RESPONSE SPECTRUM ANALYSIS OF A 600 MW AND A 1200 MW BOILER STRUCTURES

By T. Y. Yang [I], M. I. Baig [III] and John L. Bogdanoff [II]

SUMMARY

Seismic response spectrum analyses have been performed for two steam generator-supporting structure systems located in two different earthquake risk zones. The first system is located in zone III and was designed based upon the requirements of the Uniform Building Codes whereas the second structure is located in zone I and no seismic requirements were considered in its design. In addition to suggesting a realistic and practical method of analysis, this study also demonstrates through the use of El Centro Earthquake acceleration data that the structure designed based upon the Uniform Building Codes is sufficiently adequate to withstand such an earthquake without significant damage.

INTRODUCTION

A survey of seismic analysis of steam generator-supporting structure system (1) reveals that the state-of-the-art technology is not adequate to provide necessary information to the designer of such a system at the preliminary stage of the design. Since the seismic loading in the various component of the structure is dependent upon the overall dynamic behavior of the structure, the designer requires data such as the natural frequencies and associated mode shapes of similar steam generator-supporting structure system as he is designing. Various sources (2, 3, 4) including the Uniform Building Codes provide information about the natural frequencies of such systems. However, these informations are based upon dynamic analyses with various simplifications. A more realistic three-dimensional modeling has been employed in this study to evaluate natural frequencies and associated mode shapes of two steam generator-supporting structure systems. The two structures are located in two different earthquake risk zones. The first structure, a 600 MW power plant, is located in zone III and was designed based upon the requirements of the Uniform Building Codes and the second structure, a 1200 MW power plant, is located in zone I and was designed "conventionally" i.e., without the seismic considerations. The natural frequencies of vibration and some representative mode shapes of the two power plant structures are presented in this paper. It has been demonstrated through the natural mode shapes that the combined system of steam generator-supporting structure undergoes an appreciable amount of twisting motion even in the lower structural modes. Therefore, a three-dimensional modeling must be employed in the dynamic analyses of such systems.

Seismic response spectrum analysis of the 600 MW power plant structure model was performed using the acceleration time-history data of El Centro Earthquake of May 18, 1940. The Structural Analysis Program SAP IV (5) was employed to perform the analysis. The modal responses of various quantities such as joint displacements and member axial forces were obtained. The

---

I   Professor and Head, School of Aeronautics and Astronautics, Purdue University, W. Lafayette, Indiana, U.S.A.
II Professor, School of Aeronautics and Astronautics, Purdue University
III Senior Structural Engineer, Foster Wheeler Energy Corporation, Livingston, N.J., U.S.A.

modal participation factors (as defined in Reference 6) associated with the first two modes were found to be considerably greater than those associated with the higher modes. The statistical maximum of each response quantity was determined by using the root-mean-square of the modal response values. It is known to give the most probable maximum value of each quantity (7). The maximum value of axial stress for each member is compared with both the yield stress and the Euler buckling stress. The members in which the stress exceeds the yield and buckling stresses are identified.

DESCRIPTION OF THE FINITE ELEMENT MODELINGS

The finite element modelings of the two power plant structures were accomplished using three-dimensional beam, truss and concentrated mass finite elements. The 600 MW power plant supporting structure consists of numerous bracing members which help transfer the shear loads in the columns via axial loads in the bracings. Therefore, all the structural members were modeled by using truss bar elements (2). The 1200 MW power plant structure consists of relatively fewer bracing members and the columns carry all the shear loads. Therefore, the modeling of such members was accomplished by using beam elements.

The steam generator shown in Fig. 1 was modeled by 66 lumped masses interconnected by rigid massless bars as shown in Fig. 2. The location and amount of the masses closely represent the actual distribution of the steam generator mass. The steam generator was hung to the top girders by 276 hanger rods. The lateral support to the steam generator was provided by 20 tie rods, also shown in Fig. 2. Since the steam generator weighs about 60% of the combined weight of the steam generator-supporting structure system, a close representation of the steam generator in the finite element model was essential. Therefore, a sub-structure model of the steam generator was analyzed separately. The analytical analysis of the steam generator was performed using the equations of motion developed in Ref. 8 and the finite element analysis was performed for the sub-structure model. This model was supported at the top by four equivalent hanger rods located at the four corners of the steam generator and all the 20 lateral tie rods were retained at their original locations.

