Dynamic Analysis of Modular Structures in CANDU Nuclear Power Plants

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INTRODUCTION:

CANDU Nuclear Power Plants (NPP) have evolved over a 40-year period. The latest members of the high performance CANDU family are the CANDU 3 and the Advanced CANDU 6. Both maintain the successful key features of the CANDU Nuclear Power System which include a pressure tube reactor, heavy water moderator, natural uranium fuel, and on-power refuelling. A high level of modularity has been achieved for future CANDU NPP.

A typical modular structure consists of a three dimensional structural steel frame which supports equipment, piping and other components contained within a specific area of the reactor building. This modularization concept allows manufacturing of these modules to be done remote from the building. Subsequently, the completed modules are installed into the reactor building through the open top by means of a very heavy lift crane. Once in place, the modules will be connected to the internal structure at a number of preselected boundary points. Concrete, whenever required for shielding will be pumped into permanent steel formwork.

The design and analysis of a structural steel module represents a new challenge for the structural engineer. The current paper presents a comparison of the different approaches available for dealing with the dynamic analysis of modular structures within the reactor building. The objective is to address the new challenges imposed on design and analysis as a result of an extensive modularization program.

ANALYSIS METHODS:

The CANDU 3 reactor building (Fig. 1) is represented by a lumped mass stick model (Fig. 2). The model includes the containment and internal structures as well as 6 degrees of freedom springs and dashpots representing the soil/rock underneath. Since the CANDU 3 design is intended to cover a wide range of soil/rock conditions, a number of soil/rock properties are used in the analysis. A typical steel module is chosen for the current comparative analysis purposes (Fig. 3). The total weight of this module is 750 kN; which is approximately 1% of the weight of the internal structure. A conventional lumped mass model is developed from the steel member properties and the masses associated with floors dead, live and equipment loads.

Response spectrum and time-history analyses were performed for the system utilizing a coupled model for the reactor building and the module under consideration. The same analyses were performed for the decoupled reactor building alone and for the structural module alone which was subjected to the envelope input motion of the points of attachment to the internal structure. For the spectrum analysis, the ground response spectrum given in CSA CAN3-N289.3-M81 is used. For the time-history analysis, a synthetic time-history developed by the approach discussed by Aziz and Biswas (1979) is used. Both the ground response spectra and time-histories have been normalized to a peak ground acceleration of 0.3g. Damping values for steel, concrete and soil/rock have been chosen following the requirements of CSA CAN3-N289.3-M81, and using the concept of composite modal damping (Aziz, 1979).

RESULTS:

The frequencies and weight participation factors for the decoupled reactor building were obtained for each rock property using the STARDYNE system. Table (1) gives the results for the first 16 modes for the case of hard rock (Shear Modulus of 10,000 MPa). The frequencies and participation factors for the decoupled steel structure module are shown in the same table. These represent the self dynamic characteristics of the module had the reactor building been assumed infinitely rigid. The frequencies and weight participation factors for the coupled reactor building/steel module are also given in Table (1). An examination of the table would reveal that the coupled combined dynamic characteristics exhibit some of the characteristics of each of the individual decoupled systems. The low frequencies resemble those of the steel module; while the high frequencies resemble those of the reactor building. The intermediate frequencies show a noticeable degree of interaction between the two dynamic systems. For example mode 9 for the coupled system shows large X and Y participation factors which were not present in the decoupled models. Of significant importance is the spatial coupling between the two horizontal directions which was not present in the decoupled reactor building. This behavior was present, but to a lesser degree, in the steel module decoupled model.

Response accelerations, displacements and forces for the coupled systems, when subjected to the Design Basis Earthquake (DBE) of 0.3g were obtained for each of the analysis approaches considered (Response spectrum as well as time-history) and for each of the soil/rock cases investigated (shear modulus ranging from 500 to 10,000 MPa for the soft and hard soil conditions). Due to space limitations, only sample results are presented. Table (2) shows a comparison for the acceleration response at different nodes for the different components of the reactor building structure (i.e. containment, internal structure and steel module). Comparison of the acceleration response results obtained from the time-history analysis indicates that the response of the containment structure is practically the same whether developed from a coupled or decoupled analysis. However, the response of the containment from the coupled analysis using the response spectrum approach is slightly lower than that from a decoupled response spectrum analysis. This slight difference can be attributed to the approximation involved in the modal combination rule used (SRSS). Also, the response of the containment in the coupled model obtained using the response spectrum approach is, in general, slightly more conservative than the exact time-history integration results except near the base of the containment. This behavior near support points is a result of the approximation in the response spectrum method.

The results shown in Table (2) for the concrete internal structure indicate similar behavior to that observed for the containment structure.

