SEISMIC OPTIMIZATION APPROACH FOR CANDU MODULES

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ABSTRACT

The CANDU 3 is the latest generation and the smallest version (450 MWe) of the high performance line of CANDU Pressurized Heavy Water Reactor (PHWR) systems developed in CANADA. To meet project objectives of reduced construction schedule and cost, particular attention towards constructibility has been made in the CANDU 3 design. Modular construction techniques, developed by the shipbuilding and off-shore oil platform construction industries are utilized so that a construction schedule of just over three years can be achieved. A typical reactor building internal module consists of a structural steel frame containing one or more systems and floor levels that can weigh up to 500 tonnes. The CANDU 3 modules are easy to build and can be manufactured by various Canadian and international shops. Each module is completed and inspected before installation at the site. The modules are installed by use of a very heavy lift (VHL) construction crane through the open reactor top. Once in place, the modules are fastened to the adjacent concrete internal structure and base slab (if necessary) at preselected points.

The seismic design of the steel modules is based on an envelope encompassing ground accelerations up to .3 g to permit siting at most potential sites without re-design. Conceptual analysis results of the steel modules indicated large seismic response. The objective of this study is to focus in on a typical CANDU 3 steel module (RM40) and develop a process to optimize the design and reduce the seismic response of the module to an acceptable level. The process developed was then repeated for the design of Steel Modules RM10 and RM21 to obtain acceptable seismic designs.

1.0 INTRODUCTION

The CANDU 3 (450 MWe) is the latest and the smallest version of the high performance line of CANDU Pressurized Heavy Water Reactor (PHWR) systems developed in Canada. Figures 1, 2 and 3 show the configuration of CANDU 3 nuclear power plant. At present, the detail design of the CANDU 3 is 70% complete.

Significant advances have been made in the development of new concepts for the design, analysis and construction of next generation CANDU nuclear stations for both the CANDU 3 Reactor and large sizes. These advances have led to construction methods which result in a reduced schedule and construction cost and improved quality of construction. The methodologies used consider the site location and access as well as the availability or lack thereof, of the necessary skills and infrastructure at the site location.

Main CANDU 3 objectives of reduced construction schedule, cost and risk are achieved by paying particular attention towards constructibility. Modular construction techniques are utilized so that a construction schedule of just over three years can be achieved.

A typical reactor building internal module consists of a structural steel frame containing one or more systems and floor levels that can weigh up to 500 tonnes. Early seismic analysis results conducted during the conceptual design phase have indicated high seismic response levels of the steel modules.

The aim of this study was to develop a process that would optimize the design/analysis cycle and obtain steel modules that satisfy the seismic design criteria set for the CANDU 3.

2.0 CANDU 3 MODULARIZATION

The availability of mobile very heavy lift (VHL) cranes has made the reactor building open top a more economical method of construction. VHL equipment reliability has been demonstrated by a number of successful nuclear construction applications in the past 10 years and allows use of large scale modularization of the nuclear power plants.

Utilizing open top construction method for the reactor building, extensive modularization of the systems and structures has been incorporated in the design and construction of CANDU 3. Modularization of construction is a requirement which has to be considered at the conceptual phase of layout development. The new generation of CANDU stations have their concrete, steel, and system layout developed such as to make effective use of modularization.

In terms of the integration and size of the modules, 3 categories of modules are utilized in the construction plan of CANDU 3. These are a) skid mounted equipment assemblies; b) combined equipment and support steel structure; and c) combined equipment, support steel structure and concrete walls and floors. The larger modules are defined as a structural component which can be either a building or a part of a building and is, to the maximum extent possible, complete with all of the systems which form part of the volume.

2.1 Module Size

The reactor building internals can be modularized in different sizes and complexity.

The basic level of modularization is the skid mounting of adjacent equipment on the same level and installing them as a unit. In this case, the construction plan must provide appropriate interface between the Civil and equipment works capable of providing access for the installation of skid mounted modules. This does not permit the module boundaries to cross walls or floors and limits the extent of constructability improvement. Using skid mounted equipment modules leads to moderate gains in schedule.

In the second level of modularization, the equipment and the supporting structural steel are combined in a module. This permits the module boundary to include more than one floor in elevation and a large area in plan. The modules are then installed inside the reactor building and fastened to the in situ internal concrete structure if needed. This method is ideal for areas where concrete walls and floors are not required for shielding purposes. The use of steel support structures for equipment requires a more rigourous evaluation of the seismic response of the module when in interaction with the rest of the reactor building internal structure. This level of modularization results in significant gains in the construction schedule since large portions of the plant can be assembled together and in parallel with the construction of internal concrete structures. It suffers, however, from the need to use valuable space for the structural steel supports which are not required when the module is fastened to the rest of the internal structure. Elimination of this deficiency leads to the third level of modularization.

