COUPLED LATERAL–TORSIONAL RESPONSE OF EQUIPMENT MOUNTED IN CANDU NUCLEAR POWER PLANTS

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Summary

The seismic environment of a piece of equipment located in a nuclear power plant is significantly affected by the analytical model which is used to represent the physical reactor structure. In design, it is common to use a planar lumped mass system as the analytical model. However, real reactor structures are asymmetric and will respond in a combined lateral-torsional manner to a lateral seismic excitation. Consequently, it is important to be able to estimate the significance of this non-planar response.

In this paper, a coupled lateral torsional model (CLTM) is developed as a modification of the uncoupled lateral torsional model (ULTM) by including the torsional degree of freedom for each mass point and taking into consideration the effect of eccentricities between the centers of mass and rigidity at each floor level. The lateral and rotational time-histories at each floor level are characterized by lateral and rotational floor response spectra at the mass centroid. These time-histories are also combined to determine the lateral floor response spectra at the extreme edges of each floor mass.

A typical CANDU reactor building is subjected to the W-E component of the 1940 El Centro earthquake, and analysed as indicated above. The results show that the effect of torsion may cause some variations in the floor response spectra, due both to the change in coupled dynamic properties and to the contribution of rotational motion to the lateral response at the edges of any particular floor level.

1. Introduction

One of the major steps in seismic analysis is the construction of an appropriate analytical model to represent the physical structure. Basically, all dynamic models consist of masses and stiffness elements or springs. The degree of complexity of such a model will depend upon the extent of information to be obtained from the analysis. A commonly used analytical model is the discrete lumped mass system.

In this paper, the usual planar lumped mass model is modified by including the torsional degree of freedom for each mass point and taking into consideration the effect of eccentricities between the center of mass and of rigidity for each floor level, thereby developing an analytical model which includes the coupling of lateral and torsional response. This model is known as the coupled lateral-torsional model (CLTM) and the coupled dynamic properties for such a model (frequencies and mode shapes) can be determined by the usual eigenvalue method.

When determining the time history response of the structure to a base ground motion, the parameters of interest are the lateral floor acceleration at the center of the building as well as the rotational floor acceleration. These resulting floor accelerations are used to generate the extreme edge floor motions. Each floor motion time history is then used to determine the floor response spectra.

In order to be able to evaluate the effect of torsional coupling on floor response spectra, the uncoupled floor response spectra are also generated. By comparing the coupled floor spectra to the corresponding uncoupled spectra, one may develop guidelines to define situations for which a detailed coupled analysis is required.

2. Seismic Response of Asymmetric Reactor Building

The equation of motions for a lumped mass torsionally coupled system, with one axis of symmetry subjected to base ground excitation $\ddot{Y}_G(t)$ may be expressed as:

$$\underset{2n\times 2n}{\begin{bmatrix} [M] & [0] \\ [0] & [M] \end{bmatrix}} \underset{2n\times 1}{\begin{Bmatrix} \ddot{\underline{y}} \\ \ddot{\tilde{\underline{\theta}}} \end{Bmatrix}} + \underset{2n\times 2n}{\begin{bmatrix} [K_{yy}] & [K_{y\theta}] \\ [K_{y\theta}]^T & [K_{\theta\theta}] \end{bmatrix}} \underset{2n\times 1}{\begin{Bmatrix} \{\underline{y}\} \\ \tilde{\underline{\theta}} \end{Bmatrix}} = - \underset{2n\times 1}{\begin{Bmatrix} [M] \ \{1\} \ \ddot{Y}_G(t) \\ \underline{0} \end{Bmatrix}} \tag{1}$$

The eigenvalue problem takes the form

$$\left[\begin{array}{c|c} [K_{yy}] - \omega^2[M] & [K_{y\theta}] \\ \hline [K_{y\theta}]^T & [K_{\theta\theta}] - \omega^2 \ [M] \end{array}\right] \begin{Bmatrix} \underline{\phi}_y \\ \tilde{\underline{\phi}}_\theta \end{Bmatrix} = \begin{Bmatrix} \underline{0} \\ \underline{0} \end{Bmatrix} \tag{2}$$

and leads to the frequencies ω_i and the coupled lateral and rotational mode shapes $\underline{\phi}_{yi}$ and $\tilde{\underline{\phi}}_{\theta i}$, subvectors of the mode shape $\underline{\phi}$, $(i = 1, 2, ..., 2n)$.

