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Influence of flexible connections on the seismic response of a nuclear condenser

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ABSTRACT: The present paper deals with the effect of support flexibility on the seismic response of a typical nuclear condenser with thin-walled rectangular box-type cross-section. The condenser considered for analysis is modelled as a non-uniform thin-walled beam flexibly supported at the base and having a rubber bellow at the other end. Finite-element method has been used and response spectrum analysis has been carried out. The effects of rotary inertia and shear deformation are included in the analysis. The results such as natural frequencies, mode participation factors, seismic displacements at salient nodal points and forces and moments in critical regions for various values of support flexibility parameters are presented in tabular form. Important conclusions are included.

1 INTRODUCTION

An important subject within the power industry today is the seismic qualification of condensers and heat exchangers. There is an ongoing concern and discussion on this subject regarding the degree of conservatism and the accuracy of standard procedures adopted in the industry. The evolution of regulatory criteria and guidelines, in general, has placed increasingly conservative requirements on assumptions and procedures used in designing these equipments for seismic loadings. One of the several questions that a designer has to answer is the adequacy of the analysis adopted in designing the equipment with classical boundary conditions.

Condensers in conventional thermal power plants are supported on springs with a rigid connection between condenser neck and low-pressure turbine casing. This arrangement allows the condenser to freely expand under the normal thermal loading. As a result of the overturning moments and displacements resulting from the earthquake loading, the type of flexible arrangement described above gives rise to excessive displacements and may cause breakage of its connections to external piping, low-pressure turbine casing and the foundation. To overcome this problem, the condensers designed for nuclear power plants situated in seismically active zones, are supported on rigid footings and are flexibly connected to the foundation giving necessary allowance for thermal expansion. The condenser neck in this case is connected to low-pressure turbine casing by means of a rubber bellow.

Not much published literature is available on the seismic analysis of turbine housing and condenser-type equipment for nuclear power plants. Danisch and Labes (1976) discussed various methods of seismic design of turbine housing for nuclear power stations with KWU manufacture without unfavourably affecting the operational behaviour of turbine generator set. Vint (1978) recorded the experience gained in protecting a turbo-generator installation against earthquakes. Wu and Cory (1977) studied the seismic behaviour of fast breeder reactor vessel and tried to establish limits for idealising shell-type structures using beam elements based on thickness to radius and length to radius ratios.

Conventionally, equivalent static force method is employed for seismic qualification of power plant equipment which are treated as 'rigid'. This judgement largely depends on designer's experience and the customer's analysis of cost and the risk of the additional expenditure necessary for carrying out detailed seismic calculations and design improvements. Hence, there is a necessity for carrying out