The third level of modularization is applied to areas where, for space economy and effective system integration in the module shop, the module boundary includes concrete walls and floors for shielding or structural purposes. To maintain a reasonable crane capacity and largest possible module, the concrete cannot be placed in such modules prior to their installation. This eliminates the application of normal reinforced concrete design for such modules. To provide the same level of shielding and structural strength, concrete filled cellular steel components known as Concrete Steel Composite (CSC) are used in these modules. The cellular steel plate walls are prefabricated in equipment modules in the fabrication shop and are filled with concrete after installation at the site. The module equipment is supported by the cellular steel walls and floors during fabrication and installation. The operational requirements including shielding and earthquake resistance are met by the combined action of steel cellular structures and the concrete inside them. This method allows very large modules containing entire systems to be fabricated and tested in the factory. The modules can then be lifted or skidded into position.

Figure 4 shows the outline of CANDU 3 modules RM10 and RM20. For the purpose of clarity not all equipment is shown in these figures.

2.2 Description of Typical CANDU 3 Modules

The CANDU 3 modules are compact and can be easily manufactured by various Canadian and international shops. Each module is completed and inspected before installation at the site. The modules are installed by use of a very heavy lift (VHL) construction crane through the open reactor top. Once in place, the modules are fastened to the concrete internal structure and base slab (if necessary) at preselected points.

Module RM10 shown in Figure 4 is one of the largest self-supporting structural steel module and is approximately 18m high, 28m long and 8m wide. The module has one side mounted against a plain vertical concrete wall. On two other sides the module is connected to the adjacent modules. At the centre of the lowest level, the module contains the hollow steel shell of purification filter shielding cells. These shells will be filled with concrete after the installation of the module. This module includes ECC valve stations, HVAC ducting, cable trays, piping, I&C panels, tanks, filters, etc.

3.0 CANDU 3 DESIGN EARTHQUAKE GROUND RESPONSE SPECTRA

Seismic design criteria have a significant effect on the structural design of the CANDU 3 modules. The CANDU 3 NPP is designed with a capability to be sited on a wide range of soil/site conditions. Therefore the approach used in specifying the seismic design basis is that of using an envelope for a wide range of potential site conditions.

Per CSA-CAN3-N289 series of standards [1-2] the CANDU 3 seismic design requirements are specified by two level of earthquakes : the Design Basis Earthquake (DBE) and the Site Design Earthquake (SDE).

The DBE is the more severe seismic level. It is defined by means of an engineering representation of the potentially severe effects of earthquakes applicable to the site that have sufficiently low probability (10^{-3} to 10^{-4}) events/year. The DBE is defined by a Ground Response Spectra (GRS) with the following ground motion parameters:

a. Peak Horizontal Acceleration 0.3 g

b. Peak Horizontal Velocity 365.8 mm/sec

c. Peak Horizontal Displacement 274.3 mm

The GRS implemented in the CANDU 3 design are developed in accordance with the methods described in CSA-N289.3 [1].

For the vertical ground motion parameters, 2/3 of the above values are used.

The foundation soil parameters of the CANDU 3 standard design cover sites ranging from rock to alluvium or soft soils.

4.0 SEISMIC OPTIMIZATION PROCESS

The seismic optimization process has two distinct phases. In Phase I, an independent steel module was examined assuming fixed boundary conditions where the module is connected to the concrete Internal Structure (I/S). A modal analysis was performed and flexible modes and mechanisms were eliminated from the module in the first pass. The significant vibration modes of the module were determined and a response spectrum analysis was performed to determine acceleration levels. The input spectra used was taken to be an FRS curve for a concrete node generated during the earlier concrete I/S seismic analysis phase. This node was positioned approximately at the mean elevation of the steel modules.

From the Phase I analysis it was determined that the high accelerations were dependent on both the frequency of the module global sway modes and local vertical vibration modes. Any modifications made to increase the frequency of the sway modes and eliminate local vibration modes would have the beneficial effect of lowering the module accelerations levels. The sway frequency was increased through greater module stiffness achieved by using additional crossbracing, larger section sizes and increased module connections to the concrete I/S. The effects of the local vertical modes were reduced by adding more columns, using larger beam sections and increasing the use of moment connections. The modifications made to module RM40 is shown in Figure 5. In general,the seismic response improved as the module stiffness increased.

In Phase II of the seismic optimization process, a much larger analysis model was employed. In this model the steel modules were integrated with the 3D model of the concrete I/S. This model was designated the "Integrated Model" (Figure 6) and a seismic analysis of the complete structure was performed for Hard Rock, Medium and Soft Soil site conditions. The Phase II model has the capability to accurately account for the complex concrete/module structural interaction, in contrast to the Phase I model where this effect is neglected. In addition the I/S torsional characteristics were accounted for, which is important due to the asymmetric structural configuration of the I/S about the B/D plane.

4.1 Analysis Methods and Software

The response spectrum analysis method is used in the module optimization process and the modal contributions in each direction are combined by the Complete Quadratic Combination (CQC) rule. Complete details of this analysis method are found in Reference [1].

ANSYS [3,4] and STARDYNE [5] computer programs were used in Phases I and II respectively. The analytical models were obtained from the 3D CADDS database utilizing existing translator programs.

The steel module Floor Response Spectra (FRS) generated to assess the seismic behaviour of each module was generated with the AECL in-house code FRS2-MICRO. FRS2-MICRO uses the natural frequencies, mode shapes and modal participation factors contained in the STARDYNE generated TAPE4 as input for the FRS generation.