The ith modal response can be determined by solving the ith equation of motion using numerical integration procedure and the total responses $(\ddot{\underline{y}}_c, \ddot{\underline{\theta}})$ can then be superimposed to determine the overall system response.

The contribution of each mode "i" in the total response of a specific mass m_j can be measured by the modal response factors $\Gamma_i\phi_{ij}$. In the coupled analysis, the coupled modal response factors associated with the response parameters $(\ddot{\underline{y}}_c, \ddot{\underline{\theta}})$ are $\Gamma_{yi}\phi_{yij}$ and $\Gamma_{yi}\phi_{\theta ij}$, respectively.

In order to be able to evaluate the effect of coupling between lateral and torsional response, it is necessary to determine the uncoupled response as well. The decoupled equations of motion take the form:

$$[M]\ \ddot{\underline{y}}_u + [K_{yy}]\underline{y}_u = -[M]\ \{1\}\ \ddot{Y}_G(t) \qquad (3.a)$$

$$[M]\ \ddot{\tilde{\underline{\theta}}} + [K_{\theta\theta}]\tilde{\underline{\theta}} = \underline{0} \qquad (3.b)$$

The eigenvalue problems become:

$$\left[[K_{yy}] - \omega_y^2[M]\right]\{\psi_y\} = \underline{0} \qquad (4.a)$$

$$\left[[K_{\theta\theta}] - \omega^2[M]\right]\{\tilde{\psi}_\theta\} = \underline{0} \qquad (4.b)$$

and lead to the uncoupled vibration frequencies (ω_{yi}, $\omega_{\theta i}$) and the uncoupled lateral and rotational mode shapes $\underline{\psi}_{yi}$ and $\tilde{\underline{\psi}}_{\theta i}$ ($i = 1, 2, \ldots, n$). For the uncoupled response analysis the lateral floor acceleration response $\ddot{\underline{y}}_u$ is generated while the rotational response vanishes.

3. Floor Response Spectra

Mose commonly, the floor response spectrum is developed using the time history approach wherein the floor motion of the structure is applied to the series of simple oscillators with a postulated damping ratio, and their maximum responses are plotted as function of their natural periods.

In the coupled analysis, two floor motions are generated, lateral motion and rotational motion. The rotational floor response spectrum can be obtained by applying the rotational floor motion to a series of torsional single degree of freedom oscillators and plotting their maximum rotational responses as a function of their natural periods for a specific level of damping.

Due to torsional effects, floor response spectra may be generated for more than one location on the floor level. Considering the edges* as extreme cases, the edge floor spectra are determined using the edge lateral floor motions estimated by:

$$\ddot{\underline{y}}_{e\pm} = \ddot{\underline{y}}_c \pm a\ddot{\underline{\theta}} \qquad (5)$$

In order to evaluate the effect of torsional coupling on lateral floor response spectra the following four cases are considered:

(a) FRS - $\ddot{y}_u$: uncoupled floor response spectrum

(b) FRS - $\ddot{y}_c$: centroidal coupled floor response spectrum

(c) FRS - $\ddot{y}_{e+}$: (+ve) edge floor response spectrum

(d) FRS - $\ddot{y}_{e-}$: (-ve) edge floor response spectrum

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*The positive edge is on the right hand side of the floor plan (see Fig. 1).

4. Numerical Example

The floor plan given in Fig. 1 is that for a typical CANDU reactor building whose internal structure is made up of an asymmetrically arranged grouping of walls located in a particular fashion and forming an asymmetric structural system with one axis of symmetry (BD-axis). The stick lumped mass model for the example reactor building is given in Fig. 2. Using the associated geometrical and physical properties of the reactor model [6] an uncoupled and a coupled analysis are studied. The natural frequencies and modal participation factors of the building structure corresponding to both analyses are given in Table 1.