The supporting structure model of the 600 MW power plant is shown in Fig. 3 in conjunction with the first natural mode shape. The structure was designed with hinged joint conditions. The total of 439 joints are connected by 1085 horizontal and vertical members and 522 cross bracing members. All the structural members have been modeled by truss elements. In the 1200 MW steam generator model, the structural members were modeled by three-dimensional beam finite elements and the joint conditions were assumed to be rigid.

FREE VIBRATION ANALYSIS

Free vibration analysis of the steam generator was performed separately using the finite element model described earlier. An analytical analysis was also performed using the method described in Ref. 8. The fundamental frequencies of free vibration of the steam generator obtained by the two analyses are listed in Table 1. Figure 4 illustrates the corresponding mode shapes in a plan view. The free vibration analysis of the steam generator-supporting structure system was performed by combining the two substructure models described in the previous section. Twelve natural frequencies and corresponding mode shapes were obtained for the system. The

natural frequencies and periods of the 600 MW and the 1200 MW power plants are given in Table 2. For comparative purposes, the natural frequencies reported in Ref. 4 for a 1000 MW power plant are also given in this Table.

RESPONSE SPECTRUM ANALYSIS

The response spectrum analysis of the two power plants were performed using the north-south component of the ground acceleration data of El Centro Earthquake of May 18, 1940. Twelve natural frequencies and modes were used in the analyses. The earthquake acceleration is assumed to act along the north-south and east-west directions of the structure (Fig. 3). The modal participation factors corresponding to the first 12 natural frequencies are given in Table 3.

Based on the maximum relative displacements of the nodal points, the axial forces and axial stresses were obtained for every structural member. The axial stresses were compared with yield stress of ASTM A36 steel of which the structural members are made of. They are also compared with the corresponding Euler buckling stress of the members. A computer program was written which plots every structural member in different perspectives and labels it with the ratios of the axial stress to the yield stress and the Euler buckling stress. Such plotted results have been obtained for all members and given in Ref. 9. Figure 5 shows a sample plot of the stress ratios. In the figure the number without parentheses represent the ratio of axial stress to yield stress and those in parentheses represent ratio of axial stress to the Euler buckling stress.

A search of the members with excessive stresses in the entire steam generator-supporting structure system reveals that out of 1607 structural members, the maximum stress exceeds the yield stress in 158 members, the ultimate stress in 57 members, and the Euler buckling stress in 309 members in the 600 MW power plant. In the 1200 MW power plant with 1290 members, the maximum stress exceeded the yield stress in 277 members and the ultimate stress in 85 members.

The horizontal ties are the main means to transfer the lateral loads developed during an earthquake disturbances. The location and stress ratios to the yield stress for the 20 ties of the 600 MW power plant are listed in Table 4. Out of 20 tie members, 4 exceed the yield stress and 2 exceed the ultimate stress. The stresses in the same 4 tie members exceed their corresponding buckling stress values.

An inspection of the amounts of excessive stresses and the locations of the failing members in the 600 MW power plant reveals that even after the above mentioned failure of the structural members, the power plant would not suffer significant damage under the influence of an earthquake similar to the El Centro Earthquake. From the mere view point of structural integrity, the Uniform Building Code appears to be adequate for this case.

REFERENCES

1. Yang, T. Y. and Baig, M. I., "Seismic Analysis of Fossil Fuel Boiler Structures," Journal of the Structural Division, ASCE, Vol. 105,

No. ST12, Dec. 1979, pp. 2511-2528.