5.0 ANALYSIS MODELS

The analysis models used in the Seismic Optimization process are described below. A simple Reactor Building module, RM40, is used as an example to demonstrate the process.

5.1 Independent Model: Fixed Base Module RM40

The original steel module designs for RM40 is illustrated in Figures 5. RM40 is located above the Fuelling Machine Maintenance Lock 115 M Floor on the D side of the Reactor Building and contains F/M auxiliaries, D_2O valve station, Floors at elevation 117 and 122.5 m and HVAC equipment.

For Phase I of the optimization process, fixed base conditions were assumed where modules columns and beams are to be connected to the concrete internal structure. Lumped masses were applied and starting with the original steel module, an iterative analysis process was performed in which a response spectrum analysis was performed. The input was taken as the FRS at elevation 117.3 m, which is approximately the average elevation of RM40 steel module. After each analysis iteration, designer input was obtained and changes were made to improve the seismic response. These changes included using additional cross bracing to stiffen the structure to resist excessive sway, increasing beam and column cross section sizes to eliminate local flexible vibration modes, adding more restraints points from the steel modules to the concrete internal structure and increasing the use of full moment connections.

Optimized module RM40 is shown in Figure 5. A similar procedure was repeated for modules RM21 and RM10. The optimized modules were then used in the Integrated Model.

5.2 Integrated Model: Concrete I/S with Steel Modules

The optimized steel modules were integrated with the complete 3D model of the concrete internal structure and the stick model containment structure. This model has been designated the "Integrated Model" and is shown in Figure 6. The entire model was placed on soil springs used to model the soft, medium and hard rock design basis soil conditions. This model is capable of accounting for the concrete I/S / steel module interaction. An important structural characteristic of this model is its capability to model the concrete internal structure torsional natural frequency to a greater accuracy than the stick model internal structure used in the earlier conceptual analysis stage.
It was observed that the equipment placement on the steel modules via lumped masses can have a significant impact on the module dynamic response. Therefore to achieve realistic and accurate seismic analysis results, a detailed model of the concrete/steel structure as provided by the Integrated model is required.

6.0 SEISMIC ANALYSIS RESULTS

Attached in Tables 1 and 2 are sample acceleration levels in steel modules RM10, RM21 and RM40 (Figure 6) in addition to the concrete I/S and Containment Structure (C/S) based on CQC modal combination rule. Figure 7 shows representative FRS curves generated at selected module and concrete nodes for the hard rock soil case.

The following observations are noted from the seismic analysis results of the steel modules:

- The fundamental vibration mode of the system has a frequency of 3.7 Hz and 7.5 Hz for the Soft Soil and Hard Rock site conditions respectively, which is the C/S rocking mode.
- The Hard Rock FRS response is generally greater then the Soft Soil response.
- It is noted that the CQC acceleration levels predicted for modules in the integrated model were comparable with the Phase I independent model results.
- The addition of steel modules does not significantly effect the concrete I/S seismic response.
- The seismic response for steel modules have been reduced significantly from the early conceptual results. In some areas the reduction is as high as 60%.
- The peak accelerations for the modules in the A/C and B/D directions are not the same due to the non-symmetric nature of the module to concrete connections.
- The peak steel module FRS accelerations are comparable with the concrete acceleration values predicted at the the top of the steam generator box.
- The steel module response is sensitive to the location of equipment lumped masses on the steel floors.

7.0 CONCLUSIONS

Modular reactor construction advantages result in greater productivity and a reduced construction schedule. Achieving an acceptable seismic design for the CANDU 3 modules requires an iterative optimization process to be conducted in which the module Designer and Analyst work closely together to improve the module seismic performance. The main conclusions of this study are:

- It was determined that high module seismic response occurs due to the steel module flexibility, which may be local or significant lateral sway. Excessive module flexibility is dependent on lack of connection points to the concrete internal structure, insufficient use of cross bracing, use of inadequate structural sections, and the lack of floor supporting columns and moment connections in the steel module. As a result, the seismic response of a flexible steel module can vary significantly from its adjoining concrete structure when the concrete/steel interaction effects are accounted for.
- A seismically designed modularized CANDU 3 reactor building can be attained if particular attention is made to eliminate excessive module flexibility.
- A two phase seismic optimization process is proposed that will quickly ferret out module deficiencies in the first phase, followed by the second phase where integrated model developed is capable of accounting for module/concrete structural interaction accurately.
- In general the steel module Floor Response Spectra (FRS) generated from the integrated model, after performing the module optimization, are within acceptable levels.

- Benefits of the integrated steel/concrete model include greater accuracy in the base slab overturning forces and inclusion of the internal concrete structure torsional mode effects on the steel module seismic response.

- The Hard Rock site conditions produce greater peak accelerations levels in the steel modules.

- Increased connection of the modules to the concrete reduces the seismic response at the expense of higher thermal loads. However, the thermal loads appear to be with allowable limits.

Future analysis studies and development work include:

- Further studies to optimize and confirm the module/concrete connection with the aim of reducing the thermal loads without compromising the seismic response.

- Study the addition of miscellaneous steel into the integrated model. The seismic response may be improved permitting the use of smaller steel sections. The thermal loads would also need to be investigated.