The acceleration response results for the steel structure using the response spectrum method for the coupled model are slightly more conservative than the results obtained using the time-history method. The response acceleration results obtained by a decoupled response spectrum analysis for the steel module are also shown in Table (2). They do not show a particular trend compared to the exact time-history method, i.e. they can be sometimes higher and sometimes lower.

The Floor Response Spectra (FRS) for different elevations of the reactor building and different soil/rock conditions were obtained using the time-history method. Typical results are shown in Figs 4, 5, 6, and 7 for both concrete supported and steel supported cases. The FRS show the effect of supporting equipment on steel modules rather than on concrete structures. From these Figures it can be seen that the hard rock condition is more critical for the horizontal direction response; while the soft rock condition is more critical for the vertical direction response.

CONCLUSIONS:

Based on a comparative study of the different approaches which can be employed for obtaining the response of a modularized reactor building under a DBE, the following can be concluded:

a) The response of steel-supported equipment under a DBE can be significantly different from those which are concrete-supported as a result of steel flexibility. The design engineer has to carefully select the structural system in order to avoid the excessive flexibility in steel modules.

b) The response analysis results for the coupled system using the response spectrum method and a suitable modal combination rule can be comparable to those obtained using an exact time-history method. They tend to be slightly on the conservative side.

c) The approach of decoupling steel modular structures and subjecting them to an envelope Floor Response Spectrum obtained from either a coupled or a decoupled analysis of the structure can lead to unrealistic response results (sometimes higher and sometimes lower than those of the time-history analysis).

d) The seismic qualification program for steel-supported equipment should use Floor Response Spectra which accounts for the steel support flexibility. The behavior of the coupled system can be different from the behavior of the individual uncoupled systems.

e) Soft soil conditions, in general, are more critical for steel modular structures for the response in the vertical direction. Hard rock conditions, in general, may govern the horizontal response.

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Aziz, T. S.(1979). Damping in Structures and Equipment. Third International Seminar on Extreme load Design of Nuclear Plant Facilities, Berlin, Germany, August 20-21, 1979.

Aziz, T.S., Biswas, J.K.(1979). Spectrum-Compatible Time-Histories for Seismic Design of Nuclear Power Plants, 3rd Canadian Conf. on Earthquake Engng, McGill University, Montreal, June 1979.

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TABLE (1) TYPICAL INTERACTION BEHAVIOUR BETWEEN SYSTEMS
FREQUENCIES OF THE INTERACTING SYSTEMS
CASE FOR HARD ROCK - DBE - HORIZONTAL DIRECTION

(A) DECOUPLED REACTOR BUILDING

MODE NUMBER	FREQ. (CPS)	WEIGHT PARTICIPATION FACTOR GAMMA X	GAMMA Y	GAMMA Z
1	6.14	-0.000	1.509	0.006
2	6.14	1.509	0.000	0.000
3	11.19	1.650	-0.000	-0.000
4	11.29	0.000	1.662	0.121
5	16.03	-0.000	-0.028	1.587
6	16.89	-0.690	0.000	0.000
7	16.89	-0.000	-0.683	-0.010
8	22.60	0.000	-0.986	0.166
9	23.16	-0.972	-0.000	-0.000
10	25.83	-0.000	-0.029	1.404
11	29.79	0.000	0.072	-0.040
12	29.80	-0.053	0.000	-0.000
13	32.00	0.000	0.583	0.072
14	32.01	0.562	-0.000	-0.000
15	38.20	0.143	-0.000	-0.000
16	38.93	0.000	-0.041	0.582

(B) DECOUPLED STEEL STRUCTURE MODULE

MODE NUMBER	FREQ. (CPS)	WEIGHT PARTICIPATION FACTOR GAMMA X	GAMMA Y	GAMMA Z
1	3.08	0.001	0.006	1.138
2	3.09	0.003	0.002	0.171
3	3.77	-0.003	0.015	0.969
4	8.17	0.584	0.509	-0.011
5	9.33	-0.567	0.637	-0.011
6	13.27	0.345	0.887	-0.002
7	13.69	0.967	-0.370	0.001
8	15.07	-0.263	0.498	0.000
9	15.20	0.546	0.478	-0.000

