/(Fj-Fi)$$

Fi, Fj the ith, jth natural frequency of structure

Ci, Cj the damping ratio of ith, jth mode shape

Using the method of wilsion — e to solve the equation (4), we can get the displacement response, the bending moments, shear forces and axial forces of the structure.

According to the above computation method we compile the computer program of static and dynamic analysis of smokestack.

3. 2 Calculation of free vibration

The free vibration of the model and the prototype of smokestack have been analysed. The structure is divided into 10 elements. The natural frequencies of the model are listed in Table 4. The natural periods of the prototype of the smokestack are listed in Table 5.

Table 4. Natural frequencies of the Model

Frequencies (HZ)	Test	Calculated	
		Case 1	Case 2
f1	13.5	15.02	15.24
f2	45.0	49.02	51.56
f3	103.0	109.67	122.09
f4	183.0	191.99	228.40
f5	294.0	290.70	369.82
f6		401.24	545.05
f7		521.07	759.30
f8		640.81	1008.47

Case 1; bending and shearing deformation considered
Caes 2; only bending deformation considered

Table 5. Natural periods of the smokestack

Periods (Second)	Test	Calculated	
		Case 1	Case 2
T1	2.644	2.472	2.442
T2	0.793	0.748	0.719
T3	0.346	0.339	0.313
T4	0.195	0.194	0.170
T5	0.121	0.128	0.106
T6		0.091	0.071
T7		0.069	0.051
T8		0.056	0.038

From the results in Table 4 and Table 5, we can see, that calculated values are consistent with the test values basically.

In order to compare the effects of bending and shearing deformation on free vibration of the smokestack, two cases were considered in the calculation, e. g. bending deformation is considered only, bending deformation combined with shearing deformation is considered. It is clear that the effect of shearing deformation on natural frequency is quite large. Therefore the shearing deformation must be taken into consideration when the high oder mode shapes of vibration of smokestack are calculated.

3. 3 The seismic resistance analysis

The most concerned question by the engineers is how many mode shapes they will select to combine in calculation the seismic loads. According to the mode analysis procedure, the bending moments and the shear forces of the smokestack have been calculated and the results are listed in Table 6 and Table 7 respectively.

Table 6. Bending moments of the smokestack

Hight (m)	Bending moment(x1000 kN—m)					
	Case1	Case2	Case3	Case4	Case5	Case6
198	14. 4	16. 4	18. 5	18. 8	19. 5	19. 5
168	36. 6	39. 6	41. 7	42. 0	42. 1	42. 2
147	55. 2	57. 0	57. 8	58. 0	58. 5	58. 6
126	68. 3	69. 0	70. 6	71. 2	72. 4	72. 4
105	83. 0	82. 3	88. 8	89. 6	90. 3	90. 4
84	103. 7	107. 5	113. 0	113. 4	114. 4	114. 6
63	130. 4	137. 2	140. 3	140. 8	142. 5	142. 6
42	166. 8	173. 1	174. 8	175. 8	177. 0	177. 1
21	216. 9	219. 6	222. 6	223. 5	224. 4	224. 5
0	276. 6	277. 0	283. 7	284. 1	285. 6	285. 7

Case1: three mode shapes considered
Case2: four mode shapes considered
Case3: five mode shapes considered
Case4: six mode shapes considered
Case5: seven mode shapes considered
Case6: eight mode shapes considered

Form Table 6 and Table 7. we can see that the bending moments and shear forces copmuted with five mode shapes are nearly the same as those with eight mode shapes. The maximum difference is only 5%. For 210 m high smokestack we need to consider five mode shapes if the seismic load is calculated.