8.0 REFERENCES

[1] "General Requirements for Seismic Qualification of CANDU Nuclear Power Plants", Canadian Standards Association, 178 Rexdale Blvd., Toronto Ontario, M9W 1R3, CAN3-N289.1-80.

[2] "Design Procedures for Seismic Qualification of Candu Nuclear Power Plants", Canadian Standards Association, 178 Rexdale Blvd., Toronto Ontario, M9W 1R3, CAN3-N289.3-81.

[3] DESALVO, G.J., and GORMAN, R.W., "ANSYS User's Manual", Swanson Analysis Systems Inc., May 1, 1989.

[4] KOHNKE, P.C., "ANSYS Theoretical Manual", Swanson Analysis Systems, Inc., 1987.

[5] STARDYNE, Version 3.6, 1991, Supercomputer Solutions.

TABLE 1 : CANDU 3 MODULE STRUCTURAL ACCELERATIONS

			Acceleration (g)								
			Soil								
Module	Node	Elev.	Soft			Medium			Hard		
			X1	X2	X3	X1	X2	X3	X1	X2	X3
RM10	223	122.5	.57	.71	.41	.53	.93	.42	.42	.84	.50
RM21	1711	122.5	.67	1.13	.45	.76	.94	.39	.88	.86	.35
	1692	122.5	.71	1.05	.69	.92	.88	1.45	1.35	.85	1.52
RM40	1362	122.5	.92	2.04	.52	1.22	2.29	.82	1.50	2.62	.67
	1437	122.5	.81	1.22	.48	.96	1.32	.99	1.06	1.63	1.12

Table 2 : CANDU 3 CONCRETE STRUCTURAL ACCELERATIONS

		Acceleration (g)								
		Soil								
CONCRETE I/S		Soft			Medium			Hard		
Node	Elev.	X1	X2	X3	X1	X2	X3	X1	X2	X3
883	123.5	.63	.79	.40	.65	.86	.33	.58	1.01	.27
1233	131.3	.84	.92	.34	.89	.99	.33	.86	1.09	.23
CONCRETE C/S										
6	122.5	.60	.61	.31	.68	.68	.28	.77	.72	.26
9	143.5	.97	.98	.33	1.15	1.15	.31	1.36	1.27	.35