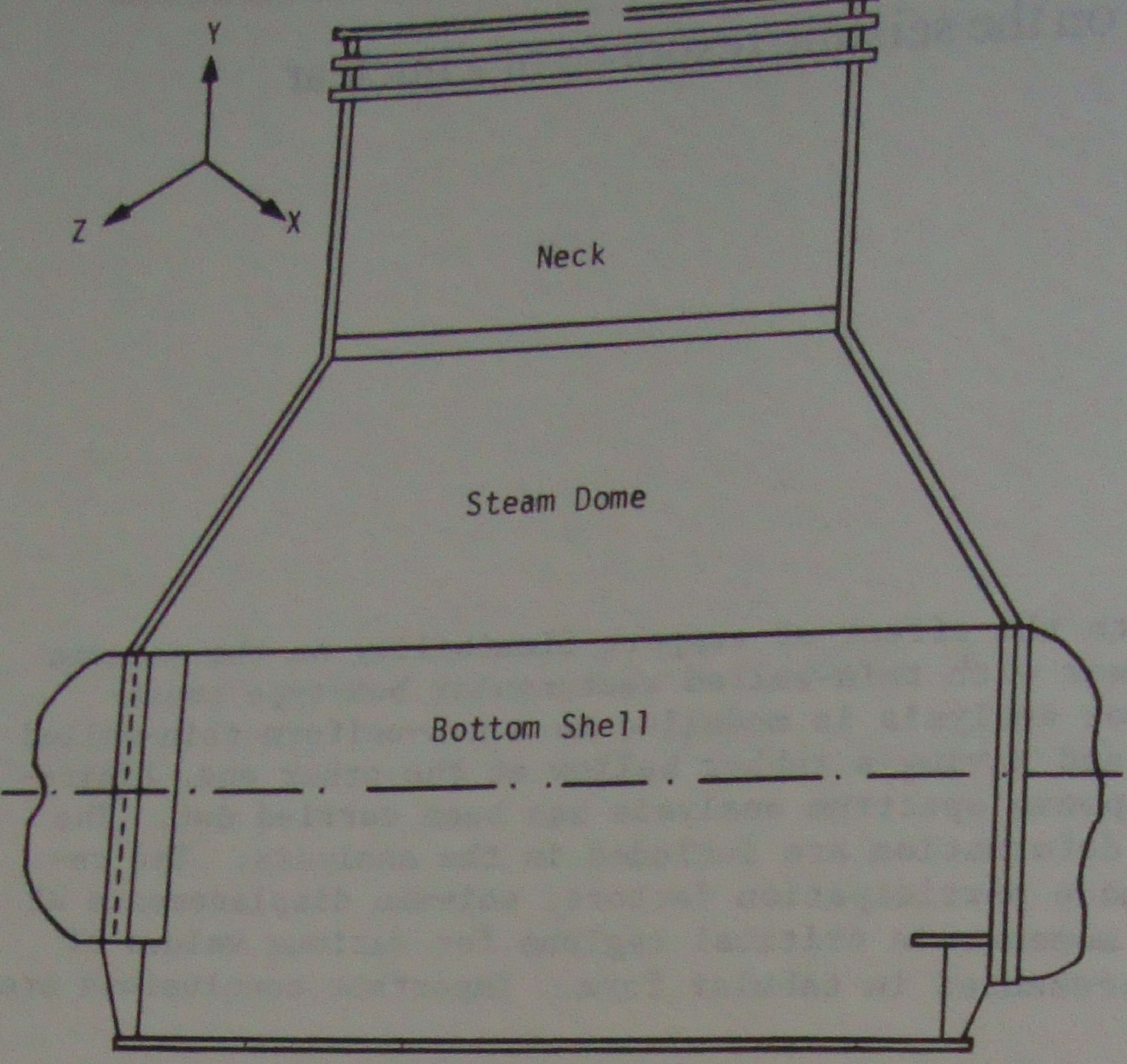

Fig. 1. Typical Nuclear Condenser.

