Seismic Analysis of a Spherical Steel Containment Vessel

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ABSTRACT

To simplify the dynamic model of a free-standing SSCV, a lumped-mass, stick model for both horizontal and vertical earthquakes is developed by matching its dynamic characteristics with those of the 3-D finite element model of the shell structure. Modal analyses are performed and modal properties for the stick and 3-D shell models are examined and compared.

The seismic analysis results computed from the stick model are applied on the 3-D shell model for stress analysis of the SSCV. Displacements of the two models are compared for both the horizontal and vertical seismic forces. The results indicate a good agreement between the simplified stick model and the more detailed 3-D shell model.

1. INTRODUCTION

The seismic response of a spherical shell can be estimated by the solution of the boundary value problem of an axisymmetric shell subjected to time-dependent boundary conditions, [1]. However, the seismic response of a shell structure in combination with other buildings, e.g., a containment vessel situated in a reactor building of a nuclear power plant, cannot be obtained cost effectively by this method. Therefore, it is necessary to simplify the mathematical model of the shell structure for the seismic analysis.

In this study, a simplified lumped-mass stick model of a free standing Spherical Steel Containment Vessel (SSCV), subjected to horizontal and vertical earthquakes, is developed to simulate the gross dynamic behaviors of the SSCV.

2. CONTAINMENT DESCRIPTION

The studied containment vessel is a spherical steel pressure vessel for a 4-Loop PWR plant. The vessel is completely enclosed in a reinforced concrete shield structure, (see Figure 1). There is no structural tie between the containment vessel and the surrounding shield building above the foundation slab. The lower portion of the vessel is embedded in a concrete cradle at approximately 50° from the bottom of the shell. The shell thickness is 38 mm and the shell diameter is 59 m. The containment polar crane system is supported on the containment shell.

3. DEVELOPMENT OF SSCV SEISMIC MODEL

A finite element model of the half shell is developed for the SSCV as shown in Figure 2. Refined elements are used at the shell support where geometric discontinuity is encountered and high stress gradients are expected. It is assumed that 90% of polar crane payload is applied at one end of the crane girder. A modal analysis and a shell stiffness analysis are performed for the 3-D FEM. The results of the modal analysis including frequency, participation factor, modal masses and cumulative masses are shown in Table 1. The first mode (f_1 = 4.33 cps) and the second mode (f_2 = 9.64 cps) represent primarily the overall deformation of the free-standing SSCV in the horizontal and vertical directions, respectively (see Figure 3). The first mode shape indicates a straight lateral deformation of the free-standing shell which represents more or less a shear deformation of the cantilever shell structure, and no apparent radial deformation due to either flexural or extensional deformation of the shell is perceived. The second modal shape shows primarily radial and axial deformation of the free-standing shell, except at the polar crane supporting area where local deformation prevails. The second mode represents the membrane elongation-shortening and through-thickness bending of the shell plate. These two modes contribute more than 70% of the cumulative mass of the corresponding direction.

A simplified lumped-mass stick model, Figure 2, is developed to simulate the gross dynamic behavior of the free-standing SSCV. The equivalent shear areas (Av) of the stick model for the horizontal seismic analysis are computed by considering the differential shear deformation of the adjacent nodal points in elevation of the center line ($\theta = 90°$) of the 3-D shell model due to a horizontal static force applied at the apex of the shell. Similarly, the equivalent axial areas (A) of the stick model for the vertical seismic analysis are computed by considering the differential vertical deformation of the adjacent nodal points in elevation subjected to the weight of the 3-D shell structure. They are expressed as

$$A_v = \frac{VL}{\delta G}, \qquad A = \frac{PL}{\Delta E}$$

where V = shear force, L = length between two adjacent points in elevation, G = shear modulus, δ = differential lateral deflection at center line, P = axial force, E = Young's modulus, Δ = differential vertical deformation at center line. The shear deformation and the axial deformation of the stick models thus developed can represent the gross shear deformation and axial deformation of the original shell structure.

The moment of inertia of the gross shell structure is used in the simplified stick model. This is adequate for the horizontal seismic load case because the overall flexural deformation is negligible for a short free-standing shell. For a vertical seismic load, the developed mass stick model cannot simulate the through-thickness flexural deformation of the shell plate. This necessitates a modification of the computed equivalent axial areas by multiplying a factor of 0.8 in order to match the frequencies of the stick model and the 3-D model.

The distributed mass of the SSCV is represented as lumped mass at the nodal points of the stick model. The polar crane is represented by a lumped mass connected to the SSCV stick through a fictitious spring simulating the stiffness of the shell due to local deformation at the crane support attachments [2]. The lumped mass and the member properties of the stick model are shown in Table 2.