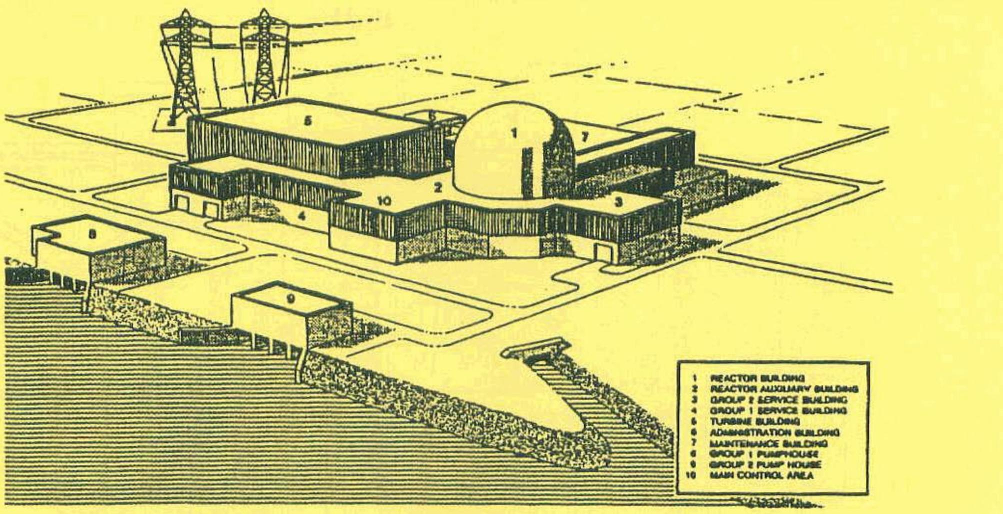


FIGURE 1 CANDU 3 STATION LAYOUT

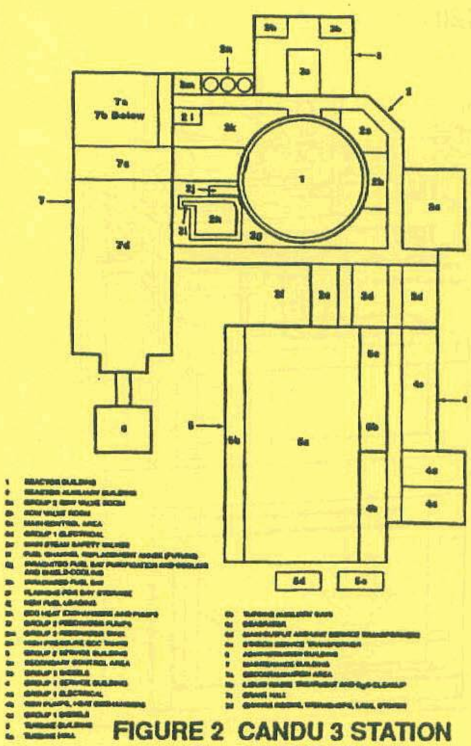


FIGURE 2 CANDU 3 STATION LAYOUT PLAN

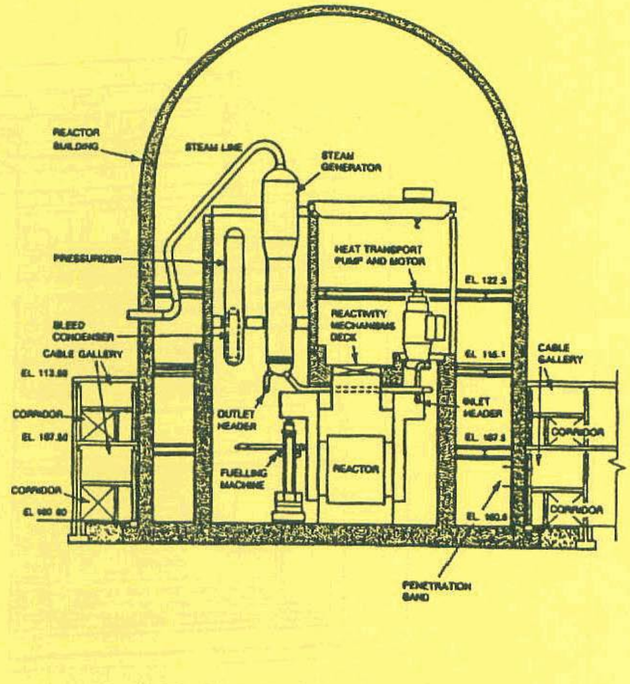
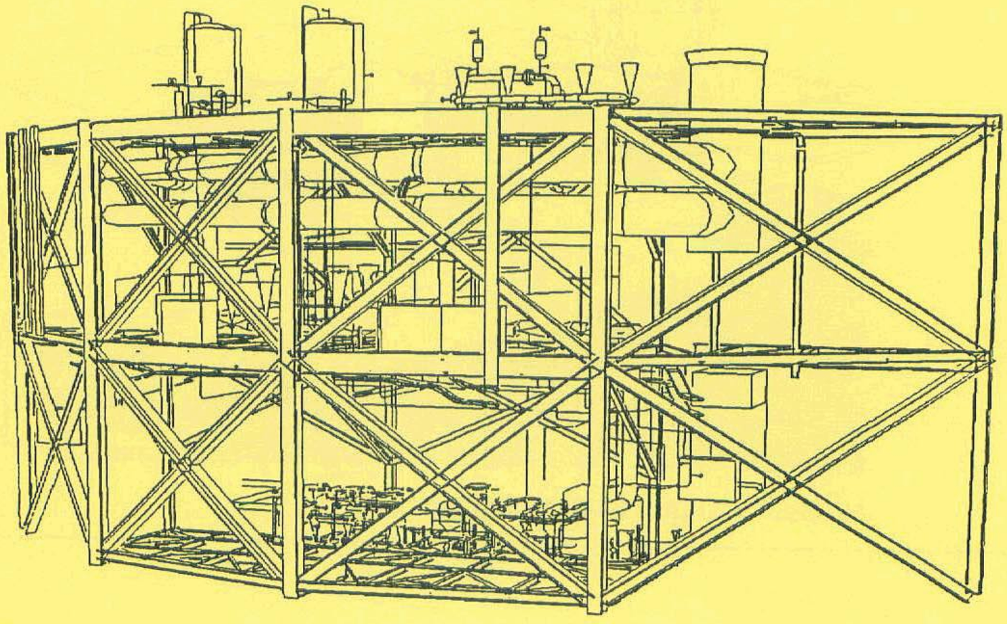