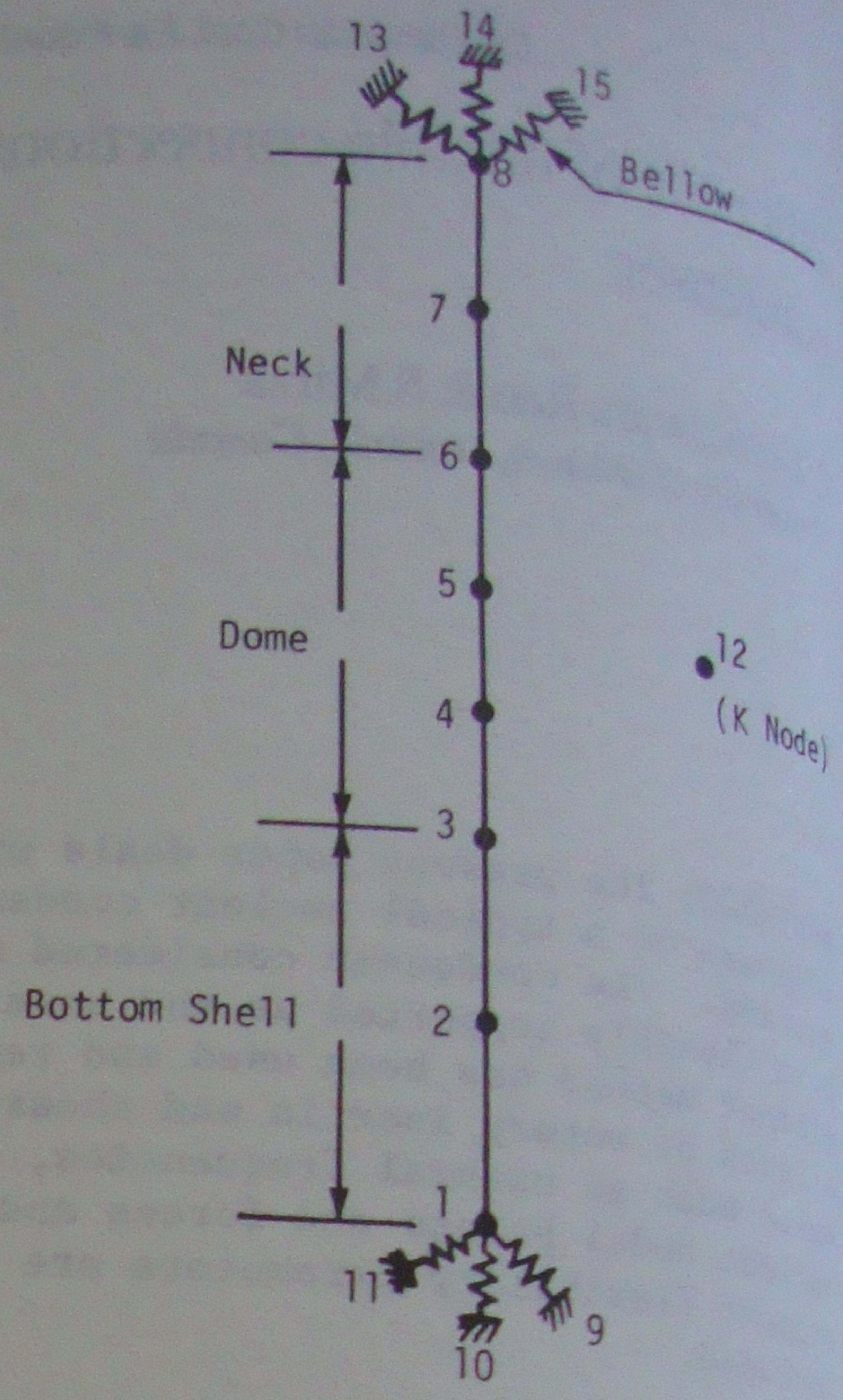

Fig. 2. Mathematical Model.

detailed dynamic analysis in order to establish the degree of rigidity and reliability of mathematical models that could be adopted for routine seismic qualification of major power plant equipment. To the best of the authors' knowledge, there is little published literature on the seismic behaviour of nuclear condensers of thin-walled rectangular cross-section flexibly connected to the foundation.

The present paper reports part of the results of a detailed investigation being carried out on seismic response of nuclear condenser of thin-walled box-type construction. The main objective of this study is to assess the influence of foundation flexibility on the seismic response of the condenser and to arrive at a range of bellow and foundation loading under earthquake conditions. The condenser is modelled as a non-uniform thin-walled beam using three-dimensional beam elements and the foundation flexibility is incorporated making use of boundary or spring elements. The effects of rotary inertia and shear deformation are included in the analysis. The seismic response of the condenser is computed for a range of foundation flexibility parameters and important conclusions are noted later in the paper.

2 STRUCTURAL ASPECTS OF THE SYSTEM

A typical box-type surface condenser, shown in Figure 1, functions on divided circulating water system. To achieve optimum utilization of enclosed volume for necessary condensing surface, the steam space is chosen to be of rectangular cross-section. The steam dome, shell and hot-well are steel fabrications. The bottom shell is a very stiff portion in the condenser and consists of a large nest of tubes separated by baffle plates. The steam dome and neck portion of the condenser are more flexible and are stiffened externally as well as internally. During the design stage itself, the condenser is analyzed for normal thermal and vacuum loading.