2. Shiraki, K., and Nakazawa, S., "Study on the Aseismic Design of Boilers and Structural Steels - Considerations on the Vibration Characteristics and Design Criteria for Boilers and Structural Steels," Mitsubishi Technical Review, Sept. 1968, pp. 184-195.

3. Anderson, J. C., Srinivasan, R., and Small, R. J., "Response of Suspended Boilers to Earthquake Motions," Electrical Power and the Civil Engineer, ASCE Power Division Specialty Conference, Boulder, Colorado, Aug. 1974, pp. 363-387.

4. Suehiro, T., "Vibration Analysis of a 1000 MW Boiler Frame Structure," Report KBD 19012, Ishikawajima-Harima Heavy Industries Co., Limited, March, 1974 (In Japanese).

5. Bathe, K. J., Wilson, E. L., and Peterson, F. E., "SAP IV-A Structural Analysis Program for Static and Dynamic Response of Linear Systems," Report No. EERC 73-11, Earthquake Engineering Research Center, University of California, Berkeley, CA, June 1973.

6. Newmark, N. M., and Rosenblueth, E., Fundamental of Earthquake Engineering, Prentice Hall, Inc., Englewood Cliffs, N.J., 1971.

7. Goodman, L. E., Rosenblueth, E., and Newmark, N. M., "Aseismic Design of Firmly Founded Elastic Structures," Transactions, American Society of Civil Engineers, Vol. 120, 1955, pp. 782-802.

8. Lo, H., and Bogdanoff, J. L., "Derivation of Equations of Motion of a Free Rigid Body Steam Generator Supported by Vertical Elastic Rods," Report Submitted to the National Science Foundation, School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana, Oct. 1977.

9. Yang, T. Y., Baig, M. I., and Bogdanoff, J. L., "Seismic Structural Response of Steam Generators and their Supporting Structures," Report Submitted to the National Science Foundation, School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana, April 1978.

Table 1--Comparison of Natural Frequencies of the 600-MW Power-Plant Steam Generator by Two Analyses, in Hertz

Mode number	Finite element analysis	Analytic analysis	Percentage difference
1	0.2134	0.2007	6.3
2	0.2380	0.2387	0.29
3	0.2451	0.2453	0.08

TABLE 2--Natural Frequencies of the 600-MW and 1,200-MW Steam Generator and Supporting Structures, in Hertz

Mode number	Frequency of 600-MW boiler structure	Frequency of 1,200-MW boiler structure	Frequency the 1,000-MW boiler structure of Ref. 4
1	0.844	0.7136	0.80867
2	1.008	0.8246	0.92051
3	1.342	1.098	1.0718
4	1.727	1.147	1.5205
5	1.758	1.609	1.8968
6	2.240	1.719	2.0344
7	2.342	2.284	2.1245
8	2.632	2.463	2.6127
9	2.639	2.675	3.0181
10	2.647	2.802	3.2897
11	2.823	2.807	---
12	2.876	3.102	---

TABLE 3--Modal Participation Factors

Mode number	North-South direction	East-West direction	Vertical direction
1	28.390	-1.0401	-0.0120
2	1.0499	28.8490	0.0217
3	-0.0862	-0.6611	1.5844
4	-0.0884	-0.3585	1.5383
5	0.0344	-0.2464	1.2053
6	3.8868	-0.1740	-0.0281
7	-0.1427	-0.1963	1.1710
8	-0.0796	0.3528	0.7162
9	-0.0767	0.2471	-1.9274
10	-0.0445	-0.0983	1.6638
11	0.0207	0.8239	0.0158
12	-0.2240	0.9844	-0.3435