FIGURE 3 CANDU 3 REACTOR BUILDING SECTION

RM10



RM20

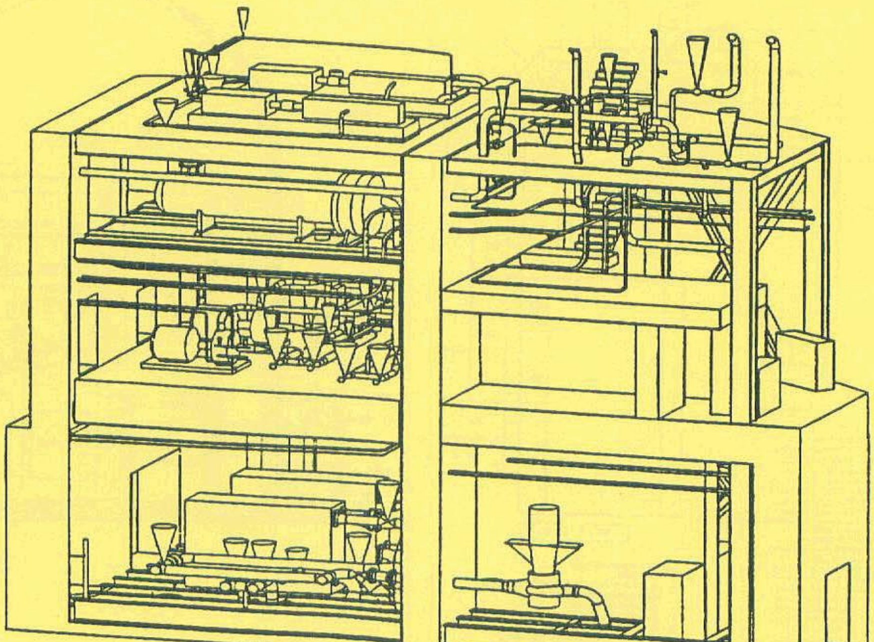
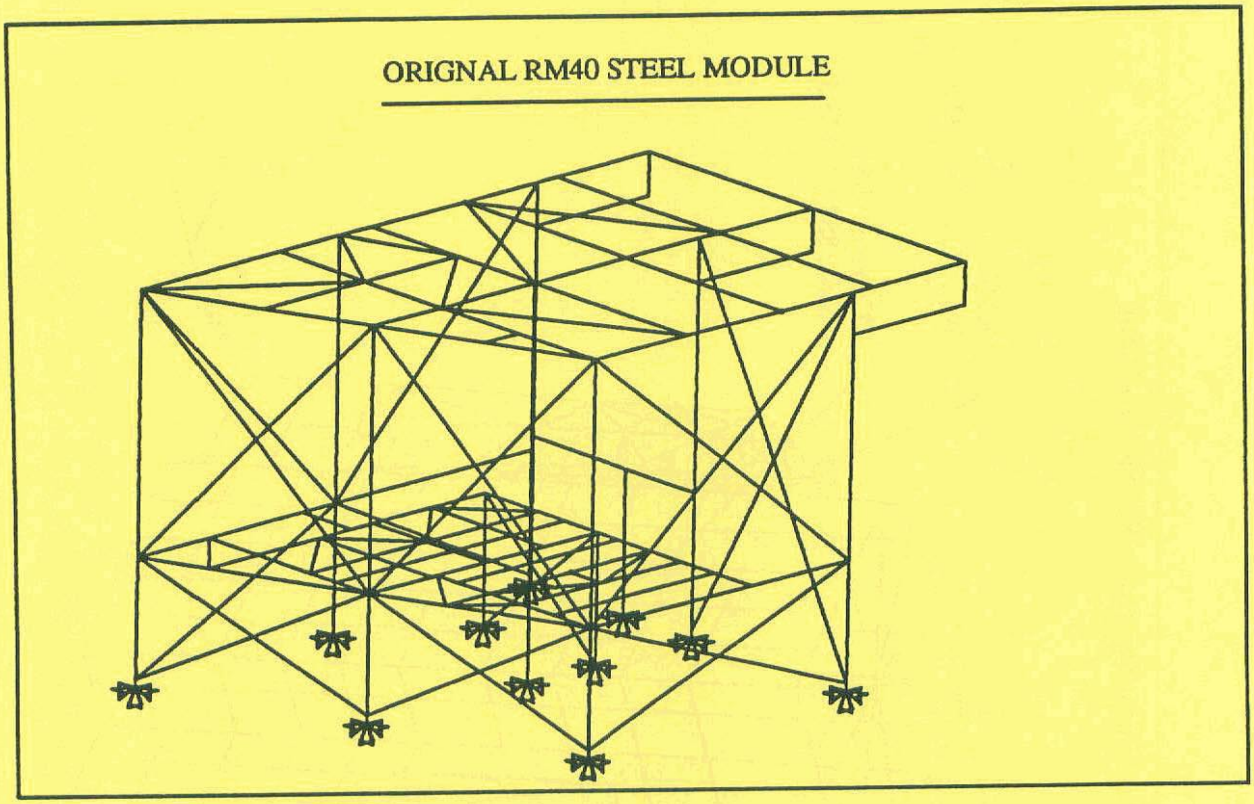