The condenser is supported on rigid footings and flexibly connected to the foundation by means of special connections provided between the condenser bottom plate and the concrete foundation. This type of arrangement is conceived mainly to allow necessary lateral thermal expansion while still providing enough strength to resist the overturning moments and axial and shear forces developed under a seismic event. The linear and rotational stiffnesses of these flexible connections vary between 10^5 and

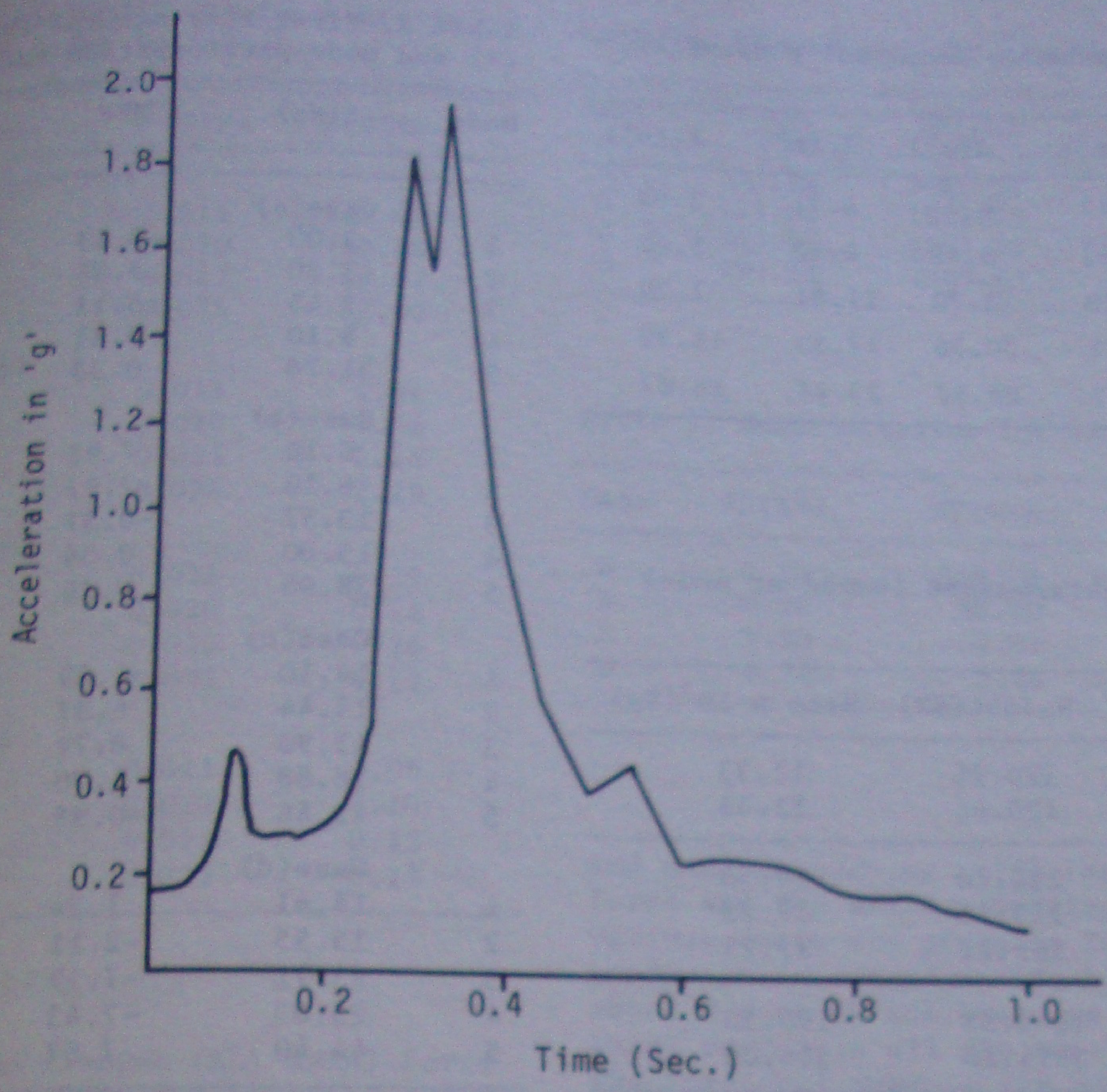

Fig. 3. Response Spectrum for 2% Damping.