The results of the modal analysis of the simplified stick model are shown in Table 3. The first mode and the third mode represent primarily the fundamental horizontal and vertical modes of the stick model, respectively. The corresponding mode shapes are shown in Figure 4. Both the fundamental frequencies and the mode shapes of the simplified stick model can match closely those of the 3-D shell model.

4. SEISMIC ANALYSIS OF SSCV SHELL

A lumped-mass stick model is developed for seismic analysis of the entire 4-Loop PWR plant, combining the reactor external building (REB), shield building (S/B), internal concrete (I/C), and SSCV, as shown in Figure 5. The shear wave velocity of the foundation material is 1500 m/s. The foundation is represented by a translational spring (K_h), a rotational spring (K_θ), and a vertical spring (K_v) attached to the bottom elevation of the basemat.

The maximum ground acceleration of the earthquake is 500 gals in horizontal direction and the vertical earthquake is half that. Both the time history analysis and response spectra analysis are performed for the stick model of the entire plant. The maximum shear and axial forces resulting from the analyses are applied to the corresponding nodal points of the 3-D SSCV model. The distribution of the force is proportioned in accordance with the mass distribution of the SSCV. The imposed seismic forces are treated as static forces in the stress analysis.

A comparison of displacements computed by the stick model and the 3-D shell model (at $\theta = 90°$) are depicted in Figures 6 and 7 for horizontal and vertical seismics, respectively. The plots show fairly good agreement between the two models for the horizontal seismic load. The displacements of the stick model due to vertical seismic load are consistently higher than those of the 3-D shell model. This could be attributed to the fact that the stiffness of the vertical stick model is reduced by 20% after matching the deformation between the shell model and the stick model in order to match the dynamic characteristics between the two models. However, the stress results of the SSCV are not expected to be affected significantly by the above difference.

5. CONCLUSION

This study provides a practical and economical method to perform the complicated seismic analysis of a shell structure. Especially in the case where the shell structure is combined with other buildings, the simplified stick model can provide uniform accuracy in seismic results among the buildings, while retaining the gross dynamic characteristics of the shell structure in the simplified stick model.

6. REFERENCES

1. Kalnins, A., Godfrey, D. A., "Seismic Analysis of Thin Shell Structures," 2nd International Conference on Structural Mechanics in Reactor Technology, Berlin, Germany; Paper K 4/5, September 1973.
2. Wichman, K. R., Hopper, A. G. and Mershon, J. L., "Local Stresses in Spherical and Cylindrical Shells Due to External Loadings," WRC Bulletin 107, 1979 Revision.

TABLE 2 LUMPED-MASSES AND MEMBER PROPERTIES OF SSCV STICK MODEL

NODES			BEAM MEMBER PROPERTIES			
NO.	ELEV. (cm)	LUMPED MASS (ton/980)	1/2 SHELL AREA A (cm^2)	MOMENT OF INERTIA I (m^4)	EQUIV. SHEAR AREA A_x (cm^2)	EQUIV. AXIAL AREA A (cm^2)
17	4900	.0069	3259.	1.5	393.	505.
16	4850	.0208	8759.	23.7	1631.	330.
15	4750	.0625	15392.	127.3	3190.	709.
14	4400	.1052	22564.	400.9	4279.	5880.
13	3994	.1284	27825.	751.8	4789.	6009.
12	3480	.3195	31704.	1112.2	5064.	9975.
11	3480	.3572				
10	2950	.1583	34101.	1384.0	5215.	18545.
9	2350	.1821	35055.	1503.4	5268.	23695.
8	1650	.2001	34107.	1384.7	5143.	27286.
7	920	.1721	31638.	1105.3	4777	15943.
6	420	.1046	29174.	866.5	4503.	14037.
5	170	.0485	27684.	740.5	3962.	1621.
4	70	.0196	27009.	687.6	3691.	612.
3	30	.0084	26704.	664.6	3784.	946.
2	10	.0042	26548.	653.0	3661.	2629.
1	0	---				