TABLE 4--Stress Ratio for Horizontal Ties of 600-MW Power Plant

| Tie No.	Elevation in feet	Direction	Location	Stress ratio
1	56	F&A	west wall	0.0151
2	56	S to S	northeast corner	0.5058
3	56	S to S	southeast corner	0.4282
4	56	F&A	east wall	0.1232
5	108	F&A	west wall	0.0366
6	108	F&A	west inside wall	0.0595
7	108	F&A	west inside wall	0.0047
8	108	F&A	west inside wall	0.0241
9	108	F&A	east inside wall	0.0280
10	108	F&A	east inside wall	0.0463
11	108	F&A	east inside wall	0.0199
12	108	F&A	east wall	0.1619
13	128	S to S	north wall	1.6506
14	128	S to S	northeast corner	1.0003
15	128	F&A	east inside wall	0.0235
16	128	F&A	east inside wall	0.0072
17	157	S to S	north wall	2.8408
18	157	S to S	south wall	2.4626
19	157	F&A	west wall	0.1469
20	157	F&A	east wall	0.0427
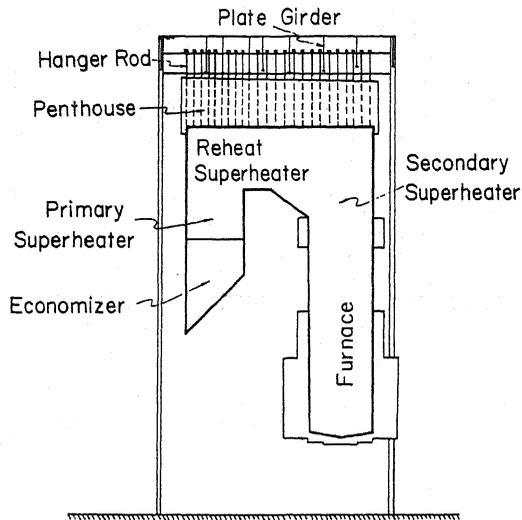
Fig. 1   A Rough Elevation View of Steam Generator.
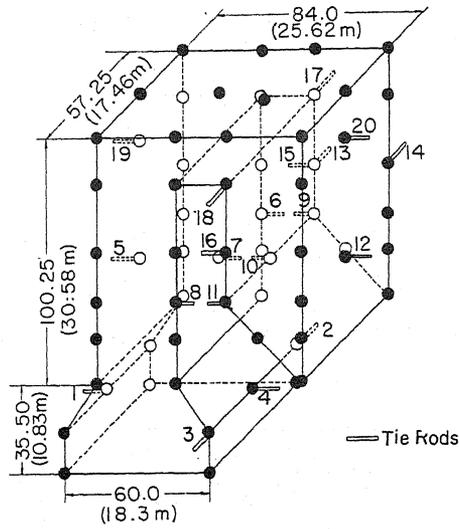
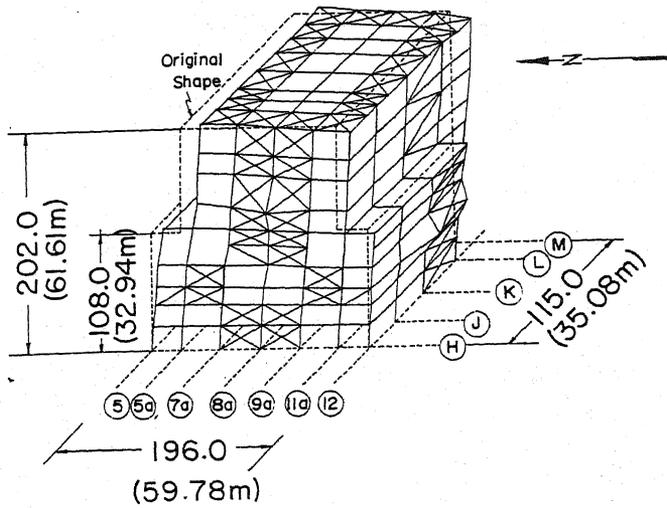Fig. 2 Lumped-Mass Model of Steam Generator and 20 Tie Rods

Fig. 3 Three-Dimensional View of Supporting Structure Vibrating
in First Mode.

Fig. 4 First Three Natural Mode Shapes of Suspended Steam Generator in a Plan View.

Fig. 5 Stress Ratios in Structural Members Shown in an Elevation View.