(C) COUPLED REACTOR BUILDING/STEEL MODEL

MODE NUMBER	FREQ. (CPS)	WEIGHT PARTICIPATION FACTOR GAMMA X	GAMMA Y	GAMMA Z
1	3.07	-0.072	0.016	1.191
2	3.08	0.022	0.022	0.772
3	3.78	0.017	0.062	1.007
4	4.95	1.713	0.664	0.040
5	5.31	0.074	-0.068	0.030
6	5.88	0.309	0.113	0.005
7	6.14	-0.356	1.421	0.005
8	6.14	1.418	0.355	0.001
9	9.90	-2.556	2.813	-0.055
10	11.24	1.985	0.432	0.023
11	11.31	0.410	-2.352	-0.175
12	13.75	0.293	0.224	-0.085
13	15.48	0.798	0.102	-0.353
14	16.04	0.001	-0.027	1.587
15	16.89	-0.679	0.083	0.001
16	16.89	-0.083	-0.673	-0.009
17	22.64	0.034	-0.981	0.161
18	23.17	-0.973	-0.026	0.004
19	25.87	0.001	-0.030	1.407
20	29.79	0.000	0.072	-0.040
21	29.81	-0.053	0.000	-0.000
22	32.00	-0.007	0.583	0.072
23	32.02	0.562	0.007	0.000
24	38.26	-0.214	0.007	0.028
25	38.93	0.001	-0.045	0.578

TABLE (2) RESPONSE ACCELERATIONS (gs)

CASE FOR HARD ROCK - DBE 0.3g - HORIZONTAL DIRECTION

NODE NUMBER	ELEV. ms	DECOUPLED REACTOR BUILDING (RB) & DECOUPLED STEEL MODULE: RESPONSE SPEC.	TIME HIST.	COUPLED REACTOR BUILDING & STEEL MODULE: RESPONSE SPEC.	TIME HIST.
CONTAINMENT :					
8	151.50	1.27	0.96	1.19	0.96
7	145.50	1.09	0.85	1.02	0.85
6	138.50	0.94	0.76	0.87	0.76
5	130.50	0.77	0.66	0.72	0.65
4	122.50	0.62	0.54	0.57	0.54
3	115.00	0.45	0.46	0.42	0.46
2	107.50	0.31	0.38	0.25	0.38
1	100.00	0.13	0.30	0.05	0.30
INTERNAL CONCRETE :					
14	129.30	1.09	0.83	1.02	0.82
13	122.50	0.81	0.68	0.75	0.67
12	115.00	0.49	0.48	0.46	0.48
11	115.00	0.45	0.44	0.42	0.44
10	111.70	0.35	0.40	0.34	0.40
9	107.50	0.29	0.36	0.25	0.35
STEEL MODULE :					
839	122.50	1.54	NA	1.35	1.34
826	115.00	0.89	NA	1.26	1.21
812	107.50	1.97	NA	0.8	0.9