TABLE 1 3-D SHELL MODAL PROPERTIES

MODE	FN (CPS)	PARTICIPATION FACTORS		MODAL MASSES		MASS (%)	
		X	Z	X	Z	X	Z
1	4.33	1183.654	-52.316	1401035.608	2736.948	75.3	.1
2	9.64	-137.633	-1152.462	18942.871	1328168.572	76.3	71.5
3	11.31	174.909	-511.797	30593.249	261935.909	78.0	85.6
4	16.95	-5.082	-44.678	25.822	1996.156	78.0	85.7
5	17.63	157.859	-19.026	24919.364	362.000	79.3	85.7
6	17.69	-10.641	-2.070	113.221	4.285	79.3	85.7
7	18.01	-127.151	19.472	16167.439	379.160	80.2	85.8
8	18.18	155.279	-18.905	24111.659	357.404	81.5	85.8
9	18.50	9.172	3.520	84.128	12.387	81.5	85.8
10	18.87	3.403	30.096	11.577	905.782	81.5	85.8
11	19.11	-.707	-16.837	.500	283.470	81.5	85.8
12	19.29	-6.894	-8.607	47.527	74.075	81.5	85.8
13	19.57	10.655	113.184	113.520	12810.509	81.5	86.5
14	19.78	-4.760	33.503	22.653	1122.460	81.5	86.6
15	19.91	28.255	-3.473	798.332	12.061	81.5	86.6

X: HORIZONTAL DIRECTION Z: VERTICAL DIRECTION

TABLE 3 LUMPED MASS STICK MODAL PROPERTIES

MODE	FN (CPS)	PARTICIPATING FACTORS		MODAL MASSES		CUMULATIVE MASS (%)	
		X	Z	X	Z	X	Z
1	4.11	-1.235	.000	1.526	.000	80.4	.0
2	8.68	-.327	.000	.107	.000	86.0	.0
3	9.69	.000	-1.339	.000	1.793	86.0	94.4
4	16.58	-.362	.000	.131	.000	92.9	94.4
5	25.89	.183	.000	.033	.000	94.6	94.4
6	27.77	.000	.232	.000	.054	94.6	97.3
7	34.43	-.172	.000	.030	.000	96.2	97.3
8	36.96	.000	-.157	.000	.025	96.2	98.6
9	44.41	-.110	.000	.012	.000	96.8	98.6
10	50.80	.026	.000	.001	.000	96.9	98.6