Table 7. shear forces of the smokestack

Hight (m)	Shear forces(kN)					
	Case1	Case2	Case3	Case4	Case5	Case6
210	686	781	880	898	926	928
189	1063	1118	1138	1139	1139	1139
168	980	981	990	991	1001	1003
147	1040	1055	1077	1102	1130	1130
126	1281	1295	1441	1446	1448	1448
105	1362	1513	1548	1552	1560	1562
84	1607	1750	1771	1773	1808	1808
63	2277	2284	2296	2320	2321	2321
42	2981	3033	3086	3088	3088	3090
21	3278	3412	3614	3627	3657	3657

3. 4 The seismic response time history of smokestack

In order to study the seismic resistance capacity, we analyse the seismic response time history of smokestack. As ground motion, the accelerogram recorded in El—Centro 1940 is considered, the maximum horizontal acceleration is 0. 2g. As parameters we have taken: the time step t = 0. 02 second and damping ratio C = 0. 05

The displaceement response of the top of the smokestack is shown in Figure 5, the maximum displacement is 0. 397 m.

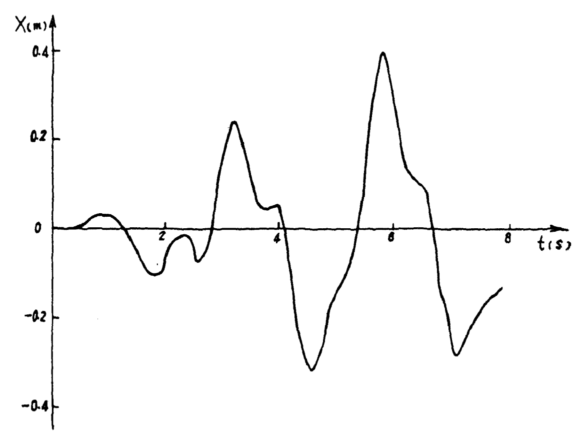


Fig. 5 Displacement response of the smokestack.

The maximum bending moments and shear forces of the smokestack obtained by the above analysis are listed in Table 8. The results of the mode analysis procedure of the smokestack are also listed in Table 8.

Table 8. Internal forces of the smokestack

Hight (m)	Bending moments (kN—m)		shear forces(kN)	
	M1	M2	Q1	Q2
210	0	0	1799	928
189	37782	19500	3400	1139
168	108386	·42200	3902	1003
147	189365	58600	3623	1130
126	250202	72400	4342	1448
105	269091	90400	5969	1562
84	280885	114450	7045	1808
63	318304	142600	8896	2321
42	445811	177100	11831	3090
21	643528	224500	13516	3657
0	844474	285700	13516	3657

M1, Q1: calculated by the seismic response time history
M2, Q2: calculated by the moed analysis procedure

Table 9. Axial forces of the smokestack

Hight(m)	Axial forces(kN)	Deal load(kN)
189	1387	2579
168	1946	4236
147	1647	5678
126	1543	7080
105	1444	8522
84	2493	10660
63	3168	13043
42	3746	16083
21	4381	20653
0	3562	21869

It is clear that the results of seismic response time history are larger, M1/M2 is approximatly 2 — 3. 4, Q1/Q2 is about 2 — 3. 9. In the mode analysis procedure, the structure related coefficient C is 0. 4, so the seismic force is reduced. Accoring to this, the ratio of M1/M2 is 0. 8 — 1. 36, and Q1/Q2 is about 0. 8 — 1. 56.

The earthquake damage of smokestack often appear in top 1/3 hight. In order to study the axial force of smokestack, the effect of the vertical seismic motion on the smokestack has been calculated. The maximum axial forces of the smokestack are listed in Table 9.

From Table 9. we can see, for the El — Centro 1940UD component with reduced Ag, max = 0. 13g, the axial force is smaller than the dead load. So, there doesn't exist the tension.

4 CONCLUSIONS.

From the results obtained in this study the following main observations can be made:

1. Even though smokestack is a flexible structure, the bending and shear deformation must be considered when the vibration is analysis.

2. When the mode analysis procedure is applied for a smokestack, there are not less then five mode shapes combined to be fit for 210 m hight smokestack.

3. Through the test and calculated, we can see, with the action of earthquake, the largest strain will aqqear at H/3 top of the smokestack.

4. The smokestack doesn't exist the axial tension for the vertical seismic motion with the maximum acceleration Ag, max = 0. 13g.

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