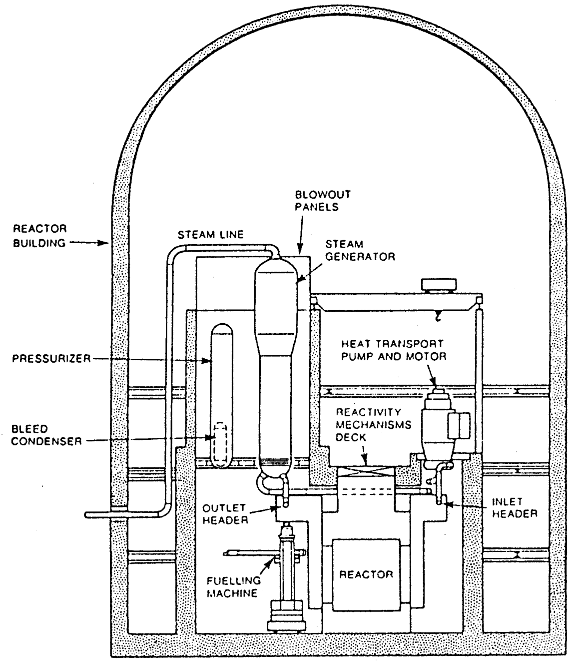

FIG. 1 CANDU 3 Reactor Building

FIG. 2 CANDU 3 Reactor Building Dynamic Model

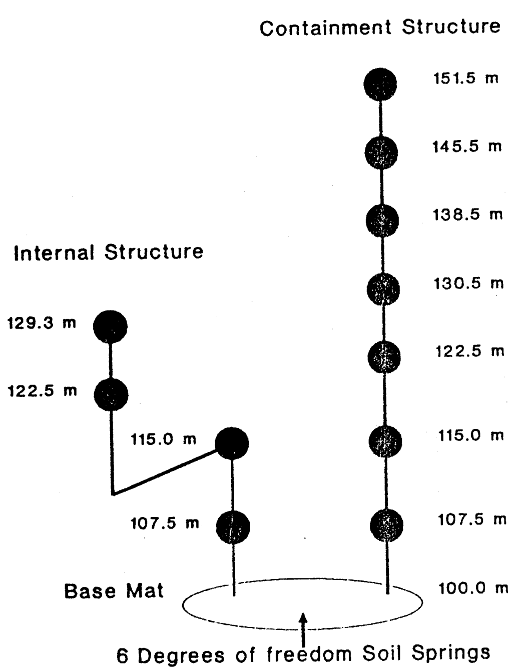

FIG. 3 Steel Module Dynamic Model

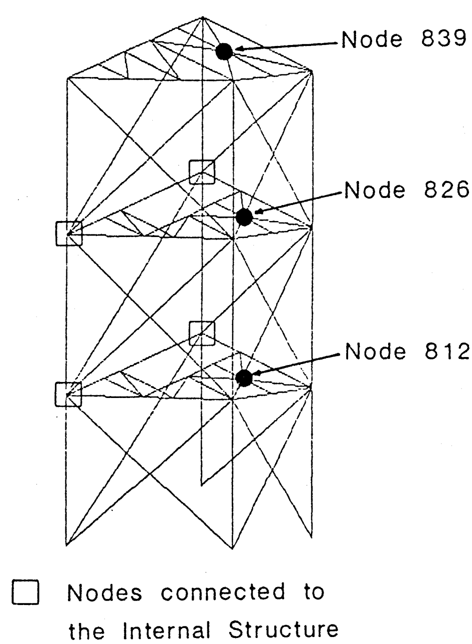

FIG. 4 FLOOR RESP. SPECTRA COMPARISON
EL.122.5 m - HARD ROCK - HORIZONTAL DBE

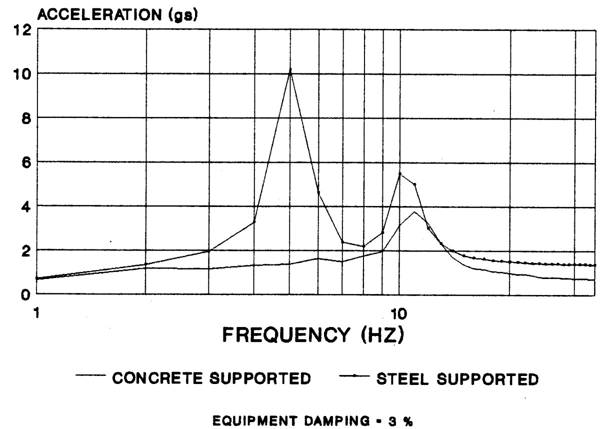

FIG. 5 FLOOR RESP. SPECTRA COMPARISON
EL.122.5 m - SOFT ROCK - HORIZONTAL DBE

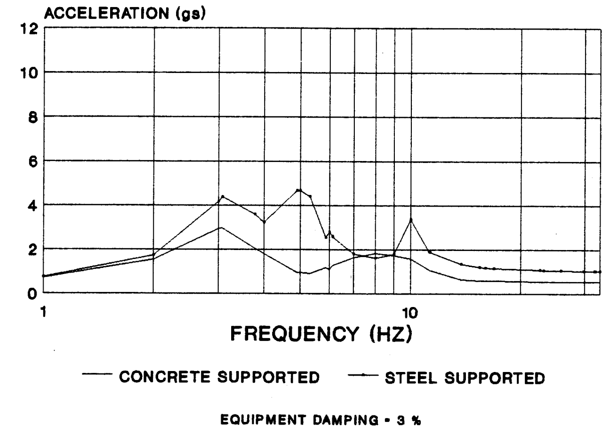

FIG. 6 FLOOR RESP. SPECTRA COMPARISON
EL.122.5 m - HARD ROCK - VERTICAL DBE

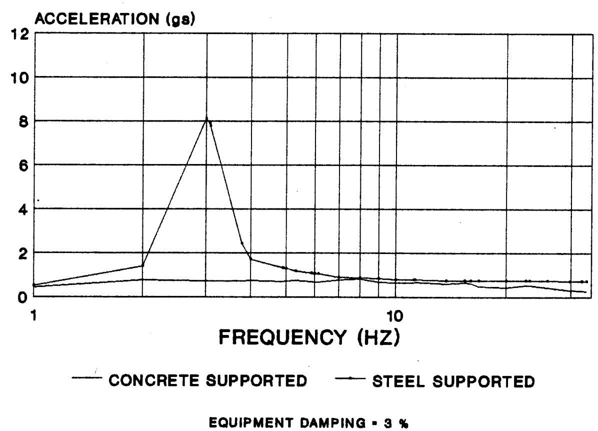

FIG. 7 FLOOR RESP. SPECTRA COMPARISON
EL.122.5 m - SOFT ROCK - VERTICAL DBE