X: HORIZONTAL DIRECTION Z: VERTICAL DIRECTION

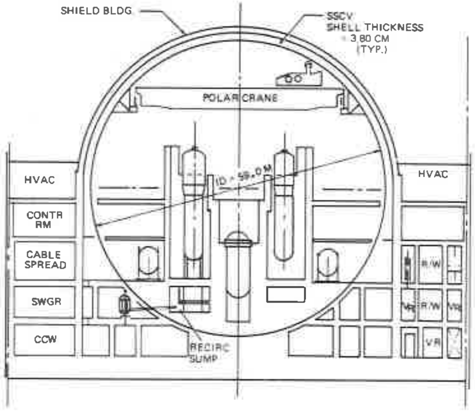


Figure 1 4—LOOP PWR PLANT

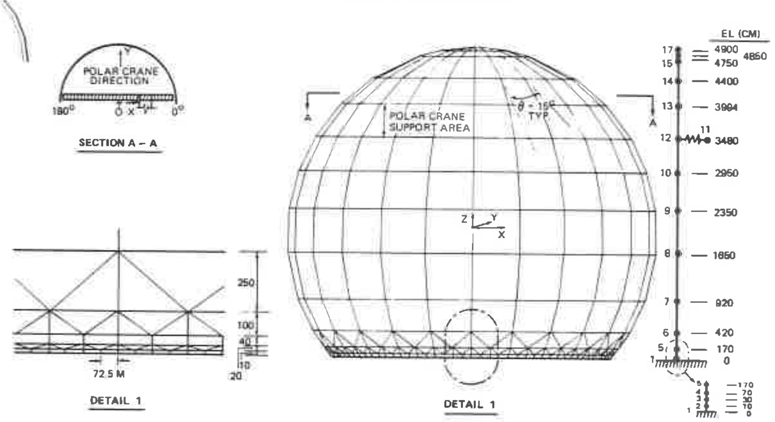


Figure 2 3—D HALF SHELL MODEL AND STICK MODEL

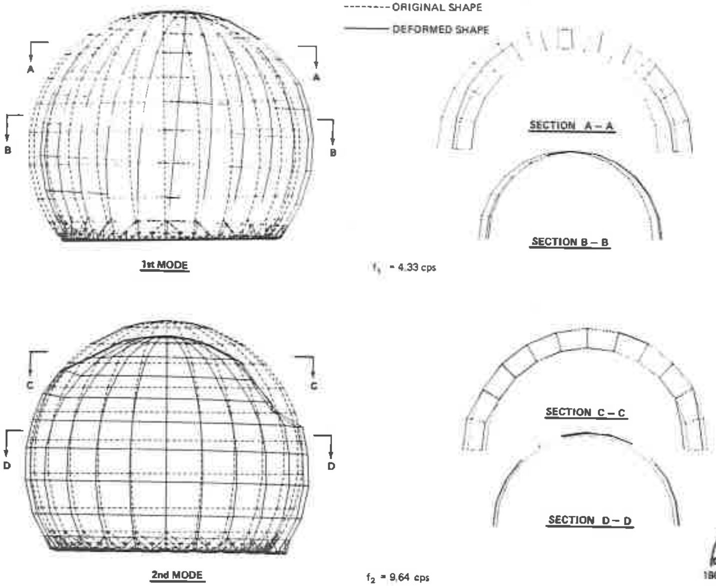
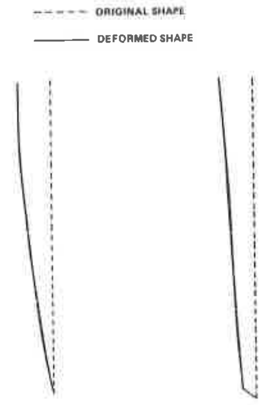


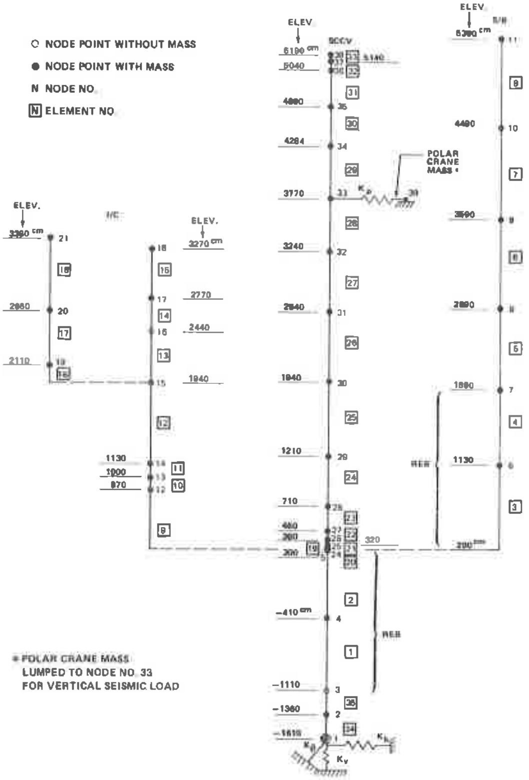
Figure 3 MODE SHAPES OF 3—D MODEL



1st MODE
f_1 = 4.11 CPS
HORIZONTAL DISPLACEMENT

3rd MODE
f_3 = 9.69 CPS
VERTICAL DISPLACEMENT

Figure 4 MODE SHAPES OF STICK MODEL



* POLAR CRANE MASS LUMPED TO NODE NO. 33 FOR VERTICAL SEISMIC LOAD

Figure 5 SEISMIC MATHEMATICAL MODEL

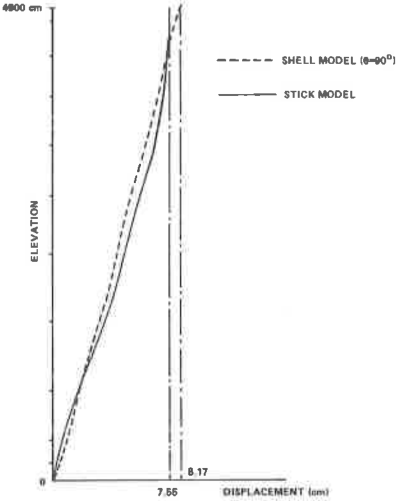


Figure 6 HORIZONTAL DISPLACEMENT DUE TO HORIZONTAL SEISMIC LOAD

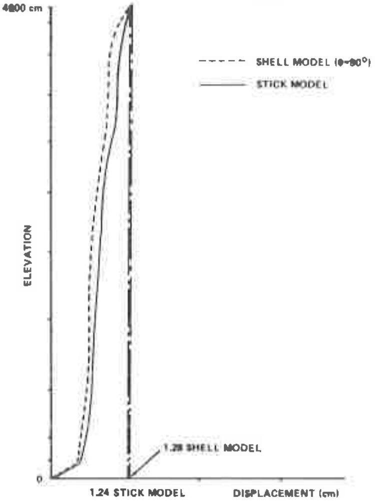


Figure 7 VERTICAL DISPLACEMENT DUE TO VERTICAL SEISMIC LOAD