Using the 1940 El Centro W-E earthquake record (normalized to a maximum acceleration of 0.2 g) as input ground motion and assuming a constant structural damping factor of 0.05, the dynamic response of the uncoupled and coupled mathematical models are computed incorporating the first twelve normal modes. The resulting uncoupled lateral floor motion and the coupled lateral-rotational floor motions are obtained. The corresponding edge lateral floor motions are generated to evaluate the effect of torsion. These floor motion time histories are then used to develop the floor response spectra. The secondary damping used is assumed to be one percent. The lateral floor spectra for mass m_4 and the rotational floor spectra for the internal structure (m_1, m_2, m_3, m_4, m_5) are shown in Fig. 3.

5. Discussion and Conclusions

The results of this investigation indicate that the following conclusions and recommendations can be drawn:

1. Torsional coupling induces rotational motion which may have some significance on the equipment response (Fig. 3). The major factor which may affect the equipment response is its lateral location relative to the center of the building. If torsional effects are of major significance it may be advisable either to develop floor spectra enveloping all floor locations or to generate floor spectra particularly for specific equipment locations. For this particular example, the largest variation of lateral floor response spectra at the same elevation due to different plan locations is approximately 1.2 g.
2. The variation of the floor spectra peaks is due primarily to the variation of the modal response factors [1]. The lateral floor spectra peaks are associated with the lateral modal response factors ($\Gamma_{yi}\phi_{yij}$). The rotational floor spectra peaks correspond with the induced rotational modal response factors ($\Gamma_{yi}\phi_{\theta ij}$).
3. The rotational floor response spectra (Fig. 3) may express the frequency range most affected by torsional coupling. These floor spectra are the result of the lateral-torsional coupling of the structure due to the eccentricity between its center of mass and rigidity.
4. The concept of the rotational floor response spectrum can be applied in the same manner as the lateral floor response spectrum.
5. More investigations need to be made in order to determine guidelines to define situations for which the torsional coupling effect must be considered in the seismic analysis.

6. Acknowledgements

The writers wish to thank the National Research Council of Canada for providing the financial support for this investigation, Atomic Energy of Canada Limited for making available the data used in the numerical example and the Computer Center of McMaster University for making possible the computations involved in this work.

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Table 1 Natural Frequencies and Modal Participation Factors

	Frequency (Hz)		Modal Participation Factors	
Mode	ULTM	CLTM	ULTM	CLTM
1	4.94	4.94	35.44	35.44
2	5.82	5.78	27.96	28.03
3	10.00	9.97	11.04	11.12
4*	10.65	10.68	-	0.41
5*	14.20	14.20	-	-
6	16.29	16.25	10.98	10.93
7	18.24	18.24	15.78	15.78
8*	19.66	19.18	-	8.42
9	23.88	24.40	28.15	23.13
10	27.89	27.74	2.92	2.55
11	28.69	28.60	6.57	6.57
12	29.46	23.40	1.31	1.90