10^8 Tons/meter and Ton·meters/radian respectively. The condenser neck is connected to low-pressure turbine casing by means of a special type of rubber bellow.

3 MODELLING CONSIDERATIONS

In view of the heavy stiffening provided to the condenser steam dome and bottom shell, it is felt that for a conservative estimate of seismic forces and moments,the modelling of condenser using beam and boundary elements is adequate. For the same reason, the dome and neck portion are treated as unstiffened for predicting the lowest possible natural frequencies which will give rise to maximum seismic forces and moments. The effects of rotary inertia and shear deformation are included to improve the accuracy of the solution. However, a detailed three-dimensional dynamic analysis of condenser using beam, plate/shell and boundary elements is in progress and the results of the same will be reported at a later date.

Figure 2 shows the mathematical model adapted for three-dimensional finite element analysis. The material of the condenser being steel, the maximum damping that can be offered is assumed as 2% and the response spectrum corresponding to 2% damping, shown in Figure 3, is utilized in the present analysis. While calculating the element sectional properties, only the plate thickness is considered ignoring the stiffness of the internal and external stiffeners. However, the masses of these stiffeners along with that of the shell are lumped at corresponding nodal points. In all the calculations performed here, the Young's modulus E is taken as 196.2 GPa and the Poisson's ratio as 0.33.

4 ANALYSIS

For the purpose of generating numerical results certain realistic dimensions were assumed which give rise to the typical properties. The condenser sectional properties such as area A, polar moment of inertia J, bending moments of inertia about Z-axis I_2 and about X-axis I_3 are given in

Table 1. Condenser sectional properties.

Section	$A(m^2)$	$J(m^4)$	$I_2\ (m^4)$	$I_3(m^4)$
1	0.47	6.49	4.71	3.92
2	0.52	8.46	6.42	5.02
3	0.70	13.70	11.81	7.79
4	0.71	20.76	17.33	11.39
5	0.77	26.57	23.44	14.07

Table 2. Weights/masses lumped at nodal points.

Portion	Node	Weight(KN)	Mass x 10^3(Kg)
Neck	8	120.96	12.33
	7	120.96	12.33
Steam dome	6	290.18	29.58
	5	169.22	17.25
	4	169.22	17.25
Bottom shell	3	1866.35	190.25
	2	3394.26	346.00

Table 3. First five natural frequencies (λ) and mode participation factors (MPF).

Mode	λ(Hz)	MPF	Dominant mode
	Case(a)		
1	3.00	-5.13	z-trans.
2	3.30	5.86	x-trans.
3	7.45	-6.11	z-trans.
4	8.10	5.41	x-trans.
5	31.78	0.33	z-trans.
	Case(b)		
1	6.10	7.97	x-trans.
2	6.10	-7.97	z-trans.
3	13.52	-0.37	z-trans.
4	15.00	0.36	x-trans.
5	38.96	0.16	x-trans.
	Case(c)		
1	14.10	-4.09	z-trans.
2	14.44	6.37	x-trans.
3	15.90	6.79	z-trans.
4	16.88	4.70	x-trans.
5	42.46	-0.95	x-trans.
	Case(d)		
1	14.41	1.24	z-trans.
2	15.55	-2.11	x-trans.
3	23.71	-7.19	z-trans.
4	23.83	-7.43	x-trans.
5	44.40	7.67	Axial

Table 1. The weights/masses lumped at various nodal points are given in Table 2.

To study the influence of foundation flexibility, four practical combinations of linear stiffness R in KN/m and rotational spring stiffnesses T in KN·m/radian about horizontal X and Z axes are chosen in the present analysis. The cases worked out are: (a) $R=9.81x10^5$, $T=9.81x10^6$
(b) $R=9.81x10^5$, $T=9.81x10^8$
(c) $R=9.81x10^6$, $T=9.81x10^{10}$
(d) $R=9.81x10^{10}$, $T=9.81x10^{10}$. The last case (d) approximately simulates the fixed base. In view of the arrangement provided at the base, it has been assumed that the stiffnesses of the foundation about X and Z-axes are equal and the condenser is rigidly fixed about the vertical axis Y. The response spectrum is fully applied in both horizontal X and Z-directions and two-thirds of the same in the vertical direction Y. The seismic excitations in the three directions are considered simultaneously and the condenser seismic response is computed combining the response of first ten modes of vibration by square root of sum of squares (SRSS)method.