FIGURE 4 CANDU 3 REACTOR BUILDING MODULES RM10 & RM20



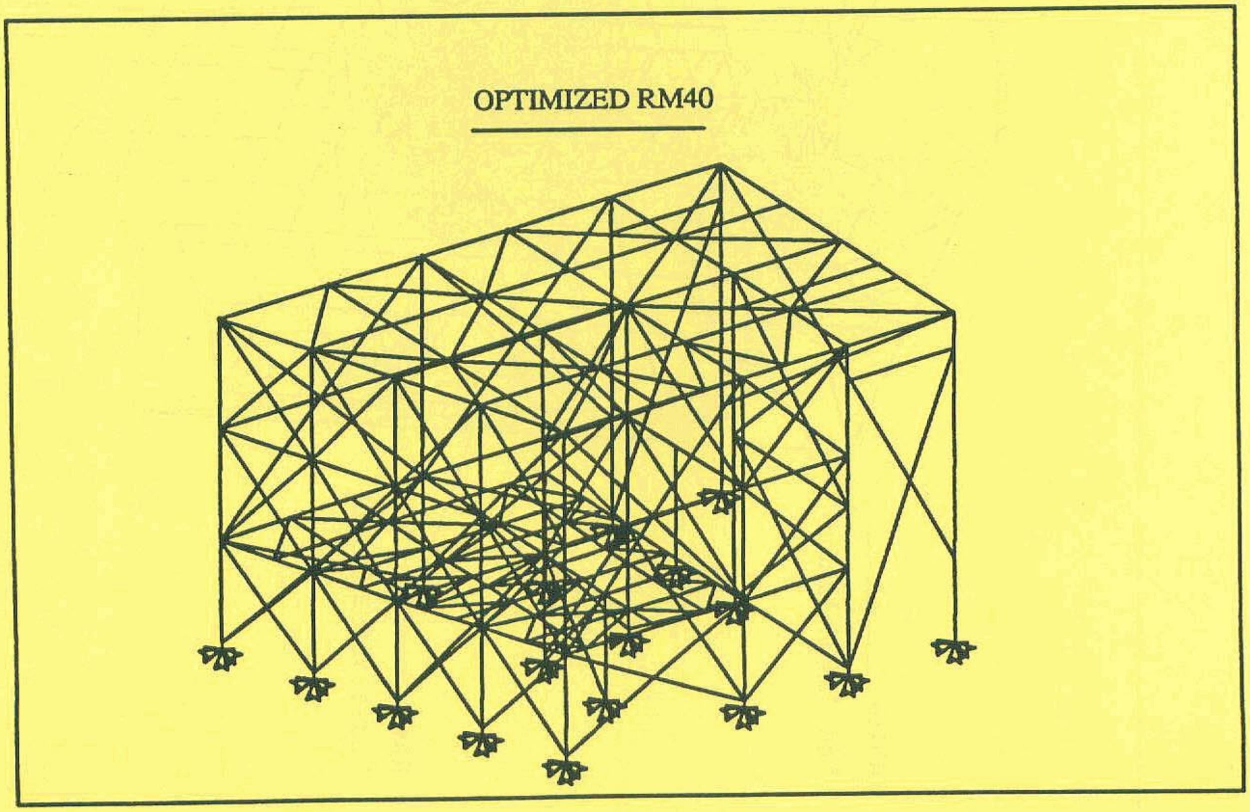


FIGURE 5 : MODULE RM40 BEFORE AND AFTER OPTIMIZATION

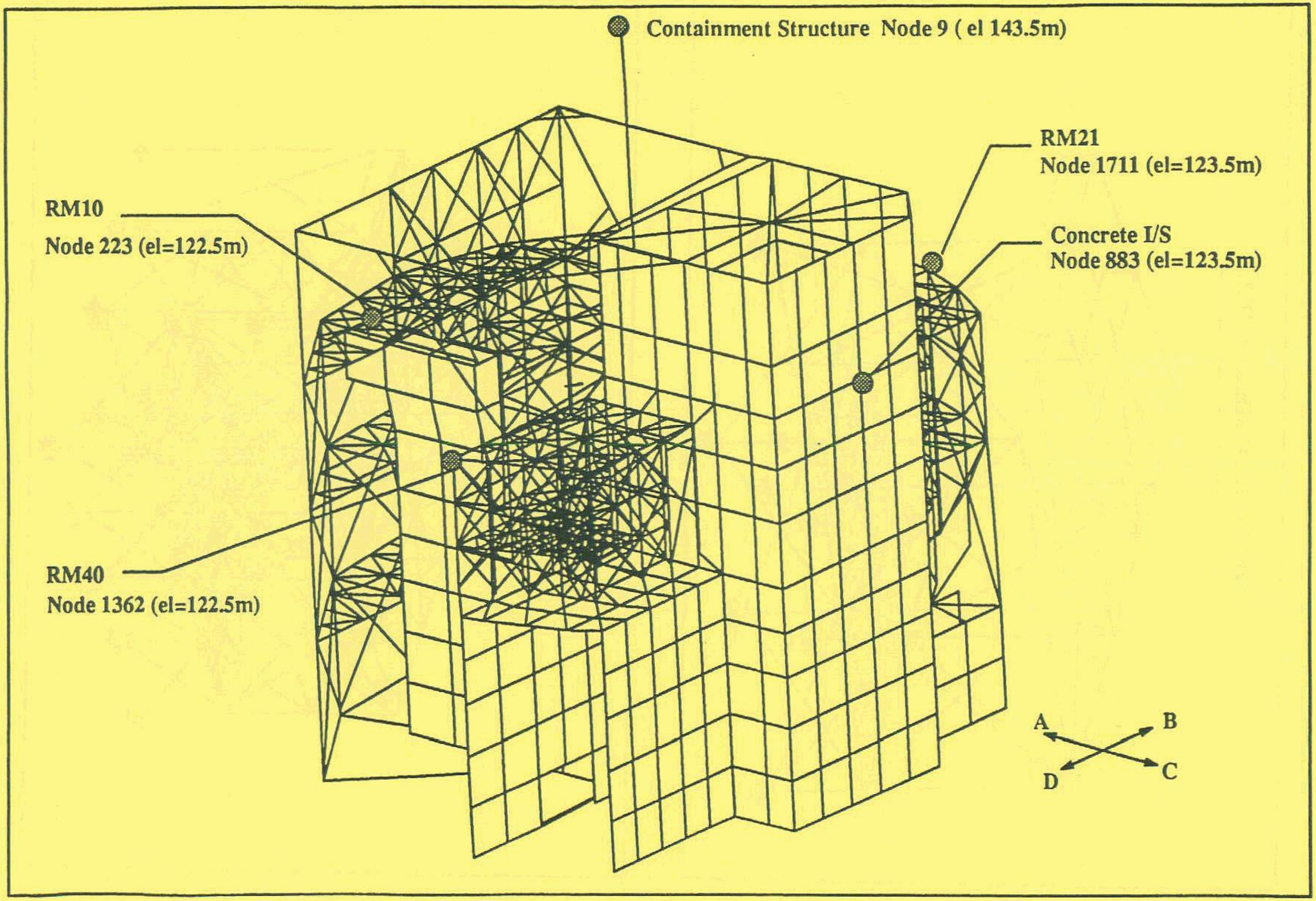
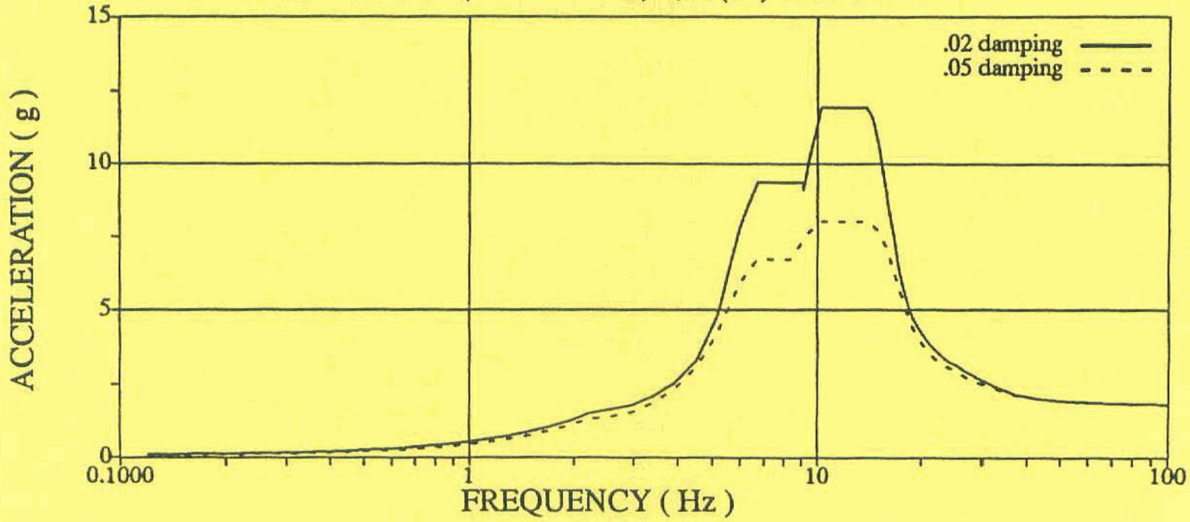