* Torsional Mode of Vibration

ULTM: Uncoupled Lateral Torsional Model

CLTM: Coupled Lateral Torsional Model

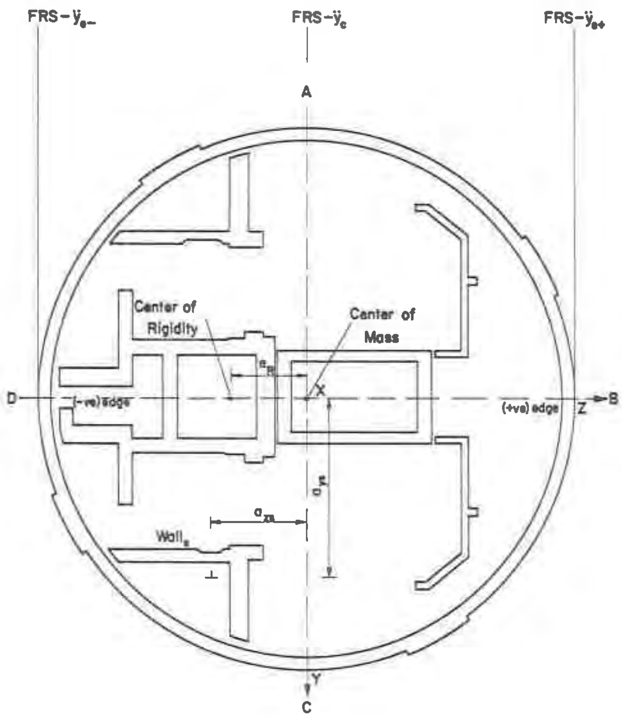


FIGURE 1 STRUCTURAL PLAN FOR A TYPICAL CANDU REACTOR BUILDING

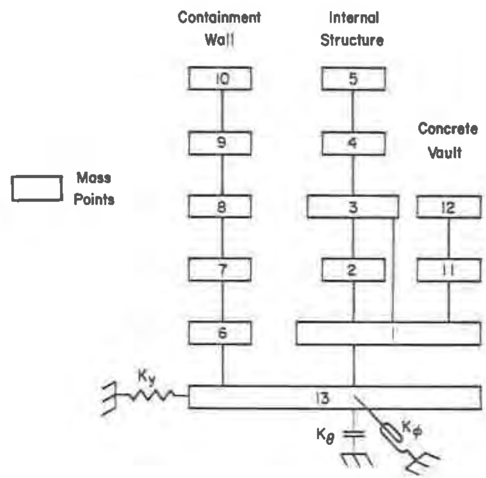
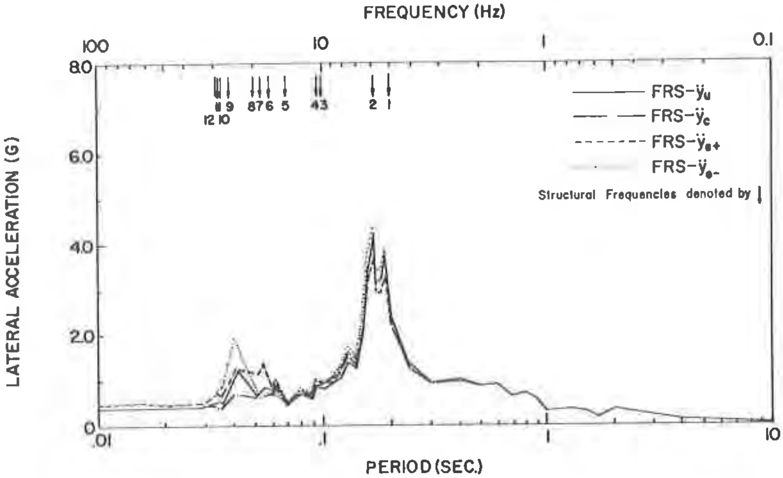


FIGURE 2 LUMPED MASS-STICK MODEL FOR EXAMPLE REACTOR BUILDING



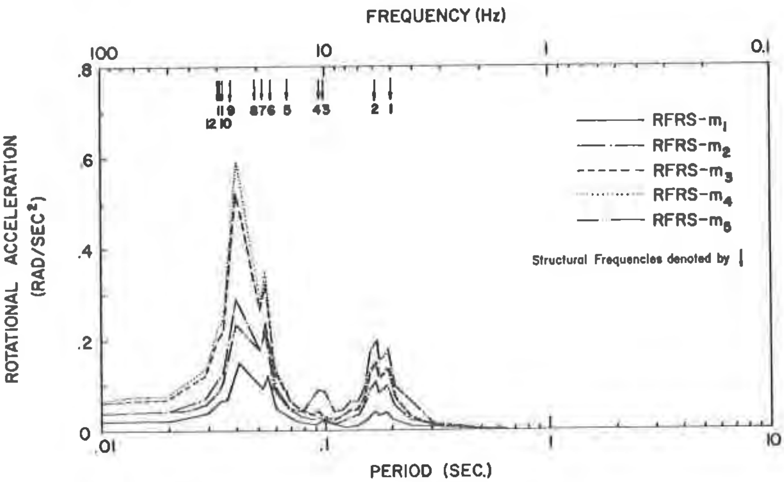


FIGURE 3 TYPICAL LATERAL AND ROTATIONAL FLOOR RESPONSE SPECTRA (ONE PERCENT DAMPING)