5 DISCUSSION OF RESULTS

The first five natural frequencies (λ) and the corresponding modal participation factors (MPF) in the predominant mode of vibration for the four cases of foundation flexibility are given in Table 3. It can be seen from these results that the first few natural frequencies are greatly influenced by the changes in the foundation flexibility. In comparison, it can be noted that the rotational spring stiffness T has much greater influence on natural frequencies than the linear spring stiffness R. As the foundation is considered to be stiff about Y-axis, we can see that the first longitudinal frequency of the condenser is as high as 44.40 Hz. The seismic nodal displacements are presented in Table 4. The results show that the maximum horizontal displacements in X or Z direction at the top end of the condenser could be as high as 63 mm for case (a). It can also be seen that by increasing rotational stiffness, these displacements could be drastically brought down to about 2 mm as in case (b). The maximum member forces

Table 4. Seismic nodal displacements in mm (first ten modes included).

Node	X-disp.	Y-disp.	Z-disp.
	Case(a)		
2	14.65	0.011	13.49
4	31.03	0.020	30.04
6	44.91	0.023	44.07
8	62.59	0.025	62.02
	Case(b)		
2	1.96	0.011	1.96
4	2.07	0.020	2.06
6	2.14	0.023	2.12
8	2.23	0.025	2.19
	Case(c)		
2	0.20	0.011	0.19
4	0.28	0.020	0.24
6	0.36	0.023	0.26
8	0.52	0.025	0.32
	Case(d)		
2	0.05	0.011	0.06
4	0.10	0.020	0.10
6	0.13	0.023	0.13
8	0.16	0.025	0.14

Table 5. Maximum element (EL) axial force (AF), shear force (SF) and bending moment (BM).

EL	AF(KN)	SF(KN)	BM(KN·m)
	Case(a)		
1	717.21	5081.58	39190.95
3	153.72	827.87	25584.48
5	98.98	318.63	23239.89
7	23.35	589.19	14587.47
	Case(b)		
1	717.21	1809.95	7745.0
3	153.72	247.60	1601.0
5	98.98	142.05	884.47
7	23.35	9.61	406.92
	Case(c)		
1	717.21	1267.45	8931.02
3	153.72	262.32	5630.94
5	98.98	177.56	5539.71
7	23.35	45.91	3805.30
	Case(d)		
1	717.21	1049.67	4433.14
3	153.72	247.70	1997.32
5	98.98	164.22	2009.09
7	23.35	37.67	1515.65

Table 6. Maximum support reactions.

Case	AF(KN)	SF(KN)	BM(KN·m)
A	717.21	5081.58	39190.95
B	717.21	1809.95	7745.00
C	717.21	1267.45	8931.02
D	717.21	1049.67	4433.14

Table 7. Maximum bellow forces.

Case	AF(KN)	SF(KN)
A	0.20	868.28
B	0.20	30.90
C	0.20	7.06
D	0.20	2.26

and moments such as axial force, shear force and the maximum bending moment for various cases are given in Table 5. As the condenser is considered to be rigidly fixed about Y-axis at the base, we find that the axial forces in all the cases are constant. The torsional moments are not reported here as they are found to be negligibly small. The maximum support reactions and bellow forces are given in Tables 6 and 7. It can be seen that the seismic shear forces and bending moments are also greatly influenced by effecting changes in the foundation flexibility.

6 RECOMMENDATIONS

From the analysis carried out and results reported, the following are the conclusions and recommendations:

1. The foundation flexibility plays a significant role in the condenser natural frequencies and seismic forces and moments. It is, therefore, concluded that the base flexibility be estimated correctly while incoporating it in the analysis and thus ensuring structural integrity and safety of the condenser.
2. Though not shown here, it is also observed that the inclusion of the rotary inertia and shear deformation terms has a significant effect on the natural frequencies and hence the resulting seismic forces and moments.

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