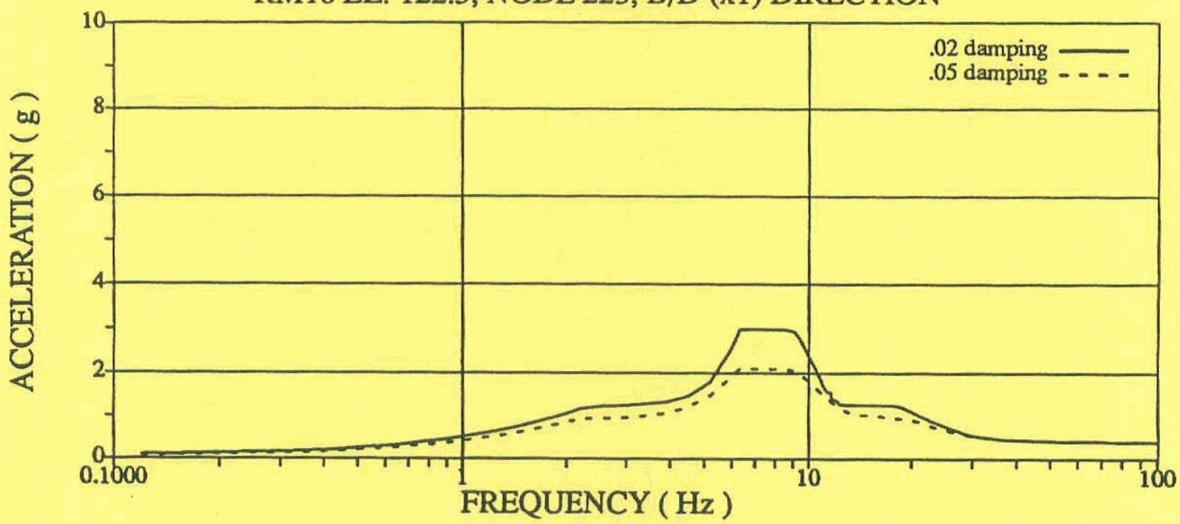
FIGURE 6 : CANDU 3 INTERNAL STRUCTURE AND MODULES RM10,21 & 40 (sample FRS points)

FIGURE 7 : CANDU 3 INTEGRATED MODEL – HARD ROCK FRS

RM40 EL. 122.5, NODE 1362, A/C (x2) DIRECTION



RM10 EL. 122.5, NODE 223, B/D (x1) DIRECTION



CONCRETE I/S EL. 123.5 m, NODE 883, A/C DIRECTION